Ground Improvement Technique – Grouting Technology
(For Irrigation Projects and Tunnelling)

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Chapter 1. Introduction

Grouting in civil works activities is performed as: (1) an element of permanent construction, (2) a post-construction remedial treatment, or (3) an element of expedient construction or repair. Examples of permanent construction are curtain grouting in foundations for dams and ground stabilization of foundation materials for large buildings.

Examples of post-construction remedial treatment include grouting voids under concrete structures and reducing leakage through dam foundations or abutments. Grouting is used for both temporary and permanent treatments. It should be considered in combination with other appropriate types of treatment for best results. Other types of treatment may include excavation, compaction, concrete cutoff walls, slurry trenches, impervious blankets, drainage blankets, and filter zones. Treatments also include relief wells, drilled drains, sheet pile cutoff, dental concrete, drainage tunnels and galleries, underpinning, and structural foundations. Purposes of expedient grouting include repair of roadways, cofferdams, and stability and groundwater control during construction.

Brief History of Injection Grouting

Origins: Injection grouting originated in Europe. The first known case history of deliberate pressure injection occurred in France in 1802, where it was used to repair the foundations of a timber weir and a sluice structure. A crude type of piston pump was used to inject clay grout into alluvial materials and mortar grout into voids. Subsequently, injection grouting was used for the repair of a number of lock structures and repair of masonry structures in the period from 1802 into the 1850s. From the mid-1850s into the early 1890s, there were a number of significant advances in grouting that led to more frequent use in foundation repair, mining, and hydraulic structures. Compressed air pressure vessels were developed to facilitate increased injection pressure, stirring systems were developed to keep grout in suspension, and improved piston pumps were developed. The first known application of rock grouting for dams occurred in England between 1876 and 1878.

Systematic grouting of dam foundations in the United States appears to have started at New Croton Dam in New York in 1893. A limestone foundation was treated on a large scale by drilling holes with compressed air drills, washing out major fissures, and grouting under a gravity head or with a hand-operated pump and/or a piston-like rammer. The first major application of cement grouting occurred in 1912 at Estacada Dam in Oregon, where three rows of grouting totalling 34,120 ft (10,400 m) of grout holes were used in its construction. Publication of the details of the grouting program by the American Society of Civil Engineers (ASCE) in 1915 led to great interest and discussion within the profession on grouting procedures, problems, and results.

Grouting at Hoover Dam in the 1930s marked as the development of a systematic approach to dam grouting, and the acceptance of cement grouting as a normal feature for treatment of dam foundations. Grouting at Hoover Dam was far less than fully successful, and excessive seepage occurred on first filling, requiring extensive remedial grouting between 1938 and 1947. From the 1930s forward, dam construction and dam foundation grouting was a prominent activity within the United States. Agencies such as USACE, the Bureau of Reclamation (USBR), and Tennessee Valley Authority (TVA) all constructed a large number of dams from that point into the early 1980s.

Recent History of Advances in Grouting

(1) Advances have been made based on available technology in computers and instrumentation. The Waterways Experiment Station's (Now known as the Engineer Research and Development Center, Waterways Experiment Station (ERDC-WES)) CAGE program (Computer Applications in Geotechnical Engineering) developed a computer program for monitoring grouting that was used at Buffalo District's Black Rock Lock in 1975 and at Center Hill in 1984. Interest by USACE in using better technology on site for grouting was revived by the Jacksonville District during the grouting of the Portuguese Dam foundation in Ponce, Puerto Rico, in 1997–1999. The results of these investigations and other field experimental efforts led to the determination that ultrafine cement was required for effective grout penetration, which marked the first use of ultrafine cement grouts.

(2) Concurrent, the private sector was in the process of implementing other major advances in technology. In 1998, Penn Forest Dam in Pennsylvania was the first project to use real-time automated data collection and display technology for grouting, along with balanced stable grout formulations.

(3) Since 1998, USACE has actively supported and embraced the latest developments in grouting, including: (1) design of grouting as an engineered feature, (2) use of balanced stable grout mixes, (3) advanced computer monitoring, control, and analysis for controlling grout injection, production of project records, and performance verification, and (4) Best Value Selection for grouting projects.

Chapter 2. Purposes of Grouting

General

Grouting is the process of injecting liquids, mixed suspensions, or semi-solid mixtures under pressure to achieve one or more desirable end results in terms of improving engineering properties. To accomplish this, the injected grout must eventually form either a gel or a solid within the treatment zone. Permeation grouting is the injection of high-mobility grouts (HMGs) into small voids within soil or rock masses, into small voids between these materials and an existing structure, and/or into small cracks or fractures within structures themselves. Void-filling grouting involves using low- (or limited) mobility grout (or grouting) (LMG) or other materials having properties suitable for effective filling of large voids. Compaction grouting is the injection of plastic, semi-solid mixtures to densify or displace deformable materials. In-situ modification or replacement includes specialized techniques such as jet grouting or hydrofracture grouting. The following paragraphs describe the engineering properties that can be improved by grouting. Depending on the specific application, grouting is used as either the primary or sole means of effecting property improvement, or it may be used in conjunction with other technologies and methods.

a. **Permeability Reduction:** Grouting is commonly used to reduce permeability, which might be necessary for reducing rates of seepage or leakage through or into new or existing structures and foundations, reducing hydrostatic forces acting on structures, altering flow gradients or flow paths to achieve specific design objectives, inhibiting internal erosion of foundation and embankment materials, and/or controlling water for excavations as required to facilitate dewatering or excavation stability. *In any critical hydraulic application, grouting is normally one of several lines of defence.*

b. **Improvement of Mechanical Properties**: Grouting can be used to improve the mechanical properties of soil or rock foundation materials for structure or excavation support purposes. Properties that can be improved by grouting include enhancement of bearing capacity, improvement in settlement-related properties such as elastic modulus and void ratio, improvement in shear strength, and elimination of voids that might adversely affect either loading conditions or the response to loads. Grouting can also be used as a settlement compensation method to prevent or repair damage to structures.

Typical Applications of Grouting

a. ***Dams and Lock Structures***: Typical applications of grouting for new or existing earth and concrete dams, and for lock structures include:

- Hydraulic barrier grouting to control leakage and pressure distributions.
- Foundation consolidation grouting to reduce foundation and structure deformations.
- Compaction grouting for densification of loose deposits or jet grouting to replace zones of loose materials.

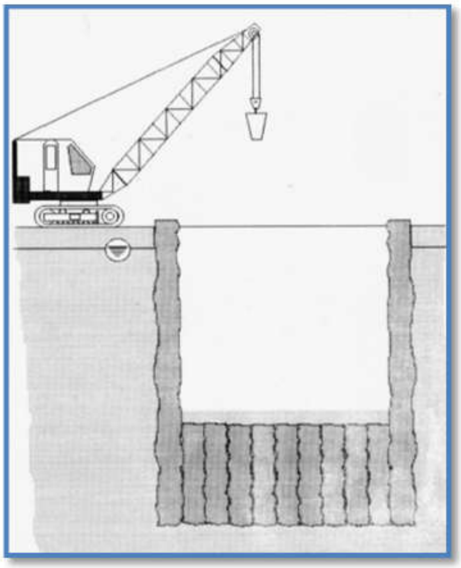


Figure 2-1 Application of Jet Grouting for Consolidation and Waterproofing

- Pre-treatment of fractured rock foundations to enable cut-off wall construction.
- Grouting of leaking cracks or joints in structures.
- Abandonment or backfilling of exploration and instrument holes.

b. ***Tunnels***: Typical applications of grouting for tunnel work include:

(1) Grouting in advance of tunnelling to reduce water inflows during construction.

(2) Grouting in advance of tunnelling to improve excavation stability and/or reduce or to prevent ground loss during tunnelling.

(3) Grouting between the tunnel lining and the tunnel excavation surfaces.

(4) Remedial grouting of joints and cracks to reduce leakage.

(5) Compensation grouting during tunnelling to prevent settlement and to protect structures that would be adversely affected by ground loss during tunnelling.

Figure 2-2. Seepage in Tunnel

c. ***Other Grouting Applications:***

(1) Rock and soil anchor grouting to develop anchor capacity and to provide corrosion protection.

(2) Lifting of structures by displacement grouting methods.

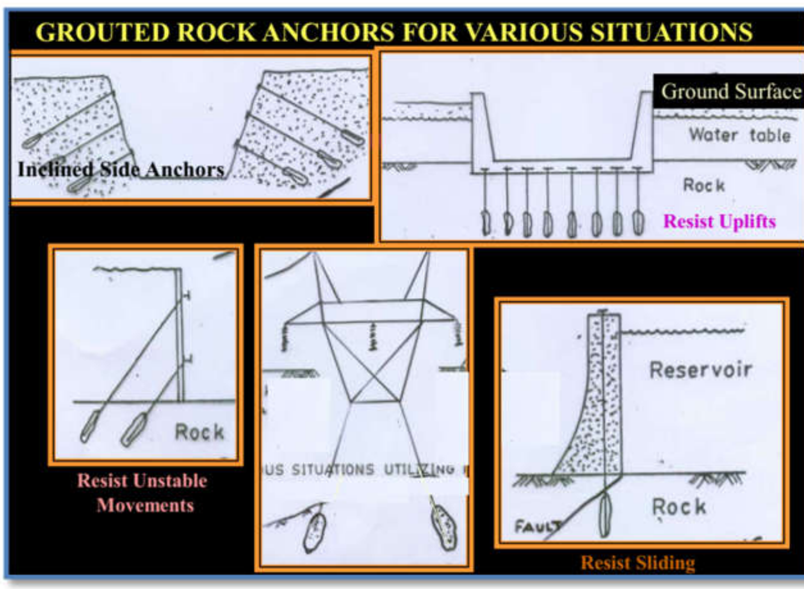


Figure 2-3 Grouting Applications for Foundation subjected to Tension

(3) Filling of abandoned pipes or other underground structures.

(4) Annular space grouting for pipes being re-lined.

(5) Environmental applications.

(6) Filling of mine voids.

(7) Vibration Control.

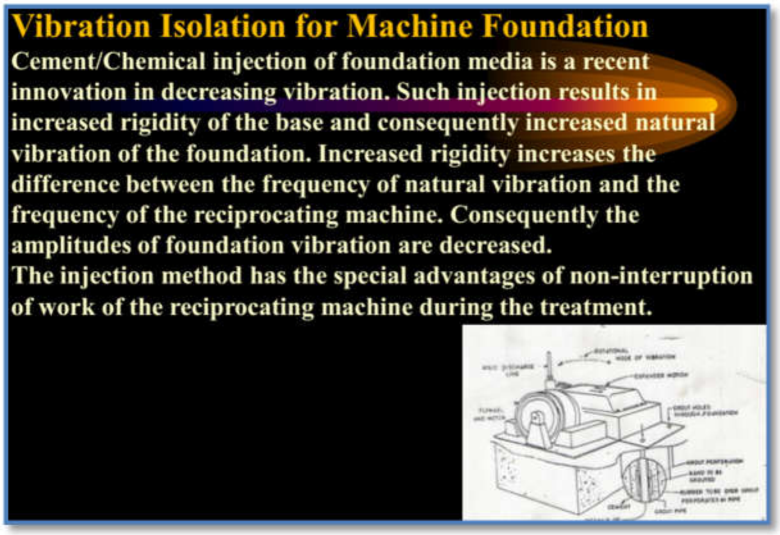


Figure 2-4 Vibration Isolation by Grouting

Selection of Treatment Methods

Grouting is one method of treating problematic subsurface conditions to reduce permeability or improve engineering properties of the foundation. However, other methods of treatment may be required in addition to or instead of grouting. Where structural safety is involved, multiple lines of defence will frequently be required. The selection of grouting as the method of treatment should be based on an evaluation of all pertinent aspects of the problem, including engineering needs, subsurface conditions, and economic considerations.

Potential Risk and Reliability Issues of Grouting

a. ***Reliability of Grouting***: Grouting will be a technically reliable means of accomplishing an intended purpose in any given application only if the following factors are present in the program: (1) geologic exploration that has been sufficient in scope and nature to allow proper characterization of the site specifically for grouting, (2) sound interpretations based on that information, (3) reasonable performance expectations for grouting that are consistent with the site conditions, the design, and the expected level of execution and quality control, (4) a thorough evaluation of the risks involved in pressurizing sensitive foundation materials, (5) well written and detailed plans and specifications that clearly define expectations, procedures, and QA/QC requirements, (6) and a thorough results verification program that is included as part of the construction. In the absence of one or more of these items, grouting frequently fails to meet expectations and/or performance requirements and can result in large expenditures with little improvement.

b. ***Grouting Risks****:* Historically, grouting has been one of the higher risk elements of construction, primarily because of the number of factors that can affect the overall outcome, but also because neither the actual features are grouted nor the behaviour of the grout in those features can be directly observed during the course of the work. Frequently, grouting is executed in advance of other operations and is completed before the grout performs its intended function (e.g., before filling of a reservoir, during construction of a foundation, in advance of excavation). Grouting has also historically been an operation frequently subject to cost increases and/or extensions of time, sometimes due to unexpected subsurface conditions. Some factors that substantially reduce the overall risk of any grouting program are:

- Adequate and appropriate site investigations.
- Sound site interpretations as they relate to drilling and grouting.
- Appropriate program layout for the site conditions and intended results.
- Proper sequencing and staging requirements.
- Proper material and mix selections.
- Proper pressures.
- Proper refusal criteria consistent with the program's intent and performance requirements.
- Modeling of the site using realistic expected performance parameters.
- Appropriate, adequate, high-quality drilling and grouting equipment.
- A Quality Control and Quality Assurance Program that includes adequate inspection, control, testing, and analysis of the grouting work.
- Effective results verification program.
- Effective use of partnering to resolve technical and contractual issues.
- Adequate instrumentation to monitor project performance and distress during construction.

Permanence of Grouting

a. **Applications.** Grouting can be used for both permanent and temporary applications. The durability of grouting depends on the grout mix design and rheological properties, the environment into which the grout is placed, the quality of the final grouted product, and the service conditions. For example, the permanence of a grout curtain in fractured rock will depend on whether the rock fractures are clean or soil filled, the residual permeability achieved, and the gradient across the curtain. Where the grout formulations are properly designed, the rock fractures are clean, and the residual permeability is low, a completed curtain can be installed with a design life equal to that of the above-ground structure. When sulfate is present in the injected environment, durability can be an issue if sulfate-resistant cements or admixtures are not used. There are applications where, for expedience or feasibility, neat cement grout may be appropriate.

b. **Long-Term Strength.** Long-term strength is often a consideration for soil grouting applications. Permanence of grouted soil masses requires careful consideration of the grout materials and requires that the grout mix design be established by an experienced grouting professional. For cases where the rock fractures are not clean and are soil filled, future maintenance grouting may be needed to continue the level of protection.

Communication of Grouting Issues

Grouting, when executed properly, is often the best technical and/or most economically effective solution for a particular problem. However, it can also be a complex and expensive undertaking that is a critical element for the overall success of a project. Historically, it has been common that communication of critical information about grouting that is needed by project decision makers has been very limited and/or qualitative in nature. Throughout all phases of the project, from inception to completion, it is incumbent on the Project Delivery Team to clearly articulate all of the issues related to grouting. The project team must be able to: (1) technically substantiate the selection of grouting as an appropriate solution to a particular problem within the context of the site conditions, (2) present a rational basis for the types and amounts of grouting required, (3) quantify the expected performance results and benefits to be achieved, (4) identify the risks involved and the risk management strategy for each of those risks, (5) define the verification program, and (6) reasonable estimate the costs and contingencies.

Chapter 3. Planning, Design, and Construction Process

Application of Design Principles:

The level of technical oversight by the agency shall be appropriate for the level of risk and complexity of the project. The purpose of any grouting project, especially one designed for remediation of seepage problems involved with any water retention project, needs to be fully defined and analyzed. The unique site characteristics and dam safety issues shall be considered when determining the most effective and economical solution, ensuring that the method chosen is the most suitable to achieve the desired results. The design and extent of the grouting program depends on the purpose for which it is intended, whether it is for avoiding the loss of slurry during cutoff wall construction or for installing a seepage barrier. The involvement of experienced personnel is required from the start of the design phase and throughout the course of construction to provide technical expertise, guidance, and oversight to ensure that the grouting program satisfies the intended objective.

Effectiveness of Grouting:

Grouting is an extremely effective treatment technology, but from a historical perspective, there have been many unsatisfactory project experiences. Unsatisfactory outcomes have included: (1) unreliable prediction of end performance, (2) unsatisfactory initial performance, (3) unsatisfactory long-term performance, (4) cost overruns, delays, and claims for additional compensation, and (5) ineffective communication about the need for grouting, the amount of grouting required, and the results of grouting. Each of these types of unsatisfactory outcome is the direct result of one or more shortcomings in proper execution of the planning, design, and construction process.

Reconnaissance Phase:

The purpose of the Reconnaissance Phase is to identify an existing problem and potential solutions or to define a project to address a specific public need. Any evaluation of the possible applicability of grouting as an element of a project will be based on general geologic information, any site-specific information that might exist, and sound engineering judgment of conditions generally suitable for grouting and reasonable expectations of grouting results in comparison to other technologies that are available. An important outcome of the Reconnaissance Phase is an understanding of the scope of investigations and studies required for the Feasibility Phase.

Feasibility Phase:

a. Purpose: The purpose of the Feasibility Phase is to formulate a specific solution to address a specific public need. Work in this phase includes studying potential solutions, evaluating costs and benefits, preparing initial designs, and recommending a plan to solve the problem. An important objective is to develop the design of the recommended plan in enough detail that it can be authorized, implemented, and constructed without major changes in concept, cost, or schedule. With respect to grouting, the Feasibility Phase will include a site investigation and characterization, a preliminary evaluation of the technical suitability of the site for grouting, a determination of the potential benefits to be derived from grouting, and a preliminary estimate of the cost. Geophysical investigations can be used to define seepage pathways and to aid in the design of further investigations. The geotechnical investigations may include borings, which allow both water tests for estimating in-situ hydraulic conductivity and borehole imaging for characterizing the ability of the rock to accept grout.

b. *Quantification of Site Conditions:* Geologic and geotechnical investigation data need to be summarized in terms of engineering parameters and also in terms of the parameters needed to assess the applicability of the specific grouting methods being considered. Items that should be considered for rock materials include: (1) presence and locations of discontinuities, (2) orientation and spacing of rock fracture systems, (3) rock mass permeability, (4) rock quality as it relates to the ability to maintain open grout holes, (5) depth or thickness of weathered and infilled fractures, (6) compressive strength of the rock, (7) elastic modulus of the rock, (8) abrasiveness of the rock, and (9) effective stress conditions in the rock. Items that should be considered for soil materials include: (1) Soil classification, (2) density or consistency, (3) grain size distribution, (4) consolidation properties, (5) and effective stress conditions in the overburden. For the site in general, the piezometric levels and the nature of the flow regime must also be known with reasonable certainty.

c. *Assessment of Grouting Suitability and Special Issues:* Information gathered during the site characterization can be used to define areas that are suitable or not suitable for grouting and the probable degree of improvement. In addition, zones requiring downstage grouting and special treatment, such as zones with artesian pressures, the soil-rock interface, open and infilled voids, and alluvial materials, should be defined.

d. *Establishment of Design Criteria and Objectives:* Clear and quantitative design criteria and objectives should be established for the performance of the structure. Examples include such items as: (1) a specific maximum seepage rate, (2) a maximum foundation deformation and/or structure deflection, (3) a target density, (4) a specific pressure distribution pattern, (5) a specific shear strength, or (6) a specific permeability in a grouted zone.

e. *Analysis of Foundation and Structure Behaviour on the Basis of No Improvement in Properties:* As a baseline condition needed to assess the benefits of the proposed grouting, the foundation and/or structure should first be analyzed on the basis of the unaltered properties.

f. *Development of Cost Estimates and Selection of Recommended Program:* Preliminary cost estimates for alternatives that meet or exceed the performance requirements should be developed. Then the quantitative and qualitative benefits of each alternative and the incremental performance benefits derived from different concepts and configurations should be evaluated. Based on these evaluations, a recommended program should be selected. Once a program is selected, the details of the program should be expanded, including the development of a detailed list of work items. From this, a final cost estimate using quantities and units should be prepared and a cost-reality check using information from other successful projects and external information sources should be performed.

g. *Preliminary Assessment of Grouting Applicability:* If property improvement is of potential benefit or necessary for the performance of the structure, the next step is to perform a preliminary assessment of the suitability of the site for grouting. Some general guidelines for various rock and soil conditions are:

(1) Clean rock fractures are readily groutable at Lugeon values of 50–100 or greater, and it is possible to routinely achieve post-grouting permeabilities of 10 or less, depending on the sophistication of the grouting program.

(2) Clean rock fractures are marginally groutable at Lugeon values of about 10. It is possible to achieve post-grouting permeabilities on the order of 1 with a very carefully planned and executed program. If numerous special methods and materials are used, it might be possible to achieve post-grouting permeabilities on the order of 0.1 Lugeon.

(3) Clean rock fractures are barely groutable at Lugeon values of about 1. Rarely is grouting required at this level, but if it is needed for special applications, the permeability can be reduced to about 0.1 Lugeon if special methods and materials are used.

(4) Highly weathered and soil-infilled fractures in rock are problematic for grouting. In general, it is not possible to thoroughly wash erodible materials from the fractures before grouting. These materials have been successfully grouted by using multiple lines of grouting to confine the infilling and reduce the flow gradient across the zone. Provided all stages on all holes and on all lines are brought to full refusal at the desired grouting pressure, some level of confidence is possible that the zone has been adequately grouted.

(5) Consideration must be given to the quality of the rock and/or the frequency of water losses, as those items affect the required drilling and grouting procedures and costs. *In general, a Rock Quality Designation (RQD) less than about 40% may require downstage grouting rather than upstage grouting*. Frequent water loss during drilling is also a strong indicator that either certain geologic zones or perhaps one or more series of holes in the grouting sequence will require the use of downstage drilling and grouting procedures.

(6) Known artesian zones may require special construction techniques.

(7) The ability to effectively grout soils by permeation into the pore spaces is highly dependent on the grain size characteristics of the soils and the uniformity of the soil deposits. While chemical grouts have a viscosity similar to water, grouts may penetrate into soils extremely slowly due to very low permeability created by even a small percentage of silts, clays, and very fine sands.

(8) The effectiveness of compaction grouts is a function of soil density, soil permeability, and groundwater levels. In a semi pervious material, the desired densification will be inhibited by the build-up of pore pressures in the soil, which might also create problems in their own right.

h. *Assignment of Improved Properties for Grouted Zones:* After the determination of what zones can be effectively grouted, the properties that can be reasonably expected to be achieved in the grouted zones should be assigned. An equally important part of this step is to determine how zones that are not good candidates for grouting will be treated. Techniques for zones that are not good candidates for effective grouting include removal of materials and/or application of other technologies such as cutoff walls.

i. *Configuration of the Dimensions of Grouted Zones and Re-analysis of Behaviour with Improved Properties within Those Zones:* A trial and error modelling process should be used for a preliminary evaluation of the benefits of various grouting configurations. The results from each trial configuration should be compared with the design criteria and performance objectives, and with each other, to understand both the total performance of a particular configuration and the incremental benefit/cost relationships of different alternatives.

j. *Development of a Preliminary Cost Estimate for Grouting:* After one or more trial grouting plans are established, a rough estimate of the quantities and costs should be prepared. At this level of assessment, the simplest method is to use bulk total grouting costs obtained from reasonably similar projects converted to a simple, single unit. When using data from other projects, it is important that the data be obtained from project completion reports and records rather than from initial unit pricing, since there can be a significant discrepancy between the two.

k. *Development of a Final Cost Estimate for the Feasibility Phase:* After the recommended grouting program is developed, a final cost estimate should be based on actual estimated quantities and units. Costs may vary greatly, depending on the application, project size, and injected volumes.

Preconstruction Engineering and Design Phase

a. *Detailed Design of Grouting Program:* Whereas the Feasibility Phase elements did not require a comprehensive understanding of every element of grouting, the PED phase cannot be initiated effectively without a thorough knowledge of equipment and methodologies that are appropriate and/or required for project-specific grouting conditions and applications. After preliminary selection of appropriate methodologies and equipment, it is necessary to outline the entire drilling and grouting process for typical grout holes in the site's geologic conditions, including all the steps and sequences that might be required on a hole. All special problems and issues must be identified, and workable solutions must be devised. Special problems can include such items as: (1) special requirements for drilling through existing dam embankments, (2) grouting of structure-foundation interface zones, (3) drilling and grouting in unstable zones, (4) dealing with voids, (5) drilling and grouting in weathered rock zones, the soil-rock interface area, and soil-filled fractures, (6) handling artesian conditions, (7) establishing environmental controls, (8) special deviation requirements, (9) protection of adjacent structures or features, and (10) site access and terrain considerations for the proposed equipment.

When grouting through an existing embankment dam or other critical structure, it is essential to determine the allowable safe grouting pressure that can be used without causing hydrofracture or damage due to displacement.

Final Design Criteria: In the PED phase, it is necessary to establish the minimum verifiable end results that can be achieved by grouting. The geometry and properties of the grouted zone need to be established with certainty. Because the satisfactory performance of the design is contingent on achieving these properties, they must be selected with care, conservatism, and due consideration of all the factors that might impact achieving them. After these values (such as the target permeabilities) have been determined, the construction process must result in attaining them.

b. *Constructability Evaluation:* Considering grouting within the overall needs of the project should be done early in the design process to evaluate the advantages and disadvantages of sequencing scenarios. Sequencing the grouting operation with respect to other aspects of the construction schedules should ideally be planned and controlled for the best technical result.

c. *Development of Detailed Program Layout:* Work during the PED phase will include a detailed layout of the drilling and grouting program, including hole spacing, line spacing, and hole inclinations and azimuths. The detailed layout must also establish: (1) the surface from which drilling and grouting is to commence, (2) the surface and site preparation requirements, (3) the depth of grouting, (4) the stage lengths for grouting, (5) any special vertical or horizontal sequence requirements, and (6) a determination of whether drilling and grouting is to be upstage, downstage, or some combination of the two.

d. *Design of Monitoring, Control, and Verification Methods:* Careful consideration should be given to how the results of the program will be analyzed as the work progresses in light of the project performance requirements. This includes the level of technology to be used, the records to be obtained, and how the records will be presented and used for verification. It should be anticipated that the grouting design will be modified as the work progresses. The design should be flexible to allow for the grouting program to be "engineered" in the field.

e. *Plans and Specifications:* Provided all the steps in the Feasibility and PED Phases have been executed properly, a sound blueprint for preparation of the P&S will be well established. The documents must provide an adequately detailed description of the materials, equipment, resources, methodologies, and results that are required by the contractor, and also a clear basis for acceptance, measurement, and payment for each element of the work.

f. *Quality Control and Quality Assurance Plan:* A complete list of all personnel and requisite skill sets that are required for successful control and execution must be compiled. The list must outline their responsibilities and experience qualifications and detail when these personnel should physically be on the project site. The complete process of observation, testing, recordkeeping, reporting, and analysis activities should be diagrammed. The QC program required of the contractor should cover the entire process. After the QC program requirements and personnel needs have been thoroughly identified, the Government QA program should be detailed with the goal of assuring that the contractor's QC program is adequate and continually monitored for contract compliance.

Grouting Processes

Figure 3-1 shows generalized grouting plant arrangement at the site. Figure 3-2 to 3-3 shows the optimizing of distance between two grout holes for a particular geological formation.

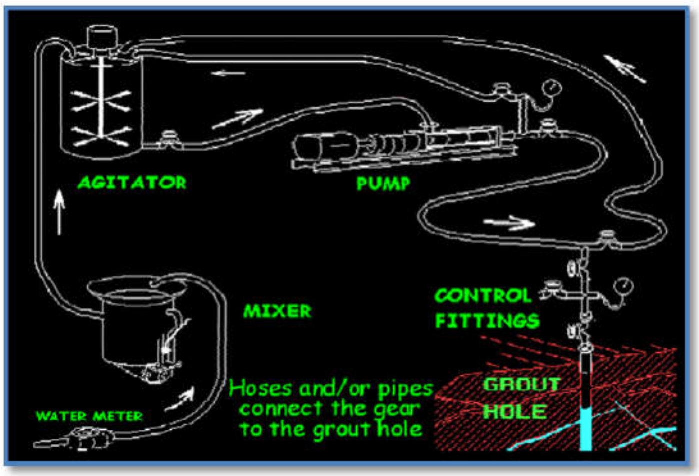


Figure 3-1. General arrangement of grouting plant at site

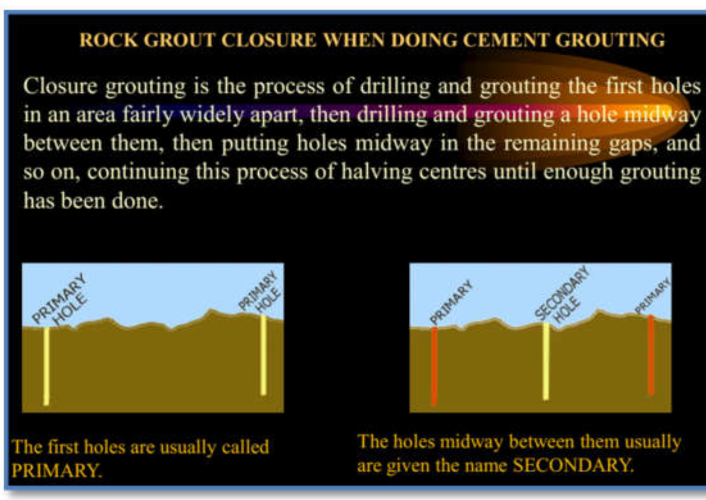


Figure 3-2. Closure spacing of grout hole

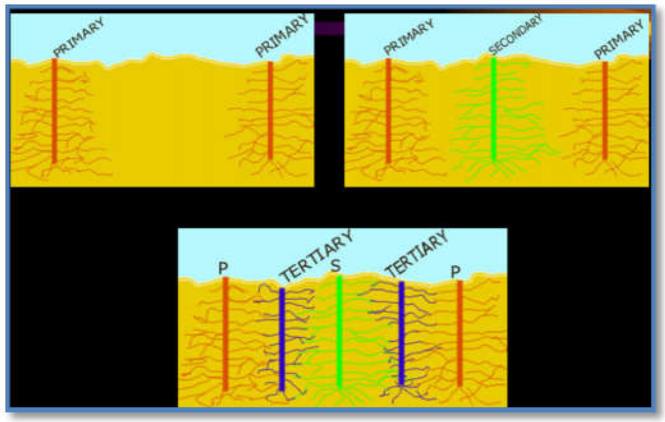


Figure 3-3(a) The concept of closure

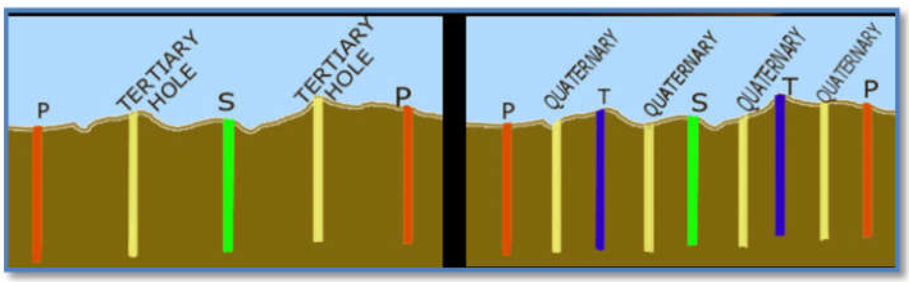


Figure 3-3(b). The concept of closure

When grout holes are longer than about 10m, it is usually best to divide them into shorter lengths, called stages, and grout each of these stages separately. This can produce better grouting because: (i) settlement of cement and rise of bleed water is less, (ii) these affect the quality of the grouting, (iii) upper stages are exposed to less pressure than if stages are not used, (iv) leaks and connections can be handled with less trouble.

Downstage and Upstage Drilling and Grouting Procedures:

In both the Feasibility Phase and the PED Phase, it is necessary to determine which portions of the work are expected to be conducted using downstage drilling and grouting procedures and which portions are expected to be conducted using upstage procedures (Table 3-1). This determination is important for structuring and preparing the contract documents and for estimating costs and schedule.

Downstage drilling and grouting involves completing drilling, washing, water testing, and grouting of a stage within the hole and allowing the grout to set before advancing the hole to the next stage. Upstage drilling and grouting involves the advancement of the hole to full depth in one drilling operation, followed by washing the complete length of the hole in one washing operation and then pressure testing and grouting the hole in stages starting at the bottom of the hole and working upwards. Figure 3-4 to 3-6 shows concept of upstage and downstage process.

Grouting of pervious soil: Pervious soils are heterogeneous, and the grain size distribution may change abruptly over a short distance. The grout flow generally concentrates along layers or pockets of coarser and relatively pervious soils. Hence it is necessary to treat short lengths of grout holesat a time and repeat injections to ensure that the least pervious and fine grained soils are treated thoroughly. Tube~a~manchette method as shown in Figure 3-7 is best suited.

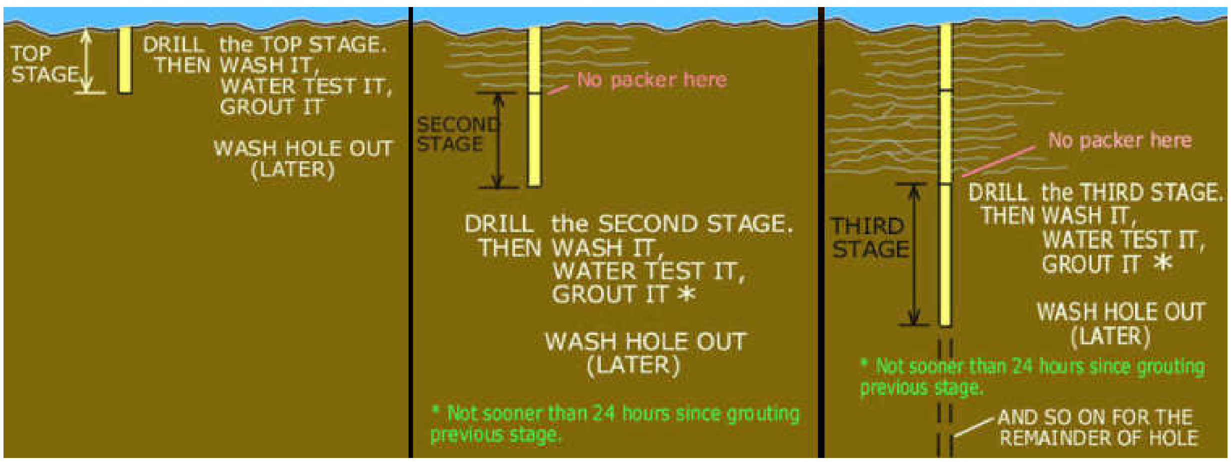


Figure 3-4. Downstage without packer

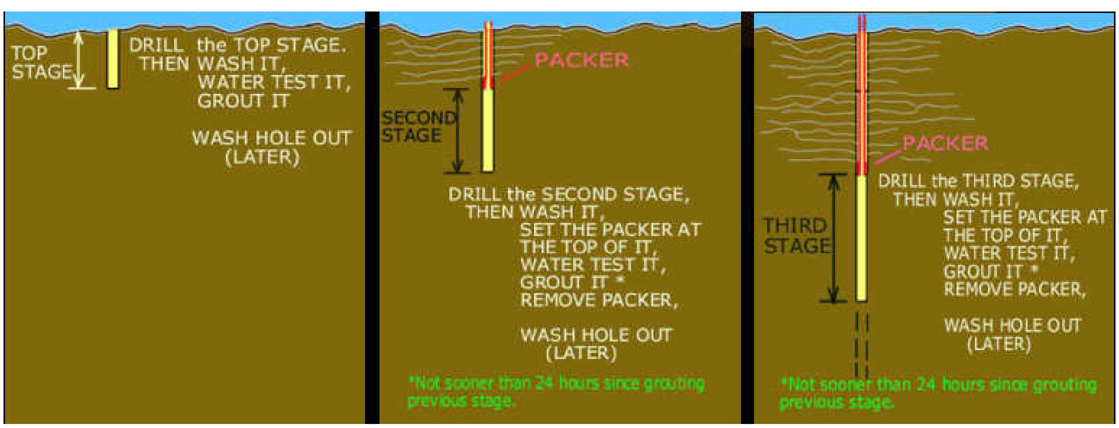


Figure 3-5 Downstage with packer

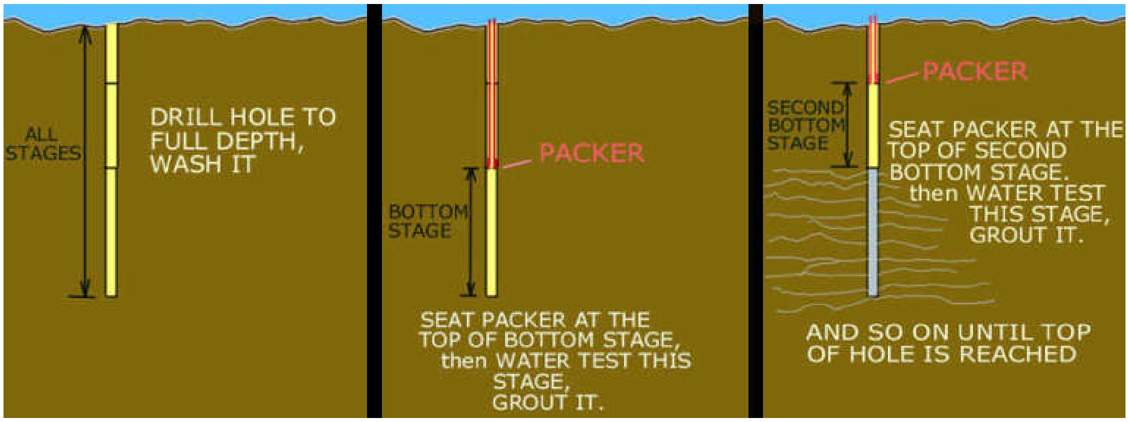


Figure 3-6 Upstage method

In Tube~a~manchette method, a pipe with rubber sleeves fitted at 30 cm intervals, is installed in a borehole by filling the annular space around the tube by sheath clay cement grout. Grouting is done by seating a set of double packers opposite the sleeves which open under pressure. The sheath grout cracks under pressure every time injections are made.

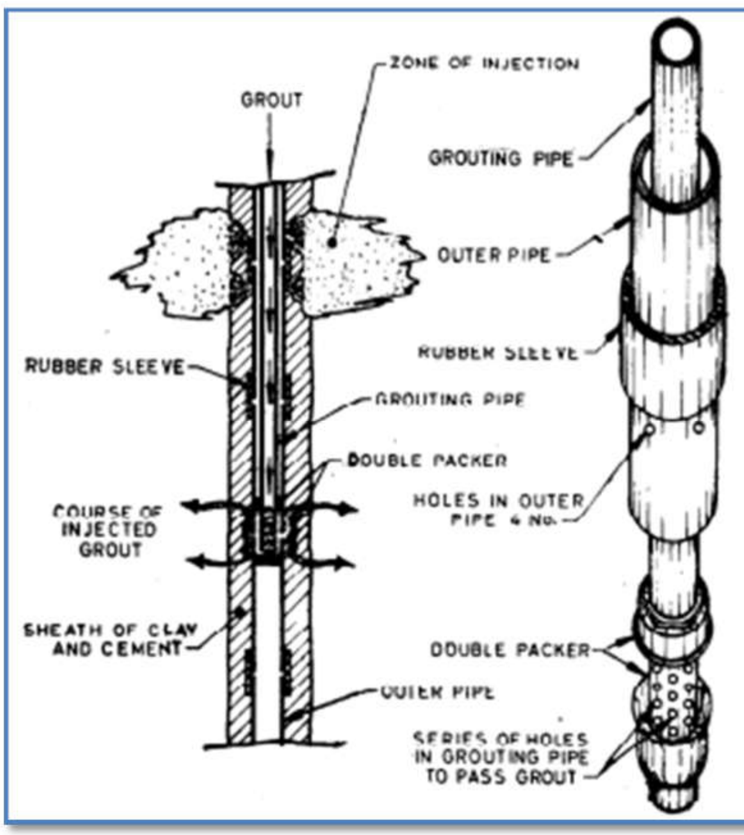


Figure 3-7. Tube~a~manchette method

Table 3.11: Advantages, disadvantages for downstage and upstage methods

Consideration	Downstage Drilling and Grouting	Upstage Drilling and Grouting
Typical site conditions favoring use	• Rock of all types and conditions. • All water loss situations and/or sites with frequent hole connections. • Known problematic zones or reaches (e.g., highly broken or weathered zones, fault zones, weak rock zones, soil-infilled zones). • Karst formations and other void areas.	• Good quality rock (i.e., RQD>40%) that results in non-collapsing boreholes. • Sound rock suitable for sealing of packers on borehole sidewalls. • Minimal number of water losses during drilling (if water loss occurs, operations must cease and zone must be grouted before continuing). • Minimal number of hole connections.
Advantages	• Shallow zones, often the most difficult and most important zones to grout, can be repeatedly grouted. • It is the most flexible method available to accommodate all conditions. • Drill cuttings from lower stages cannot clog fractures in higher zones. • It reduces hole interconnections that can result in incomplete or ineffective grouting.	• Stage lengths can be varied to fit conditions disclosed by drilling and pressure testing (e.g., short stage lengths can be used in problem zones and long stage lengths can be used in uniform, low-permeability zones). • Cheaper and faster than downstage grouting, provided conditions are favorable for upstage methods.
Disadvantages	• It is more expensive and time consuming than upstage grouting. • Potential for heaving surface rock when grouting without a heavy confining load if packer is set at surface, which can be avoided by setting packer at top of most recently drilled stage.	• Low-pressure grouting used in shallow zones. • Drill cuttings can contaminate fractures along entire length of hole. • Grout may bypass packers via the fracture system and re-enter hole above locations of packers. • Difficult to seal packers in weak or highly fractured rock, and water tests or grouting may cause loss of hole or drill tooling. • Connections with nearby holes may contaminate the holes before being grouted.
Other considerations	• It is common to use this method for upper zones of rock and known problematic zones. • This method is sometimes used to prepare site for upstage operations (e.g., sometimes for primary and secondary holes only, sometimes for first two lines, but not the middle line).	

Chapter 4. Geology and Site Characterization

General

Sufficient investigations are required to assess the suitability of grouting, to prepare flow models and the design, to determine the technical procedures and requirements for drilling and grouting, and to estimate the costs. Information should be available on: (1) the nature and characteristics of unconsolidated materials, (2) the geologic structure, stratigraphy, and engineering properties of rock types, (3) the orientation, attitude, and spacing of fracture systems, (4) the fracture condition characteristics including the existence or absence of infilling, (5) the infill material type, (6) the boundaries of differing physical zones within the rock mass, (7) the boundaries of zones with differing permeability, (8) the locations of special features such as faults, highly broken zones, and solution features, and (9) the position of the water table.

Application of Information

Site investigation information is the basis for design and for establishing the specific requirements for: (1) hole orientation, (2) hole depth, (3) selection of upstage vs. downstage methods as the anticipated method(s) of operation, (4) stage length, (5) number of grout lines, (6) initial spacing for primary holes, (7) minimum number of holes, and probable final spacing of holes. These items can only be rationally established based on an understanding of the site geology, on the physical characteristics of the rock and its fracture system, and on the project goals and requirements. If the exploration and testing program does not produce an accurate assessment of the site conditions, the basic elements of the drilling and grouting design may prove to be ineffective and may result in major changes during construction. In addition to its use for grouting design, site information is also the basis for determining the extent of required excavations, groundwater control requirements, foundation preparation and treatment requirements, and site access design.

Impacts of Geology on Grouting:

A partial list of the multitude of factors that will be affected or controlled by the geologic environment includes: (1) design of the site investigation program, (2) site access and site preparation, (3) drilling equipment and methods, (4) hole orientation and depth, (5) hole pattern and spacing, (6) hole staging and sequencing, hole stability, (8) choice of grouting materials, (9) rate of grout injection, (10) grout travel distance, (11) uniformity of properties within the grouted zone, (12) grout program quantity estimates, (13) need for special procedures, (14) verification program design, (15) interpretation of drilling and grouting results during the execution phase, and (16) reliability and/or permanence of the grouting program.

Generalized Grouting Geology Profiles

a. **General:** Depending on the particular grouting application, one or all of the zones of rock formation may be of interest. In some geologic settings, not all of the zones may be present. Additionally, the nature and the characteristics of the zones will vary greatly according to the geologic environment in which the zones were formed.

b. **Unconsolidated Materials:** Unconsolidated materials include all types of non-lithified materials, regardless of geologic origin. Unconsolidated materials include all soil types identified in the Soils Classification System, and other materials such as cobbles and boulders and mixed soil/cobble/boulder materials. Man-made fills constructed of these materials, such as embankments and other engineered or non-engineered waste fills, are also unconsolidated materials.

c. **Completely Weathered Rock:** A completely weathered rock zone is present in some geologic environments. This zone is characterized by materials having soil-like characteristics, but retaining an in-situ relict structure from the parent rock material. Drilling in these materials can be difficult because they can be both erodible and prone to hole collapse.

d. **Highly Weathered Rock or Mixed Soil/Rock:** This zone is characterized by predominantly lithified materials with a readily identifiable rock structure and fracture system, but substantial portions of the fracture systems are partially or completely filled with soil-like materials resulting from either severe weathering of the fractures or infilling of fractures with overlying soils. *A common misconception is that joint infillings can be effectively removed by washing*. Even with extended washing until the return flow from the top of the hole is clear, it has been found that the effective washing distance is either very small or that only a limited number of joints have been washed clean. Due to the potential for structural damage, hydrofracturing shall not be considered an appropriate measure for remedial grouting at existing dam projects. For projects where the potential for damage is less of a concern, hydrofracture grouting of infill may be beneficial.

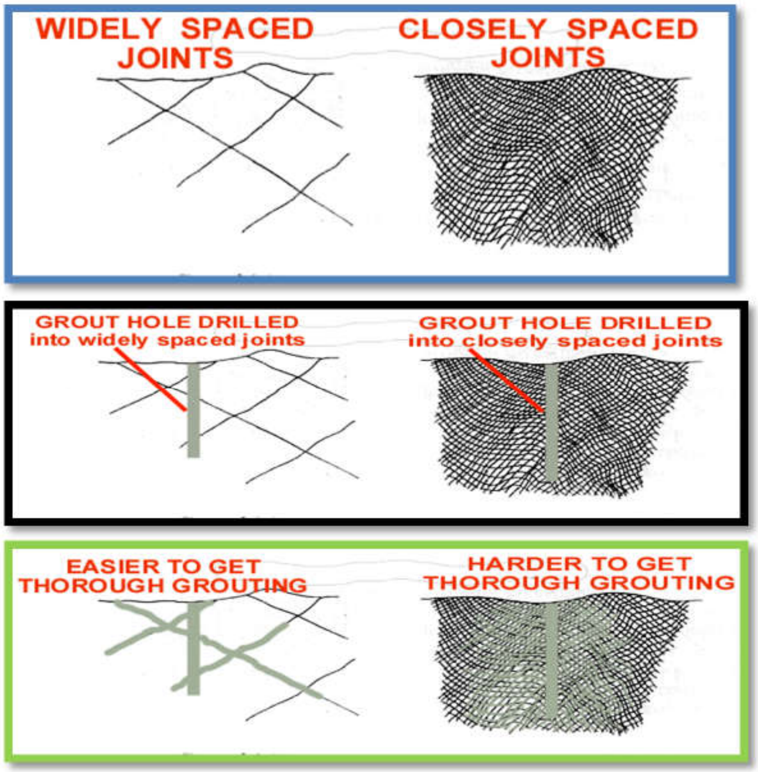
e. **Moderate to Slightly Weathered Rock:** This zone is characterized entirely by lithified materials. The fractures are generally open, but may show evidence of staining extending several inches into the parent rock. After drilling, holes typically stand open. Upstage grouting should be possible, but the presence of highly fractured zones may warrant downstage techniques at some locations.

f. **Unweathered Rock:** Most geologic profiles contain unweathered rock with clean fracture systems. Weathering of fractures, if present, is sufficiently slight that staining is surficial. Similar to moderate to slightly weathered rocks, holes stand open indefinitely and the formation readily accepts grout.

Grouting Considerations*:* Since many rock types have low primary permeability, but relatively high fracture and joint permeability, the importance of grouting the structural discontinuities is apparent. The type of structural feature (e.g., fault, fold, or joint) will dictate to a large part the type and extent of excavation treatment and the grouting methods. The spacing and nature of the fractures (e.g., open, weathered, or solutioned) influence the type of grout treatment selected, such as consolidation grouting and curtain grouting. The selection of a single-line or multiple-line curtain and the grout hole spacing are also affected. The orientation (dip and strike) of these features in relation to a structure influences the planned angle and direction of the grout holes and the drain holes. The spatial variations in the permeability of the fractures affect the depth of a grout curtain. The grout holes should intersect all the features, and each inclined or vertical feature should ideally be intersected by several holes at different depths. Faults may be gouge filled and impermeable, thereby forming a barrier, or they may be open and carry groundwater. Joints may be filled or open, may have weathered or non- weathered faces, and may intersect and be connected over a wide area. The condition of the joints will affect the drilling, cleaning, pressure testing, and grouting of the hole.

Various geological considerations are deciding factors for planning a grouting project. The aspects described in following section are exaggerated to better illustrate each point. Actual cases usually fall between these extremes. Some of them are shown as under (Ref. Houlsby A C):

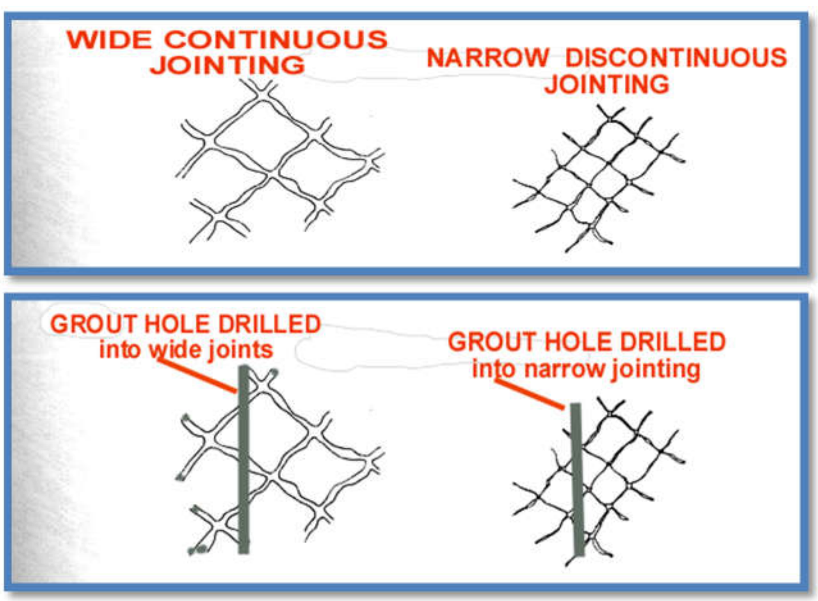
1. **Spacing of Joints**



The sketch shows the extreme conditions encountered during grouting operations.

As far as cement grouting is concerned, it is the open, groutable joints that are of interest. If they are widely spaced, the grouting is usually easier than if closely spaced where troubles such as frequent surface leaks, collapsing holes and patchy penetrations can happen. These make for more expensive grouting, perhaps requiring special surface treatment.

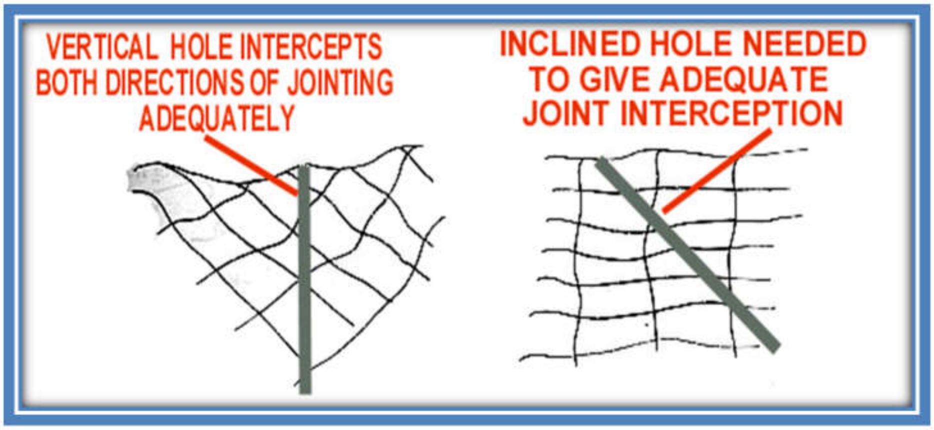
2. Joint Width and Continuity



The easiest joints to grout have widths in the range between about 0.250 in [6 mm] and 0.020 in [0.5 mm].

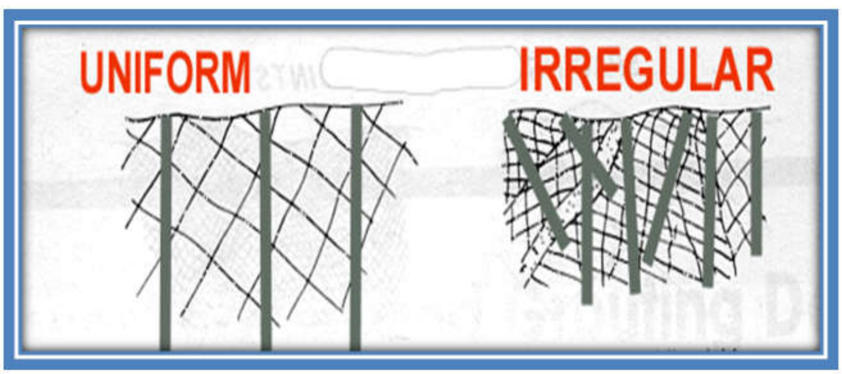
Continuity of open jointing systems affects penetration: lack of continuity means that more grout holes will be needed than if grout can travel appreciable distances through the systems.

3. Joint Inclination



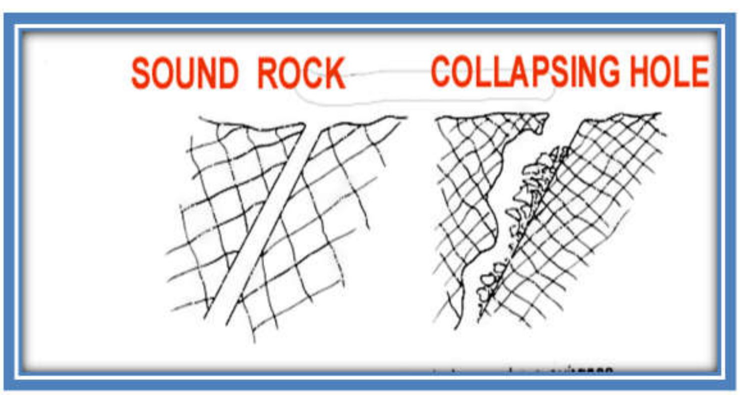
Where dipping is mainly between 20° and about 60°, vertical grout holes may give optimum interception. These are the easiest to drill and are preferable. Steeper jointing usually requires use of inclined holes.

4. Uniformity of Site



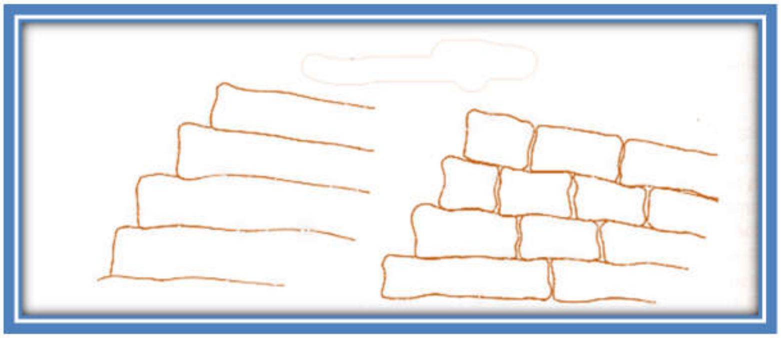
Uniformity of jointing permits a regular layout of grout holes, whereas irregular jointing, dykes, disconformities, and so on may require placement of holes at various inclinations and spacing. Weaknesses may need to be treated intensively.

5. Rock Soundness



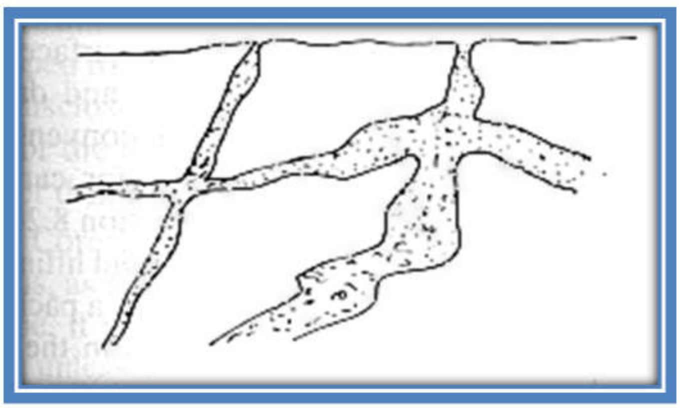
Holes that don't collapse permit easier grouting than those that do. In the latter case, packers cannot be used, and stage lengths may have to be shorter than usual if collapsed material blocks holes.

6. Strength



Grouting of strong, massive, well-anchored rock, as sketched at left, is usually easier than when working in weak, broken, loose materials where holes repeatedly collapse, or where blocks move as shown at right.

7. Piping



Where material in joints can be removed by seepage, either by taking the material into solution or by eroding it, the grouting will need to be more intensive than otherwise in order to ensure that seepage through such joints is virtually eliminated.

8. Chemical Attack

The presence of coal or other carbonaceous material or of other deposits that may provide chemically aggressive seepage can warrant provision of a higher standard of grouting than would otherwise be the case.

9. Karst and Other Voids

Large voids such as karst, and also old mines, shafts, and so on, require special provisions when grouted, possibly using fillers in the grout.

Photographs of some of the geological formations are as shown below:

Photo 4-1: Differential bed thicknesses, bed orientations, and joint spicing in sandstone

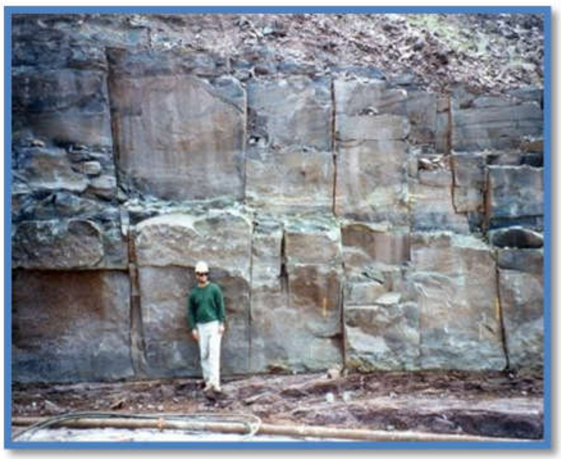


Photo 4-2:Thick sandstone unit with large, widely spaced vertical fractures terminating at mudstone units located above and below.

Photo 4-3: Rock outcrop adjacent to a dam abutment.

Photo 4-4: Sheeted and blocky jointing in Granite.

Photo 4-5: Abutment area of Olivenhain Dam, CA.

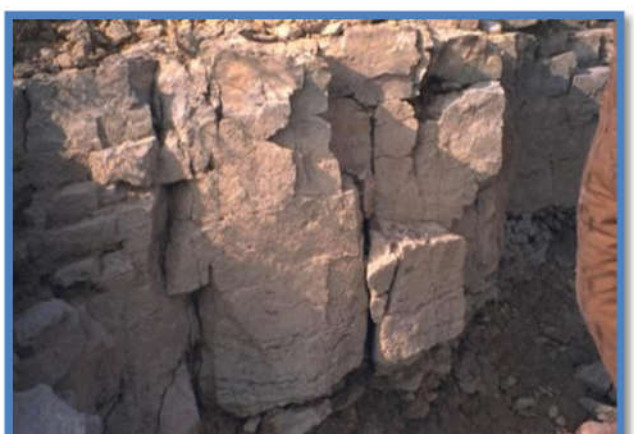


Photo 4-6: Weathered limestone exposure.

Pressure Testing

a. **General.** Pressure testing consists of isolating a segment of a hole by packers, injecting water at a known effective pressure, monitoring the behaviour during injection, interpreting the results, and calculating a permeability value for that stage. The permeability unit that is normally used is the Lugeon value, which has been found to be very convenient and is in widespread use in grouting. The results of the test are, of course, affected by many factors, including whether the interval of hole being tested is representative of the overall rock mass

b. For the test results to reasonably reflect the overall characteristics of the rock mass, the holes must be oriented such that they intersect the fracture systems, a sufficient number of tests must be performed to ensure that the rock mass is reasonably characterized, and the stage lengths must be sufficiently short to ensure that tests are performed within zones of similar nature (i.e., similar fracture size and/or spacing).

c. **Lugeon Unit.**

(1) The Lugeon value for a test stage in a hole is calculated by:

Lugeon value = water take in L/m/min x (10 bars / effective test pressure in bars).

(2) In English units, the Lugeon value can be calculated by:

Lugeon value = (Q/L) x $(1801/P_{eff})$

where: Q = flow rate in gallons per minute; L = stage length in feet 1801 = conversion factor; P_{eff} = effective pressure applied to test stage in psi.

(3) The approximate conversion equations for Lugeon units to other common permeability units are: 1 Lugeon unit = 1.3 x 10^{-5} cm/s 1 Lugeon unit = 2.6 x 10^{-5} ft/min.

d. **Exploratory Phase Testing:**

Specifically, the goal of exploratory phase testing is to thoroughly define the site geology as it pertains to grouting. This includes having a thorough understanding of the geologic formations, the geologic structure, the fracture systems, and the permeability characteristics, particularly how the permeability varies by formation, depth, and horizontal location. Exploratory phase pressure testing should be performed on cored holes; it is also highly recommended to use borehole video on those holes.

(1) *Stage Lengths*. Exploratory phase pressure testing should be performed in short stages to maximize the resolution of permeability variations. Long stages create an averaging effect that may lead to an erroneous understanding of actual conditions. Normally, the maximum stage length for pressure testing for this purpose should be 3m, and it may be of value to use even shorter stages for

special conditions, particularly where geologic interfaces or other special features are of concern. The use of real-time monitoring systems to display pressure testing data will significantly reduce the duration of pressure tests since the behavior of the stage and the permeability can often be obtained with test durations of 2–5 minutes per stage.

(2) *Stepped Pressure Tests*.

Stepped pressure tests are tests in which the pressure is incrementally increased and then decreased, usually in five discrete steps, with each pressure increment being a complete test. The results for each test are plotted, usually as a bar graph. The variation of the Lugeon value at different pressures provides much information about the nature of the fracture systems. Specifically, the tests can clearly disclose: (1) whether the fractures are clean, fine or coarse in nature, (2) the pressure required to lift the rock, dilate the fractures, and/or hydrofracture through unconsolidated materials, (3) the presence of infilling or weathered materials that are prone to being washed out, or (4) whether the fractures are prone to clogging. A sufficient number of stepped pressure tests should be performed so that the nature of each geologic unit is understood. The duration of testing for each step should be as required for the results to stabilize or, for non- stabilizing increments, at least 5 minutes. Figure 4-1 shows schematic diagram of water pressure testing in the field. Figure 4-2 to 4-7 shows schematic example of ideal characteristic mode of behaviour, along with their interpretation. With the exception of Figure 4-5, these schematics are based on illustrations by Houlsby (1990).

(3) When Lugeon values decrease with increasing pressure, but then increase to prior values as the pressure is subsequently reduced, it generally indicates the presence of larger fractures with turbulent flow, causing increased head loss in the fracture and reduced permeability at the higher pressures.

(4) When Lugeon values abruptly increase at a particular pressure increment, but then return to a constant lower value at lesser pressures, it indicates dilation of fractures followed by a return to the normal condition after reducing the pressure. It can also indicate reversible hydrofracturing through void infill materials or into embankment materials. During the exploratory phase, before production grouting is undertaken, the stepped pressure test can be intentionally structured to achieve these results so that the pressure at which dilation begins to occur is known. Normally, dilation is avoided in North American practice, and the dilation pressure can be used to help establish the “safe” pressures for production pressure testing and grouting.

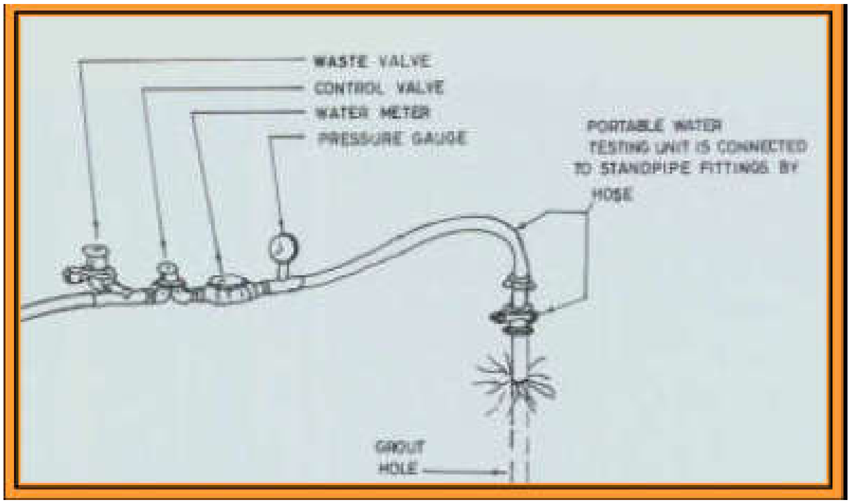


Figure 4-1 Typical setup for water pressure test in field

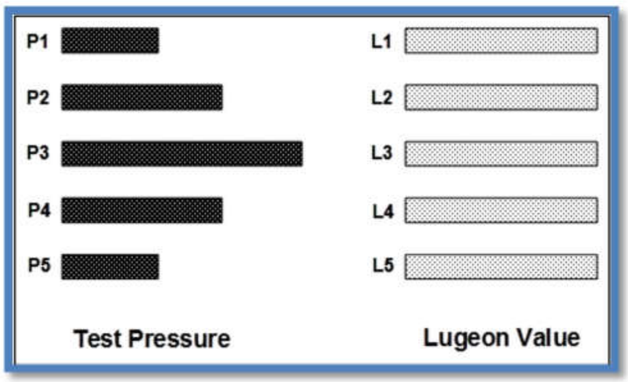


Figure 4-2. Laminar flow behavior.

When the test section is composed of clean, finer fractures, there will normally be little variation of the Lugeon value with pressure because it is dominated by simple laminar flow. The permeability is constant within the range of pressures used.

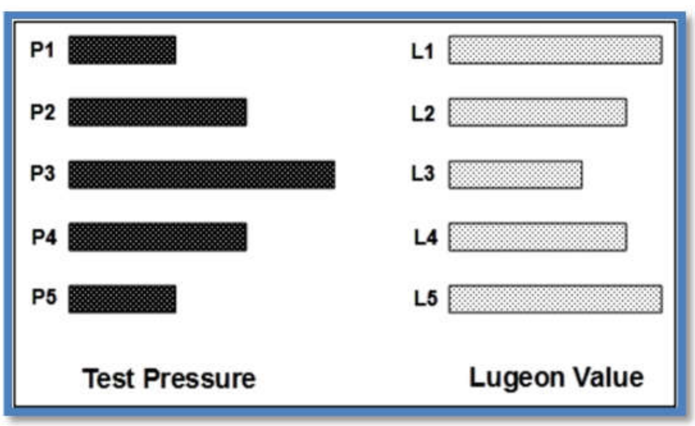


Figure 4-3. Turbulent flow behaviour. (After Houlsby 1990)

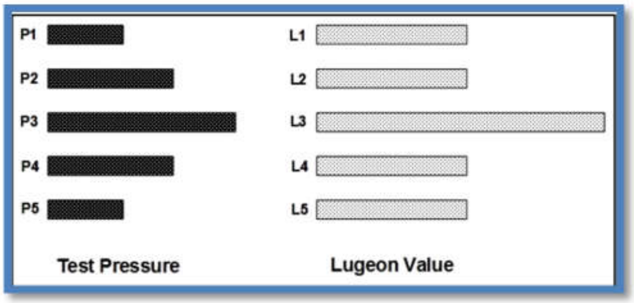


Figure 4-4. Dilation behavior. (After Houlsby 1990)

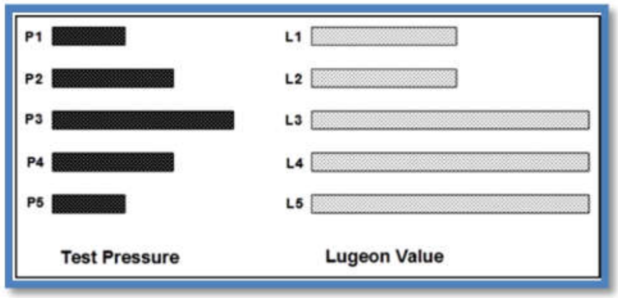


Figure 4-5. Permanent uplift behavior.

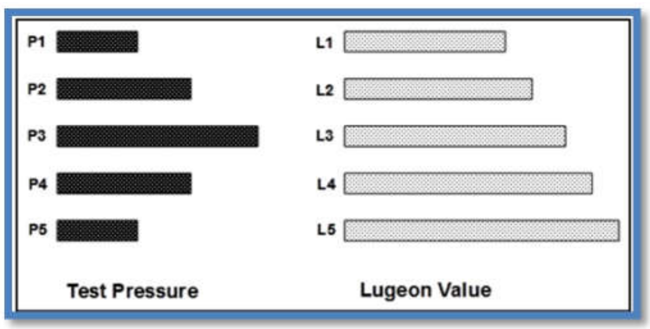


Figure 4-6. Washout behavior. (After Houlsby 1990)

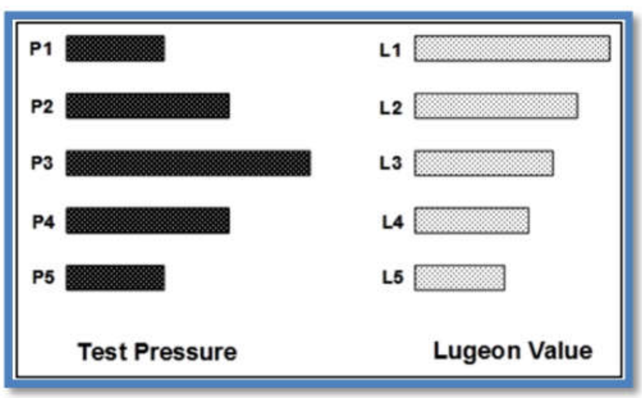


Figure 4-7. Clogging behavior. (After Houlsby 1990)

(5) If the dilation results in "locking open" of the fracture, the permeability will stay at the increased level as pressure is reduced.

(6) When Lugeon values continually increase throughout the testing sequence, it suggests that washout of material is occurring with time.

(7) When Lugeon values continuously decrease through the testing sequence, it suggests that clogging of the fracture is occurring with time.

e. **Production-Phase Pressure Testing**. Pressure testing in the production phase of the grouting program serves numerous purposes, as described in the following paragraphs. In general, the stage length for production-phase testing should be the same as the length of stages to be grouted. The pressures for production-phase testing should, in general, be the pressures that will be used for grouting.

(1) Identification of Hole Connections and Surface Leaks in Advance of Grouting. Pressure testing will allow advance identification of connections of the stage to be grouted with other holes and with surface leakage points. This allows the contractor to assemble, in advance, the necessary equipment and personnel that will be needed to effectively respond to these conditions.

(2) Lubrication of Dry Fractures. Injection of water in advance of grouting will wet fractures located above the water table. Injecting into pre-wetted fractures is desirable to prevent rheology changes in the grout.

(3) Guidance on Selection of Initial Grout Mix. In most cases, grouting is always started with the thinnest mix to be used for the project to ensure that the fine fractures are filled before the thickening required for larger fractures in the stage. However, using a thicker initial mix may be appropriate for some formations. Pressure testing in advance can provide guidance in those cases where variable starting mixes are used.

(4) Combining Stages for Grouting. Normally, grout stages in the primary and secondary series of holes are fixed in length, and each stage is grouted individually because the stages may contain fractures of different sizes. However, by the time the tertiary or quaternary series of holes are being grouted, there has normally been travel of grout into the regions around those holes, particularly in the larger fractures.

(5) Closure Analysis and Program Verification. The fundamental goal of any curtain grouting

program for a hydraulic structure is to produce a grouted zone of the desired width and residual permeability. When those results are achieved with certainty, satisfactory closure has been achieved. The process by which it is determined that closure has been achieved is termed “closure analysis.” Closure analysis involves intense analysis and scrutiny of the data, and an extrapolation process. Verification holes are drilled and tested after closure is deemed to have occurred to test the closure decision and extrapolations. It is logical to place great reliance on the pressure test data because the purpose of the grouting is to act as a barrier to water.

Chapter 5. Grout Materials, Mixes, and Their Properties

Types of Grout

This part provides an overview of the commonly used grouting materials and mixes and provides guidance on material selection for a grouting program.

Cementitious Grouts: Cementitious grouts are the most commonly used materials for grouting and can be categorized based on their mobility. For a grouting program to be cost effective, the grout must have sufficient mobility to fill the discontinuities intended for treatment without being so mobile that the grout will flow significantly outside the treatment zone. High- Mobility Grouts (HMGs) behave as a fluid and can be mixed, circulated, and injected with relative ease using normal grout mixing and pumping equipment. HMGs range from pourable to a thick consistency that is just barely able to be mixed and pumped with normal equipment.

Low-Mobility Grouts (LMGs) are of a mortar-like consistency and exhibit both plasticity (they stay together when deformed) and internal friction. LMGs expand as a non-permeating bulb of plastic material to either fill open voids or displace soil materials. HMGs are commonly used for permeation grouting of coarse soils and fractured rock, while LMGs are typically used for soil densification (compaction grout) and void filling.

(1) **High-Mobility Grouts.**

(a) *Unstable Suspension Grouts:* Until recently, most grouts used for permeation grouting have been unstable suspensions, which, in the absence of continuous agitation, will separate into two distinct phases (water and a very thick suspension). A commonly used definition of unstable grout is that it exhibits more than 5% bleed or sedimentation when placed in a graduated cylinder. At all locations except within the agitator itself, the properties of unstable suspension grouts are in a process of change throughout the grouting process.

(b) *Balanced Stable Suspension Grouts:* Stable grouts, which began to be used in the 1990s, do not separate into distinct phases in the absence of agitation and do not undergo significant property changes until they begin to take a set. Numerous additives are available to modify the flow and set characteristics (rheology) of cementitious grouts. As implied by the name, balanced stable grouts contain additives to create a stable grout (significantly reduced or zero bleed potential) with the desired rheological properties that remain nearly constant during injection. Additionally, if silica fume is used in the balanced stable mix formulation, this highly reactive pozzolan interacts with calcium hydroxide liberated during cement hydration and results in property improvement.

(c) *Bulk Fillers in HMGs:* Houlsby (1990), Warner (2004), and Weaver and Bruce (2007) all discuss the extensive array of fillers that have been used in HMG formulations. One of the most commonly specified bulk fillers is sand, which can be added to the HMG mix in limited proportions. Sand might be added in a special circumstance when extremely large quantities of the thickest consistency HMG have been used without apparent gain in pressure build-up and when it is simultaneously desired to grout to complete refusal without interruption.

(2) **Low-Mobility Grouts:** LMGs are grouts that behave as plastic materials. These grouts are not pourable and typically do not behave as a fluid. They have high internal friction due to the high concentration of solids in the mix. The best known application of LMG is for compaction grouting, where the grout is injected into a soil for displacement and/or densification, resulting in a higher modulus and higher strength. Other common uses of LMG are void filling in karst terrain and mine works. LMGs are sometimes used to provide containment barriers within a large feature, which then allows the feature to be thoroughly grouted to completion with HMGs. Figure 5.1 illustrates the typical consistency of LMG.


Figure 5.1. Low-mobility grout. (Courtesy of Dr. Donald Bruce)

a. *Non-Cementitious Grouts:* There are times when the desired impact of a grouting program requires the use of materials other than cement. Applications such as structural grouting in soil and control of strongly flowing water commonly lead the grouting specialist to chemical or solution grouts. The following paragraphs describe commonly used non- cementitious grouts.

(1) *Chemical Grouts:* Often identified as simply chemical grouts, these grouts are more correctly termed “colloidal,” “chemical solution,” or “solution” grouts. Commonly used solution grouts are sodium silicate, urethane, acrylate, and acrylamide. Sodium silicate has commonly been used for

structural or water control applications. Urethanes are the material of choice for control of flowing water in structures. Acrylates and acrylamides are highly penetrable in all mediums and form a gel when reacted. These materials are highly effective for water control because of their ability to set almost instantly within variable, but controllable periods of time. However, there are disadvantages, including shrinking and swelling during wetting and drying cycles, and some real and some perceived environmental impacts.

(2) *Asphalt Grouts:* Asphalt grouts or hot bitumen are used in special circumstances to stop rapidly moving water, as in, for example, a large leak into a quarry from a nearby stream or river. Asphalt is a solid at room temperature and must be heated to above 275 °F (135 °C) to create a flowable, viscous liquid. The hot bitumen is pumped into the flowing water, where it cools rapidly and thickens, forming a low-strength plug. After the flowing water is stopped or slowed, cementitious grouts are usually employed to increase the permanence of the application.

(3) *Clay Grouts:* Clay grouts are inexpensive grouts created from a suspension of clay minerals and cement. Two parts clay is typically combined with one part cement and water, resulting in a grout that forms a weak solid. Although clay grouts have been reported to have been used successfully in the former.

Process for Selecting Grouting Materials

a. **General:** Figure 5.2 shows schematics of various types of grouting applications. The selection of suitable grouting materials requires the answers to several questions:

(1) What medium is being grouted (soil, rock, concrete, or combination, e.g., karst)?

(2) What is the purpose of the grouting (strengthening or modulus reduction, permeability reduction, or water control)?

(3) What grouting methods can be used to achieve the purpose?

(4) How critical is the grout performance?

(5) How permanent must the grouting be?

(6) What is the rate of flow, if any, that must be stopped?

(7) What are the environmental considerations?

(8) What are the cost considerations?

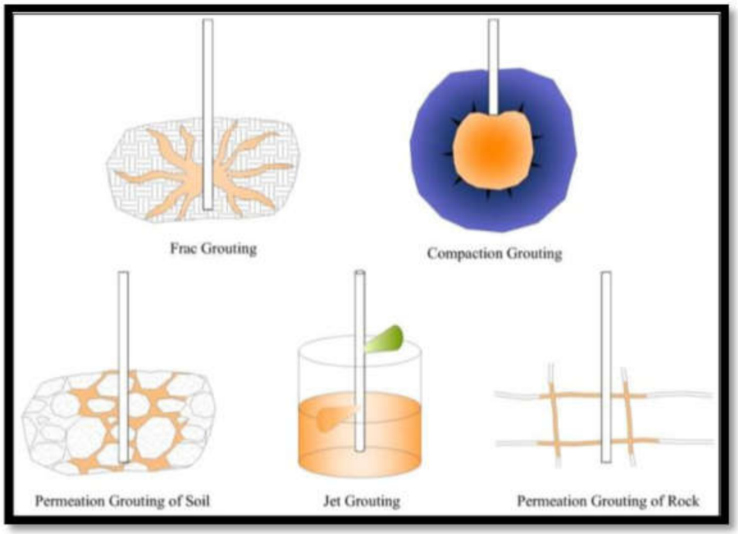


Figure 5.2. Schematic of grouting methods.

b. **Selection of Primary Grouting Material:** After the questions above are addressed, candidate grouting methods and associated grouting materials can easily be identified. The primary grouting method and material should be selected to treat the majority of the anticipated conditions. If the desired improvements or results can be achieved with more than one material, the final selection should consider long-term durability and cost. The cost should not be based solely on the material cost, but on the total project cost for using that material.

c. **Selection of Secondary Grouting Material:** More than one grouting method or type of grout might be appropriate or necessary to achieve the goals established for a project. For example, a grouting program in karst terrain might be developed using HMG as the primary grouting material to permeate the rock fractures. However, LMG might also be provided to treat open or soil-filled solution features. A second example is a dam foundation grouting project. If the performance criterion of the completed curtain requires a low permeability (less than 1×10^{-5} cm/sec), then achieving this goal might require a combination of portland cement and ultrafine cement. A typical project with a multiple-line curtain might require that the outside lines be grouted with an HMG mix formulated with a standard portland cement and that the interior line be grouted with an HMG formulated with a microfine cement.

d. **Guidelines for Common Grouting Applications:**

(1) ***Rock Fracture Grouting*:** Applications involving grouting of rock fractures to cut off or reduce fluid flow are the most common types of permeation grouting. Permeation grouting is also used for mechanical applications where the purpose of the grouting is to strengthen a rock or soil

mass or reduce the potential future deformations. Littlejohn (2003) defines permeation grouting as the introduction of grout into ground without disturbing the ground structure. Rock grouting requires that a hole be drilled that intersects existing fractures in the rock. The fluid grout is then pumped into a zone of rock under pressure. The expectation is that the pressurized grout enters the fracture at the intersection with the hole and fills the network of fractures connected to the intersected fracture in the proximity of the hole. Grout holes are typically drilled and grouted using the *split-spacing* method until areas of overlapping influence are created. Stable cementitious grouts are almost always the material of choice for routine rock grouting applications. Figure 5.3 provides guidance on selecting the appropriate grouting material for applications in fractured rock. On rare occasions, a solution grout might be used in a highly specialized or critical application where a near-zero residual permeability is required. Nearly all of the grouting between 1930 and 1990 was performed using unstable cement grouts, but due to concerns about bleed and variable rheology, the use of portland cement stable grouts has increased and is required on many projects. If the fracture size requiring filling is too small for penetration with Portland cement, ultrafine cements with a smaller average grain size are available.

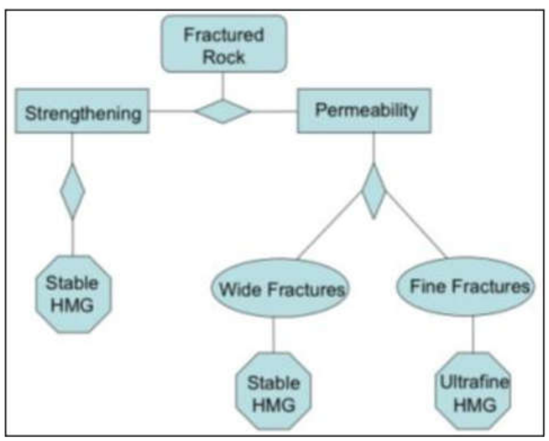


Figure 5.3. Grouting materials for use in fractured rock.

Starting grout mix for rock grouting recommended is water:cement ratio 2 : 1 (by volume)for most of the grouting project. However, if the majority of cracks are known to be relatively fine such as 0.75 mm or finer, starting with 3:1 could be better. At the other extreme, if cracks are fairly wide such as 1.25mm, it is usually wise to start with 1:1 (w:c by volume). There is no need to use any other mixes than 5:1 (by volume), 4:1, 3:1, 2:1, 1:1, 08:1, 0.6:1 and 0.5:1. When thickening the grout during grouting, precede down the list one mix at a time – never jump a mix. For instance, if thickening from 3:1, go to 2:1 for a while and then 1:1and perhaps on. Never go straight from 3:1 down to 1:1 or else too sudden thickening is liable to prematurely block cracks in the job.

(2) ***Soil Grouting:*** While only permeation grouting is used in rock, a variety of grouting methods and materials are commonly employed in soil grouting. The available grouting methods include permeation, compaction, mixing or replacement, and fracture grouting.

(a) Permeation Grouting: Due to cost considerations, permeation grouting of soil is limited to soils that can be permeated relatively rapidly. As a rule of thumb, permeation grouting can be considered possible for soils with less than 15% fines. This percentage is not exact and will vary, depending on the coefficient of uniformity of the soil, the plasticity of the fines, and the grouting material. When grouting of soils at the upper limits for fines content, permeation will be very slow. The type of grout used for permeating soils will vary, depending on the soil type and the application. Grouting of clean coarse sands and gravels can be accomplished with Portland cement mixes. Permeation grouting of most natural fine sands requires ultrafine cements or a solution grout. The ultrafine cements have the advantage of higher achievable strength, lower cost, and greater durability for permanent applications. At times, strength and permanence are not crucial. For example, for soil tunnel applications, permeation grouting might be used to minimize water infiltration and increase the stand-up time of the soils. In this case, a moderate to low strength might be desirable so as not to impact the speed of the tunnelling operation, so a sodium silicate grout might be a better choice.

(b) Compaction Grouting: Compaction grouting requires the use of an LMG. In compaction grouting, soil improvement is achieved by gradually injecting a growing mass of grout, which displaces the adjacent soils and results in densification. Soil improvement from compaction grouting is identical to applying static compaction to a fill. However, it also results in a pattern of embedded elements of substantially higher strength, which further modifies the behaviour of the soil mass. The bearing capacity of the soil is increased, potential settlement is reduced, strength is increased, and permeability is reduced. Compaction grouting is the method of choice for repairing damage due to settlement and mitigating future damages by decreasing future settlement by densification. When used for compaction grouting, LMG consists of aggregate, cement, and minimal water. To be effective in densifying the soil without losing control and possibly causing damage by hydro-fracture and uncontrolled heave, the grout mixture must stay together and act as a growing solid in the soil. To act in this manner, the grout must exhibit internal friction, and the rheology of the grout must be closely controlled. The data shown in Figure 5.4 indicate the recommended gradation band for the aggregate component. The gravel-size particles should be rounded, if available. If rounded aggregates are not available, the finer side of the envelope should be used (Warner 2004). The aggregate is commonly obtained from local borrow sources. Pre-blended aggregates can also be obtained from some aggregate producers. Cement content can vary from 0 to 12% by volume (Warner 2004). The water content is low, just enough to allow pumping. Many specifications require that the slump be less than 1 in.

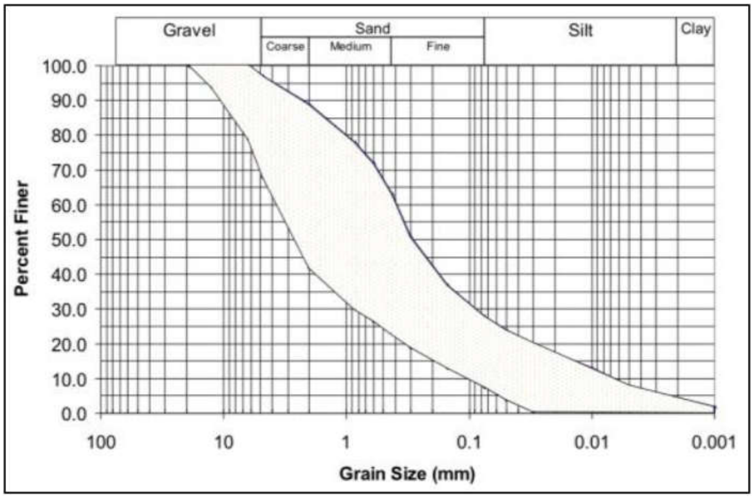


Figure 5.4. Recommended aggregate gradation for compaction grout. (Courtesy of Warner 2004)

Figure 5-5 and 5-6 shows applications of compaction grouting.

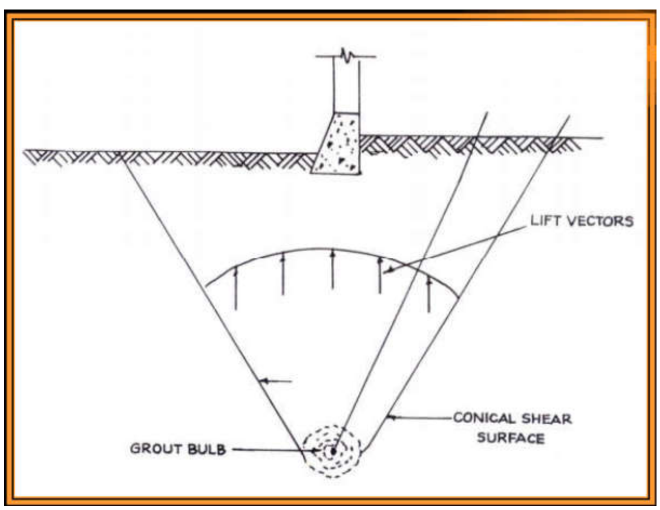


Figure 5-5. Controlled lifting with compaction grouting

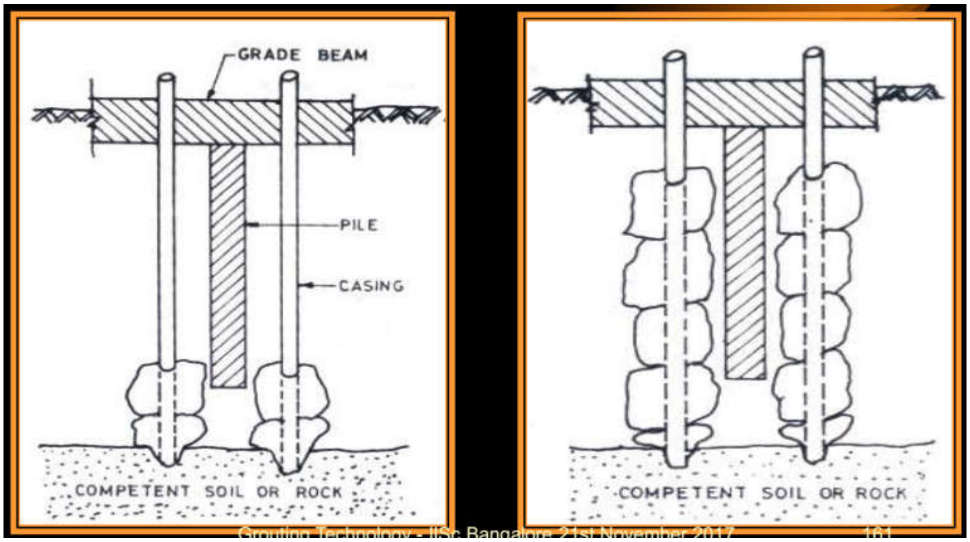


Figure 5-6. Compaction grouting increases end bearing and shaft friction

(c) Jet Grouting: Mixing or partial replacement of soils can be achieved using deep mixing methods or jet grouting. Deep mixing uses mechanical means to mix the in-situ soils with grout. Jet grouting involves the injection of grout (often assisted by air and/or water jetting) under high pressure to mix the in-situ soil with cement to form “soilcrete.” Three methods of jet grouting are commonly recognized: single tube, double tube, and triple tube. The number of tubes or rods is consistent with the number of fluids used in the process. Single tube uses only grout to excavate and mix the in-situ soils. Double tube incorporates a shroud of air around the grout to assist in the excavation process and to concentrate the grout jet. Triple tube uses water encapsulated in a shroud of air for excavation and injects grout separately near the bottom of the drill string to create the soilcrete. Depending on the jet grouting method selected and the withdrawal rate, jet grouting results can vary from minor mixing to almost complete replacement of the in-situ soils with grout. Jet grouting can be applied to any soil type. A speed jet of water released from a 1 to 2 mm nozzle at the end of a grout pipe at a pressure of 200 to 5000 kg/cm2 cuts through the soil or soft rock. When the slot has been formed, a chemical solution grout is substituted for the water and stabilizes in place as a solid mass. The achievable parameters of the soilcrete are greatly impacted by the soil type. Higher strengths and greater diameters can be achieved in clean sand or gravel. As the soil becomes finer and more plastic, the achievable strengths are reduced and the diameter of the soilcrete columns is reduced (assuming that the installation method is constant). Highly plastic clays are especially problematic, as they are difficult to break down and mix with the grout. Figure 5-7 to 5-9 shows jet grouting process and few applications for jet grouting.

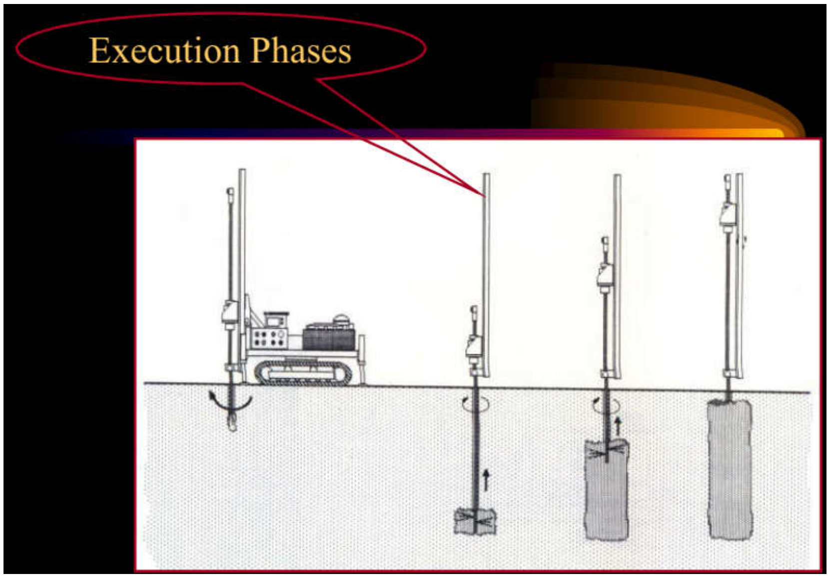


Figure 5-7. Execution phase – Jet grouting

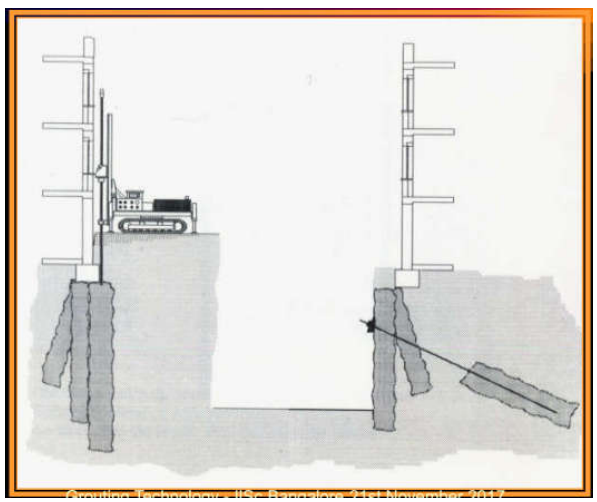


Figure 5-8. Underpinning for deep excavation

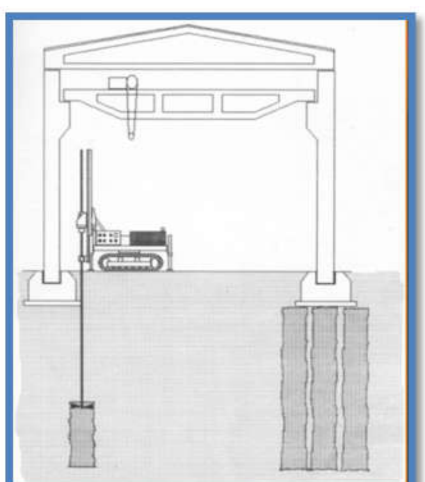


Figure 5-9. Improvement of existing building foundation

Strengths over 2000 psi have been achieved in sands and gravels, while 300 psi might be the maximum achievable strength in plastic clay. Large cobbles or boulders in the formation result in the high-pressure grout jet being deflected and can result in untreated soil areas or shadows behind the large-diameter obstruction. The grout material used in jet grouting is portland cement. The grout mix design is typically a neat cement grout prepared at water-to-cement ratios by weight ranging from 0.6 to 1.2.

(d) Hydrofracture Grouting: The premise of hydrofracture grouting, or "frac" grouting, as it is commonly called, is to inject grout under pressure, causing tensile failure of the soil, resulting in the injection of grout lenses within the soil. These pressurized lenses of grout densify the soil by plastic deformation in the vicinity of the lenses and also reinforce the soil mass due to the higher strength of the grout in comparison to the soil. In clay soils, there can also be a chemical reaction of the grout with the clay minerals (cation exchange) in the immediate vicinity of the lenses, which increases the strength. Stable grouts are used in frac grouting, so future deformations due to bleed water dissipation do not occur.

(3) **Structure Grouting:** Grouting in structures can take many forms and can be performed for a variety of purposes. Structural grouting is commonly performed to fill voids or cavities resulting from the original construction, such as honeycombed or segregated concrete. Grouting might also be performed to fill voids in masonry structures caused by incomplete mortar coverage, or to fill cracks and joints. The most recognized form of structure grouting is waterproofing of structures such as basements, concrete tanks, conduits, and dams. Other forms of structure grouting include contact grouting around buried structures, slab jacking, rock and soil anchors, post-tensioned tendons, conduit abandonment, and slip lining. Grouting is also a common element in the construction or rehabilitation of underground structures such as tunnels and shafts. Grouting materials used for structure grouting include cementitious grouts (portland and ultrafine), epoxies, urethanes, acrylates, and low-mobility grout.

Basic Elements of Cement-Based Suspension Grouts

a. **Portland Cements**. Portland cement is the most widely used material in grouting. The fineness defined by ASTM is the Blaine fineness and is a measure of the specific surface area available for reaction. This method is based on air permeability and is expressed in units of cm^2/g or m^2/kg. Ordinary Portland cement typically has a Blaine fineness of 300–500 m^2/kg and a maximum particle size on the order of 45 microns.

b. **Other Types of Cements.** Other types of cement and cementitious materials that may be used include:

(1) Finely ground cementitious materials are used for achieving better penetration. These cementitious grouts are known as ultrafine or super-fine cements. The Blaine fineness for ultrafine cement is greater than 800 m^2/kg, and the maximum particle size is on the order of 10 microns.

(2) Supplemental cementitious materials (SCMs) may be used, depending on the required grout properties or the availability of portland cement. SCMs include natural pozzolans, fly ash, ground granulated blast furnace slag (slag), and silica fume. Typically the Blaine fineness and the maximum particle size for fly ash and slag are similar to ordinary portland cement, but the properties may vary significantly among different sources. Silica fume is extremely fine, with a fineness of about 20,000 m^2/kg and a maximum particle size of 1 micron.

(3) Blended hydraulic cements are Portland cement that is pre-blended with pozzolans or slag.

(4) Several other specialty cements include air-entrained cements, expansive cements, calcium aluminate cements, plastic cements, masonry cements, rapid-setting cements, and oil well cements (Warner 2004). These cements are not appropriate for the majority of grouting applications, but in some specific instances their properties may be desirable and their use should be further explored.

(5) Wherever grouting must be performed, it is recommended that soil and subsurface water conditions be assessed for the potential for alkali and sulfate attack. These conditions are prominent in the presence of or proximity to seawater or brackish water, or where sulfates or alkalis are present in the subsurface due to contamination or as a natural product of the environment. Type V cement is the most resistant to sulfate attack under these conditions.

c. **Mixing Water.** Water is a major component of any grout mix. The minimum percentage of water required for complete hydration of cement is 30% when expressed by weight (45% by volume) of cement. Greater quantities of water are used in grouting than in concrete, as the water is the carrier of the products in suspension during injection. The simplest manner to specify or control the quality of the mix water is to require the use of potable water. Potable water can be used in grout without any testing. Obtaining potable water on some grouting sites is not always convenient or economical. Where potable water is not readily available, groundwater or surface water can normally be used if proper controls are put in place.

Behavior of Cement-Based Suspension Grout

a. **General.** It is widely accepted that cementitious suspensions behave as Bingham fluids. Some grouts also behave as visco-plastic fluids (Weaver 1991). Figure 5.5a illustrates the behavior of a Bingham fluid in comparison to water, which behaves as a Newtonian fluid (Figure 5.5a). It is helpful to think of the shear stress (or Y-axis shown in Figure 5.5a) as being a function of grouting pressure and the x- axis or shear rate as the flow rate of the grout. The most important aspect of a Bingham or visco-plastic fluid is that it has a yield point or cohesion that is equal to the minimum pressure required for the grout to move and a viscosity that is a measure of the incremental increase in resistance to flow (i.e., additional pressure required) for a change in the pumping rate. For some grouts, the viscosity does not remain constant as the flow rate increases. Grouts where the viscosity or slope increases with increasing flow rate are identified as exhibiting shear thickening (Figure 5-5b). Shear thinning behaviour (Figure 5-5c) refers to a grout for which the viscosity reduces with increasing flow rates. Grouts for which the viscosity changes with shear rate are identified as visco-plastic.

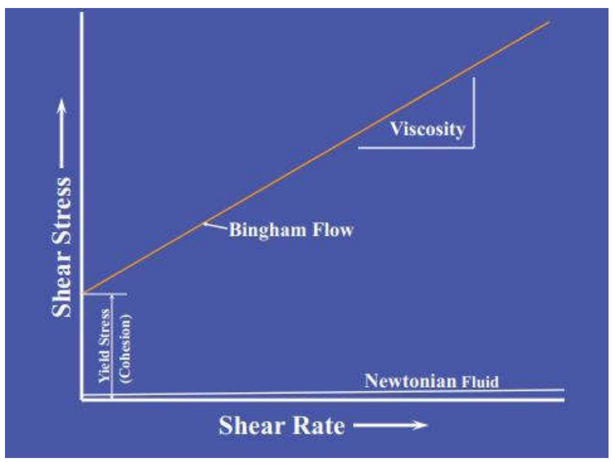


Figure 5.5a. Bingham fluid behavior. (After Houlsby 1990)

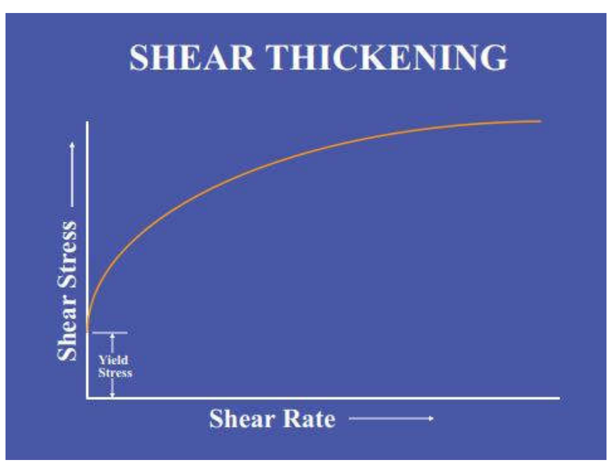


Figure 5.5b Shear thickening behaviour

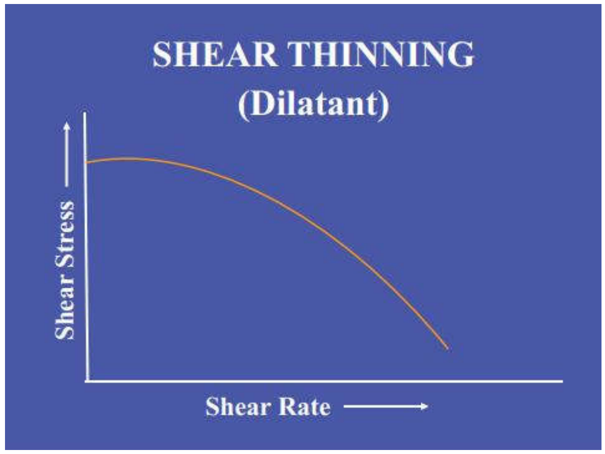


Figure 5-5c Shear thinning behaviour

b. **Yield Point.** The yield point defines the pressure required to start grout flowing and the pressure at which grout stops moving (refusal) within a fracture. At any stress greater than the yield point, grout will continue to flow in the fracture. For a constant fracture width, the rate at which grout flows in the fracture is controlled by the pressure in excess of the yield point and the grout viscosity. As grout moves away from an injection hole, the pressure decreases due to head loss within the fracture. As the pressure experienced (or "felt") by the grout farthest from the hole reduces, the flow rate continues to drop.

Desired Properties of Cement-Based Suspension Grout

General.

According to Wilson and Dreese (1998), the perfect grout for rock foundations of dams would have zero cohesion, since it would then penetrate all fractures in exactly the same way as the water. It would also have: (1) a low viscosity to permit fast penetration rates, (2) instant set at pre-defined, controllable time intervals, (3) zero shrinkage, (4) and a strength and durability similar to concrete. Obviously, that perfect grout does not exist. Solution or chemical grouts come closest to meeting the properties of this perfect grout. However, due to cost, durability, and/or environmental concerns, cement-based suspension grouts are normally the material of choice for dam foundation grouting.

The perfect grout cannot be developed using a cement-based grout because the resulting grout would be a suspension and not a solution. However, the achievable desired properties of a cement-based suspension grout are:

a. Zero bleed, so that the fractures or voids that are filled during the injection remain filled.

b. High resistance to pressure filtration, so that the water-to-solids ratio remains constant during the injection.

c. Water repellent, so that the grout suspension does not dissociate when injected into water.

d. Resistant to particle agglomeration due to electrostatic and chemical interactions, to prevent the development of macro-flocs (increase in grain size) from the hydration process during the period of injection.

e. Cohesion values consistent with the desired penetration distance. A low cohesion is desirable to maximize penetration from a given hole and limit the total drilling footage required. In karst or very high permeability formations, a mix or mixes with a high cohesion might be desirable to keep the travel distance within the intended treatment zone.

f. Viscosity compatible with the pumping pressures and low enough that an economical injection rate is achieved.

g. Thixotropic, so that the grout is resistant to wash out after placement.

h. Well-graded grain size distribution of the cured grout (a well-graded structure of the cured grout reduces the matrix permeability and thus improves durability).

i. Long-term durability.

Unstable Suspension Grouts

a. *Introduction.* The term "unstable suspension grout" is widely accepted to mean a grout with 5% or more bleed.

b. *Neat Cement Grouts.* The simplest and most basic recipe for grout is to add cement to water and mix them together to produce a neat cement grout.

c. *Commonly Used Additives.* The majority of past projects employing neat cement grouts did not incorporate any additives into the mix. However, in the 1980s, began to take advantage of super plasticizers to lower the water-cement ratio. It was also fairly common at the time to employ bentonite as an additive to neat cement grouts to reduce sedimentation. During the mix design process, careful attention should be given to the effects that additives like super plasticizers have on grout mixes. It is suggested that grout mix formulations be evaluated through laboratory testing.

d. *Fluid Properties.* This lack of stability is evident in the rapid occurrence of sedimentation or bleed when unstable cement grouts are not being continuously sheared, and in their low resistance to filtration (separation of water from the solids in suspension) when under pressure.

e. *Setting of Grout.* Set times for neat cement grouts depend on the type of cement and the water-to-cement ratio. Additionally, the set time may be impacted by the amount of water forced into adjacent fractures as a result of pressure filtration or possible water losses into the porous rock mass. Grouts with a water-to-cement ratio by weight of approximately 1.3:1 or less generally set in less than 8 hrs.

f. *Grout Behaviour in Rock Fractures.* The relatively rapid occurrence of sedimentation and low resistance to pressure filtration in an unstable grout results in unpredictable behaviour within rock fractures. This low resistance to pressure filtration results in the mix water separating from the grout when the flow velocity decreases and/or when placed under a moderate pressure. This results in changes in the grout rheology as the grouting application is in progress.

g. *Water Separation.* As the water separates from the grout, it moves more rapidly through the fracture due to its significantly lower viscosity. This reduction in water content in the grout results in the remaining suspension becoming thicker as more and more water escapes. Figure 5-6 illustrates how unstable grouts are envisioned to behave when injected into a rock fracture. Some authors believe that this separation of the water from the suspension results in the grout acting first as a Newtonian fluid and then progressing to a Bingham fluid with internal friction (Gause and Bruce 1997, Chuaqui and Bruce 2003). The behaviour is likely Newtonian in finer fractures, where a filter cake forms at or near the borehole walls and only water is being injected; Bingham behaviour likely occurs in the wider fractures until such distance is reached that the shear rate in the fracture decreases and the sedimentation process begins. Once the sedimentation process begins in the fracture, the grout quickly develops internal friction and refusal will develop rapidly. The effects of segregation, groundwater, bleed during the setting process and consolidation, and fracture geometry all make the final grout properties uncertain.

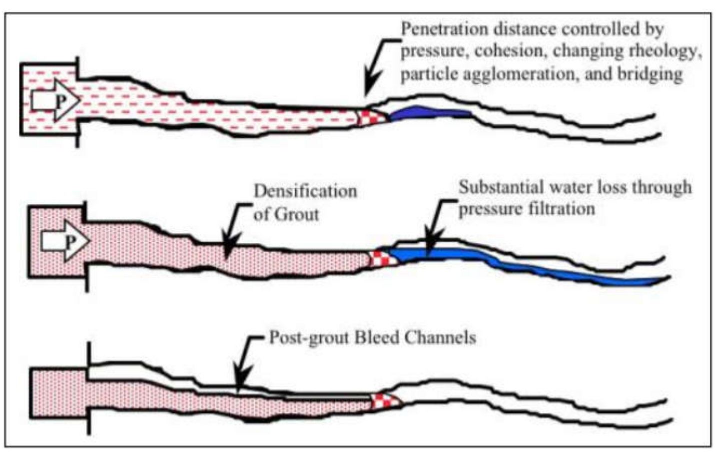


Figure 5.6. Grouting theory for unstable cement grouts

Balanced Stable Grouts

General. Admixtures can be used to improve bleed characteristics, cohesion, penetrability, durability, and workability characteristics and therefore should be considered in grouting projects requiring HMG. The number of admixtures and desired properties will vary, depending on the application.

a. *Definitions.* The term "stable grout" was previously defined as a grout mixture that exhibits less than 5% bleed. The term "balanced grout" refers to a grout mixture that is formulated to provide the desired rheological properties that also remain constant during the injection process. Balanced stable grouts are grouts that exhibit minimal bleed with desired properties and a rheology that remains constant throughout the injection process since the pressure filtration coefficient is low.

b. *Commonly Used Additives and Admixtures.* The use of additives in cement-based suspension grouts can improve the rheological properties of a grout. Each additive is used to improve one or more properties of the grout, although, unfortunately, the additive may improve one property while adversely affecting other properties. The grout mixture proportioning should be conducted by an individual experienced with the use of admixtures and proportioning to achieve the required properties. Table 5-1 lists common additives and admixtures, identifies their beneficial and adverse effects, and provides other comments pertinent to their use.

Table 5-1. Common grout additives. (After Wilson and Dreese 1998.)

Additive	Beneficial Effects	Adverse Effects	Other Comments
Fly ash Class C or Class F	• Improves grain size distribution of cured grout. • Inexpensive filler with pozzolanic properties. • Can be used as a replacement for some of the cement and reacts	• Increases cohesion and can be used to increase viscosity.	• Fly ash is a waste product and the properties vary depending on the source.
Bentonite	• Reduces bleed and increases resistance to pressure filtration. • Slight lubrication and	• Increases viscosity and cohesion.	• Should be added as pre- hydrated suspension.

Silica Fume	• Fine-grained powder that improves pressure filtration resistance and reduces bleed. • Improves water repellency and enhances penetrability.	• Increases viscosity and cohesion.	• Difficult to handle due to fineness.
Viscosity modifiers (diutan gum)*	• Makes the grout suspension more water repellant. • Provides resistance to pressure filtration.	• Increases viscosity and cohesion.	• At higher doses, provides some thixotropy to the grout which is
Dispersants or water reducers (superplasticizer,	• Overprints solid particles with a negative charge causing them to repel one another.	• Depending on chemistry chosen, may accelerate or	Dispersants have a distinct life span.
*Welan gum previously used.			

(1) Silica Fume. The typical dosage is 5–10% by weight of portland cement.

(2) Bentonite. The typical dosage is 2–5% by weight of cementitious material. Bentonite is added as a pre-hydrated suspension, typically hydrated a minimum of 12 hrs before use (Weaver and Bruce 2007). When pre-hydrated bentonite is used, the amount of water in the pre- hydrated suspension must be considered in the batch calculations.

(3) The superplasticizer concentration is optimized when an increase in concentration does not change the apparent viscosity of the grout. After the superplasticizer concentration is optimized, the thinnest mix should be formulated to establish the percentages of bentonite and viscosity modifier required to stabilize the mix and to provide adequate pressure filtration resistance. After the percentages of all the admixtures and additives have been determined, the water content is then systematically reduced to provide the range of apparent viscosities desired (Figure 5.7).

Figure 5.7. Testing for apparent viscosity and pressure filtration. (Courtesy of Gannett Fleming)

c. *Sequence of Mixing.* The typical sequence of mixing when preparing stable grouts with multiple admixtures is to add the water to the mixer followed by the pre-hydrated bentonite slurry. (The bentonite slurry contains a significant portion of the mix water.) After the water and bentonite slurry, the cementitious materials are added. This includes the cement and any pozzolanic additives such as fly ash or silica fume. Once the cementitious materials have been added and mixed, the water reducer or super plasticizer is added, followed by any viscosity modifiers. Any accelerators or retarders are added at the time recommended by the material supplier, but these are generally added last. For very thick mixes, the super plasticizer might be added to the water before the cement. While adding the super plasticizer to the water in advance of the cement does facilitate mixing, a higher dose (up to two times) of super plasticizer will be required if added before the cement.

d. *Other Admixtures.*

(1) Retarders. Retarders are commercially available from several manufacturers. Set times can be delayed from hours to days. Retarders are rarely used in typical grouting applications. For projects in hot climates and where extended permeation periods are desired in soil grouting, a retarder can be appropriate.

(2) Accelerators. Accelerators are not typically used in standard rock or soil grouting programs. However, there are times when an accelerator might be appropriate, including

accelerators are calcium chloride and sodium silicate, both of which can have negative impacts on long-term grout properties.

(3) Anti-Washout Agents. Viscosity modifiers such as diutan gum provide resistance to

washout. Additional resistance to washout can be achieved using commercially available anti-washout agents. These admixtures can be employed if flowing water is encountered when using cementitious grouts. These products are cellulose based and may have compatibility issues with other admixtures. Consultation with the supplier is recommended before use, along with additional mix design testing.

e. *Fluid Properties.* The fluid properties of balanced stable grouts can be varied widely depending on the application. For a typical grout curtain in fractured rock, a low cohesion is desirable, and a range of apparent viscosities as measured with a marsh funnel ranging from a low of 35–40 sec to a maximum of 60–70 sec would be common. A minimum 5-sec change in marsh funnel flow time should be provided, and a 10-sec change between mixes is common for thinner mixes. With balanced stable grouts, the various mixes are designed to achieve the desired viscosity and cohesion. Thin mixes have low viscosity and low cohesion, while thick mixes have higher viscosity and higher cohesion. The injected mix is progressively thickened in response to conditions observed in the stage, as with neat cement grouts.

(1) The other major fluid property to consider is the resistance of a grout to pressure filtration. Pressure filtration is measured by placing the grout in a filter press and applying pressure. The test, conducted in accordance with American Petroleum Institute Test Procedure API RP 13B-1, measures how easily water is removed or squeezed out of a grout. A high resistance to pressure filtration or a low-pressure filtration coefficient is desirable to ensure that the grout rheology is constant during the injection process. The pressure filtration coefficient K_{pf} is calculated as:

$$K_{pf} = \frac{\textbf{Filtrate Volume}}{\textbf{Initial Volume of Grout}(\textbf{400 mL}) \times (\textbf{Filtration Time})^{1/2}}$$

(2) Figure 5.8 shows pressure filtration coefficients of neat cement grouts and balanced stable grouts, side by side, for comparison. The standard test duration is 30 minutes. The neat cement grouts thinner than 1:1 blow air after less than 10 minutes, indicating that nearly all the mix water has been squeezed out of the grout. For most grouting projects, a pressure filtration coefficient of 0.05 or less should be targeted.

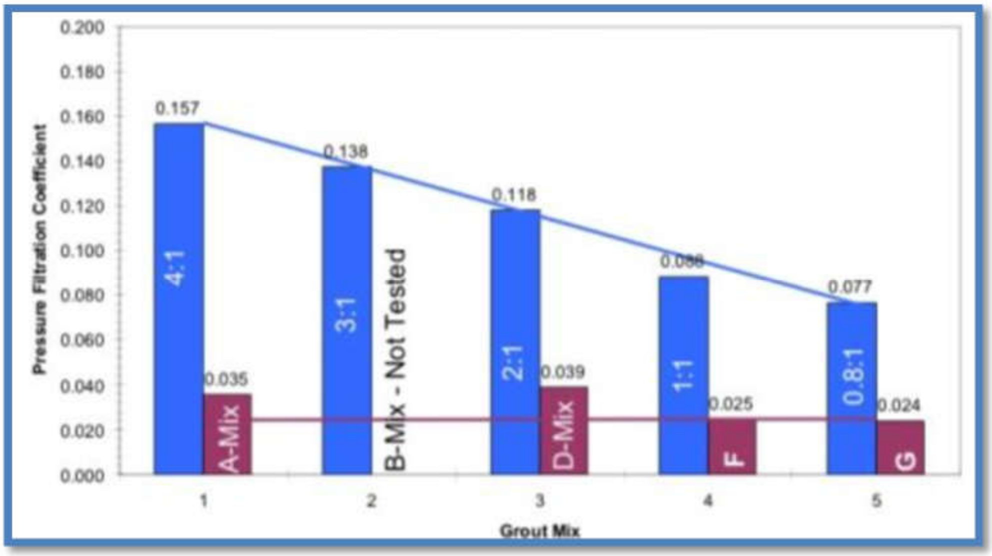


Figure 5.8. Pressure filtration coefficient values from the Penn Forest Dam mix testing program. (Courtesy of Gannett Fleming)

f. *Setting of Grout and Hardened Grout Properties.* Balanced stable grouts generally have a longer set time (whether initial gel or initial set) than neat cement grouts because the formulation of a stable grout with a fully dispersed structure delays the hydration process. Set times and strengths vary, depending on the water-to-cement ratio. A suite of mix designs for grouting fractured rock might have initial set times of 10–16 hrs and final set times of 12–20 hrs. The set time can be varied, depending on the purpose of the grouting program, by using admixtures such as retarders or accelerators. The 28-day unconfined compressive strength of typical balanced stable grouts varies from 750 to 1,500 psi. Due to the variables of the constituents in balanced stabilized grouts, the grout can be designed to be stronger or weaker than a neat cement grout by altering the mix proportioning.

g *Testing Grout Properties.* Quality control testing is an important component of a grouting program. The type of testing performed must be appropriate for the application, and the testing must be frequent enough to ensure that the materials being used have been correctly formulated. Table 5.2 lists common tests used to evaluate the rheology of HMGs and the corresponding recommended test frequencies. Figure 5.9 shows a typical on-site laboratory for quality control testing.

Table 5.2. Quality control tests for HMG.

Test	Equipment	Frequency
Apparent viscosity	Marsh funnel	Once per mix per day
Specific gravity	Mud balance	Once per mix per day

Bleed	Graduated cylinder	Once per mix per week
Pressure filtration coefficient	API filter press	Once per mix per week
Set time	Vicat needle	Mix testing program only
Cohesion and gel times	Viscometer	Mix testing program only
Strength	Grout cubes	Mix testing program only
Apparent cohesion	10-x10-cm steel plate	Mix testing program only

Figure 5.9. On-site quality control testing lab (Courtesy of Advanced Construction Techniques)

(1) The marsh funnel and specific gravity tests can be performed rapidly and economically. In general, if these two tests show satisfactory results and thorough mix testing has been performed in advance, it can be assumed that the other parameters are in compliance.

(2) Typical test frequencies would be once per day per mix type for measuring the apparent viscosity with a marsh funnel and the grout density using a mud balance. Bleed and pressure filtration tests are typically performed once per week. Cohesion, gel time, set times, and compressive strengths are generally only tested once per project, depending on the grouting objective.

h. *Grout Behavior in Rock Fractures.* The fully dispersed structure of balanced stable grouts, combined with the significant resistance to pressure filtration, results in a grout mix that remains virtually unchanged during the course of the injection process. The super plasticizer delays the cement particles from coming together, resulting in a nearly constant grain separation within the grout over the course of the injection. The high resistance to pressure filtration assists in maintaining a nearly constant water-to-cement ratio.

(1) Figure 5.10 shows how balanced stable grouts are envisioned to behave when injected

into a rock fracture. The consistent rheology of balanced stable grouts allows the injection process to be both mathematically modelled and analyzed. The flow of a Bingham fluid may be expressed as (De Paoli et al. 1992):

$$\tau = C + \eta_B \frac{dv}{dx} \cong \eta' \frac{dv}{dx}$$

where:

τ= shear stress.

C= grout cohesion or yield point.

η'= dynamic viscosity.

ηB= plastic viscosity.

$\frac{dv}{dx}$ = shear rate.

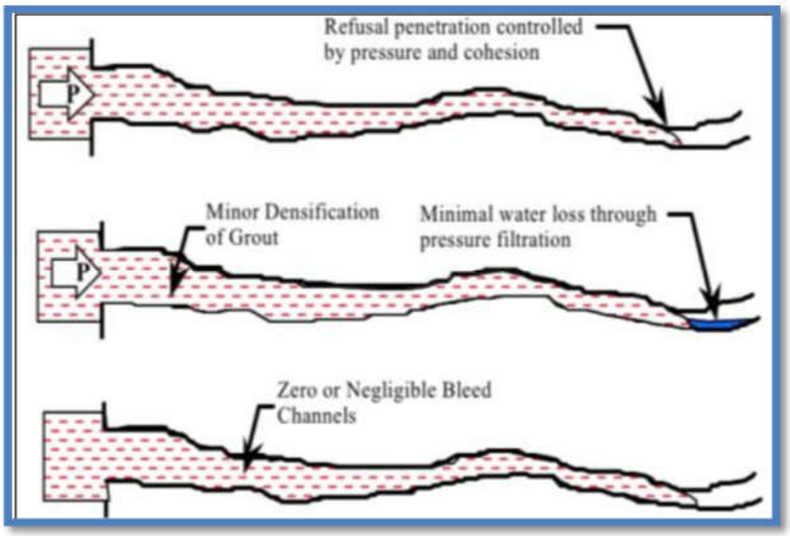


Figure 5.10. Grouting theory for balanced stable grouts

(2) It is appropriate to consider the Y-axis of the Bingham model as pressure or resistance to flow and the x-axis as flow rate (Figure 5.5). Evaluation of the model then results in the following simplified explanation of the injection for a constant injection pressure in a fracture of uniform thickness: as a grout penetrates a fracture, the head losses increase and the pressure at the grout fringe decreases. As the pressure decreases, the flow rate decreases proportionally to the viscosity. This continues until the pressure at the grout fringe is equal to the cohesion, at which time refusal occurs and grout flow stops. Conclusions based on this simplified explanation are:

(a) Cohesion controls how far a grout will travel in a fracture of a given opening for a given injection pressure.

(b) For that same fracture aperture and pressure, the viscosity controls the flow rate and ultimately the time required to grout that fracture.

(c) Head losses will be greater in a finer fracture than in a wider fracture. Therefore, grout penetration distance will increase as the fracture aperture increases.

i. *Penetrability.* The Bingham flow model (Figure 5.5) shows that the penetration distance into a fracture depends on the cohesion and the applied pressure. The penetration distance also depends on the fracture aperture for two reasons. The first is that head loss is greater in narrower fractures. The second is that the larger grains of the grout suspension might clog the fracture. Lombardi (1985) developed the equations that relate the maximum radius of penetration, the maximum volume of injected grout, and the maximum total uplift force to the injection pressure, the grout cohesion, and the fracture aperture:

$$R_{max} = \frac{p_{max} t}{C}$$

$$V_{max} = \frac{2\pi p_{max}^2 t^3}{C^2}$$

$$F_{max} = \frac{\pi p_{max}^3 t^2}{3C^2}$$

where: p_{max} = applied pressure; t = half thickness or aperture of the fracture; C = grout cohesion or Bingham yield point; R_{max} = maximum radius of penetration; V_{max} = maximum volume of injected grout; F_{max} = maximum total uplift force.

Lombardi's equations for the maximum volume of grout and the uplift pressure are of limited practical use, as they assume uniform flow of grout radially in all directions, a uniform fracture aperture, and a horizontal fracture. The penetration distance also assumes a uniform fracture aperture and can generally not be used to predict the actual field penetration distance. The equation for grout penetration distance is still highly useful because it recognizes that the penetration distance is proportional to the injection pressure and the radius (half thickness) of the fracture and is inversely proportional to the grout cohesion. Therefore, a low cohesion is generally desirable for most grouting projects. However, in highly permeable or open formations, such as karst, grouts with a higher cohesion might be desirable to minimize the grout travel distance.

(1) Other relevant grouting equations pertaining to penetrability and grain size have been published by various authors. These include the groutability ratio (GR) (Mitchell 1981) developed for

fractured rock:

GR = width of fracture / (D95) grout; where:

(D95) grout = the 95% size of the grout particles

GR > 5 indicates that grouting is consistently possible

GR < 2 indicates that grouting is not possible.

(2) The data shown in Figure 5.11 indicate the range of particle sizes that are typical of various grout materials. The advantage of using the ultrafine cement in fine fractures is obvious in light of the GR defined above and the significantly smaller grain size in comparison to the Portland cements. Evaluation of the range of material sizes also indicates that fly ash should not be used with ultrafine cements, as the fly ash particles would be the largest and would control the penetrability.

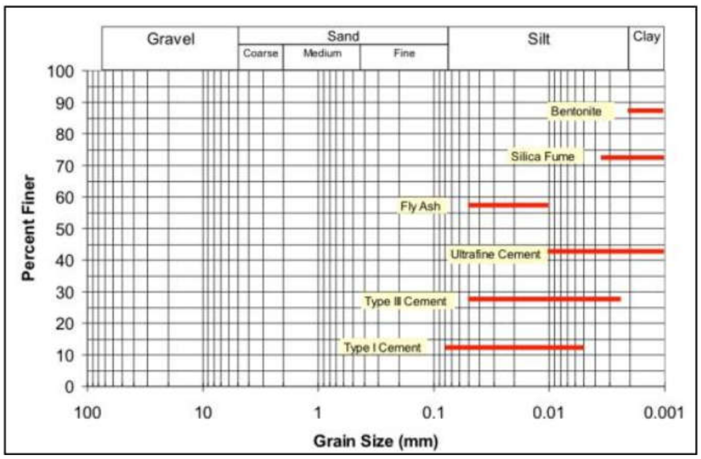


Figure 5.11. Range of grain sizes of typical admixtures. (After Warner 2004)

(3) Mitchell also provided the following equations for soil grouting:

N = D15soil / D85 grout

Nc = D10soil / D95 grout

N and Nc = GRs for the soil.

D15soil = 15% size of the soil.

D85grout = 85% size of the grout particles.

D10soil = 10% size of the soil.

D95grout = 95% size of the grout.

N < 11 or Nc < 6 indicates that permeation is impossible.

N > 24 or Nc > 11 indicates that the soil is readily groutable.

Chapter 6. Tunnel Grouting

Introduction.

Grouting is used in tunnel applications for one or more of the following purposes: reducing groundwater inflows, strengthening the surrounding soil/rock mass to facilitate tunnelling, controlling ground subsidence, and enhancing soil/rock-structure interaction. This chapter provides a limited overview of the various grouting techniques commonly applied to tunnelling.

Applications

a. **General.** Grouting in tunnel applications may be performed before, during, or after completion of tunnel excavation. Depending on its intended purpose and access issues, grout holes may be drilled from the ground surface, from within the tunnel, or both. A wide variety of grouting techniques can be applied to soil, rock, or mixed face conditions, depending on the site conditions and outcome desired. Table 6-1 lists grouting techniques that are commonly employed along with their general application to tunneling in both soil and rock.

b. **Soil Grouting Techniques.**

(1) Jet grouting involves the use of high-pressure jets of cement grout discharging perpendicular to the direction of hole advance. The high-velocity jets simultaneously excavate and mix the grout with the in-situ soil to create soilcrete columns. Jet grouting can be used either from within the tunnel or from the ground surface, as shown in Figures 6-1 .

(2) Compaction grouting, is the process of injecting very stiff, mortar-like grout at high pressure and in a controlled manner for the purpose of densifying the soil around the injected mass. In soft ground tunneling applications, compaction grouting is commonly used from the ground surface for settlement control (Figure 6-2).

(3) Permeation grouting in soil involves the injection of either cementitious or chemical grout into the pore spaces of soils to reduce seepage and/or improve the soil. Permeation grouting is typically performed before tunnel excavation. Injection holes can be horizontal or inclined from within the tunnel or from the ground surface (Figures 6-3). The soil particle size (grain size distribution) of the host formation will dictate the type of grout used.

Table 6-1. Grouting techniques and their general application to tunneling.

	Grouting Techniques	General Applications
Soil	Jet grouting	Reduce seepage Improve strength Settlement control
	Compaction grouting	Settlement control
	Permeation grouting	Reduce seepage Improve strength
	Hydrofracture grouting	Improve strength Settlement control
Rock	Consolidation grouting	Reduce seepage Improve strength
	Permeation grouting	Reduce seepage
	Contact grouting	Void filling-structure interaction

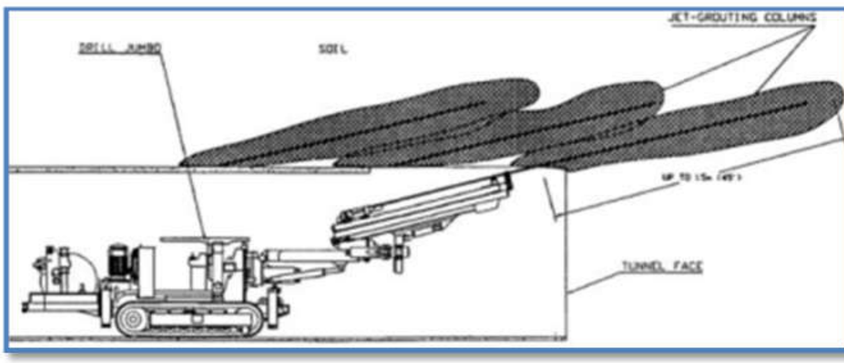


Figure 6-1. Jet grouting within a soft ground tunnel. (From Henn 1996)

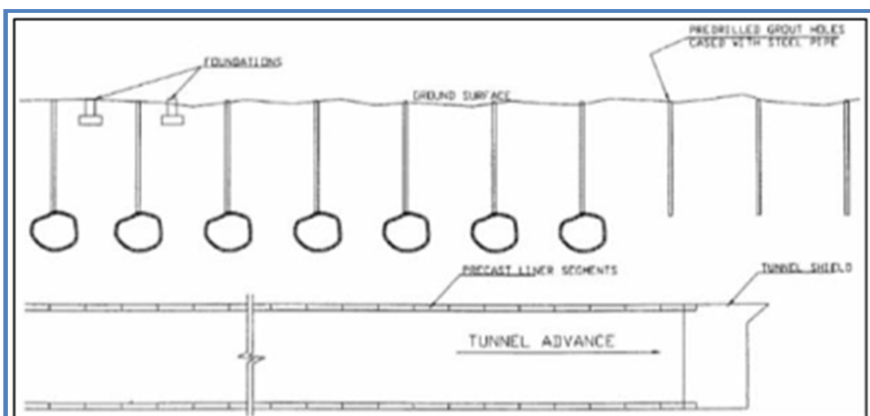


Figure 6-2. Compaction grouting from the ground surface for a soft ground tunnel. (From Henn 1996)

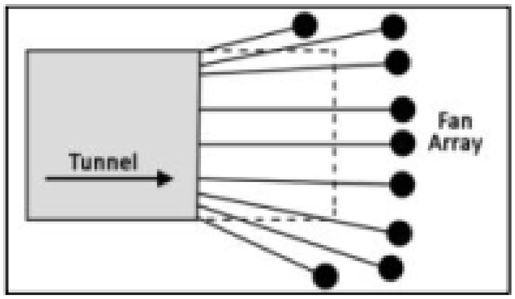


Figure 6-3. Permeation grout fan array from a tunnel heading.

(4) Hydrofracture grouting, involves the injection of a high-mobility stabilized cement grout at a pressure sufficient to induce tensile failure of the soil, resulting in the formation of grout lenses within the soil. These pressurized lenses of grout densify the soil by plastic deformation in the vicinity of the lenses and also reinforce the soil mass due to the higher strength of the grout in comparison to the soil. Hydrofracture grouting is used to compensate or offset settlements experienced during soft ground tunnelling. Hydrofracture grouting is typically conducted from the ground surface along the tunnel alignment similar to the compaction grouting process shown in Figure 6-2.

c. **Rock Grouting Techniques.**

(1) Consolidation grouting strengthens rock masses and reduces permeability by filling open fractures and other discontinuities within the rock mass. Consolidation grouting may be performed before tunnel excavation to improve the in-situ rock mass conditions (Figure 6-3) or after tunnel excavation in areas of poor rock quality or to remediate excessive seepage.

(2) Permeation grouting for water control in rock tunnelling operations is most often performed in advance of tunnelling through probe holes performed from the tunnel heading. Probe holes are drilled ahead of the tunnel during advancement. If the probe holes detect excessive groundwater inflows, additional drilling and permeation grouting is conducted ahead of the excavation. As with grout curtain construction, secondary holes are drilled following the initial series of drilling and grouting to verify the effectiveness. If the secondary holes again detect excessive groundwater inflows, a second phase of permeation grouting is performed. The process is then continued until an acceptable level of inflow is achieved.

(3) Contact grouting is employed to fill the annular space between tunnel liner materials and the excavated rock surface. This is also commonly referred to as “backpack” grouting. Contact grouting is performed to provide uniform contact and structure interaction with the formation, to fill voids that might otherwise result in relaxation or raveling of the host formation, and/or to reduce seepage into the

tunnel or eliminate seepage paths along tunnels.

(a) Selection of methods and materials used in contact grouting depend on the size of the annular space to be filled, on the size and frequency of planned grout holes, on the presence of water, and on the purpose (i.e., need for strength, seepage reduction, or simply bulk fill). Typical grout materials may consist of: cement grout with or without aggregates, fly ash, bentonite, or other additives to facilitate placement; cellular (foamed) grout; flowable fill; or chemical grouts.

(b) Grout hole patterns and sequencing vary, but normally begin with grout placement in the lowest portion of the tunnel. Grout is placed under pressure and forced upward, with grout holes at higher elevations used as vents and for verification of complete filling. As grout emerges from pre-drilled vent/grout holes at higher elevations, packers can be used to seal those holes, allowing grouting to continue from lower elevations until grout emerges from vent/grout holes in the uppermost portion of the tunnel. Figure 6-4 shows the grouting sequence used for contact grouting in the rehabilitation of an existing horseshoe-shaped tunnel that contained large void spaces behind the original tunnel lining and shoring system.

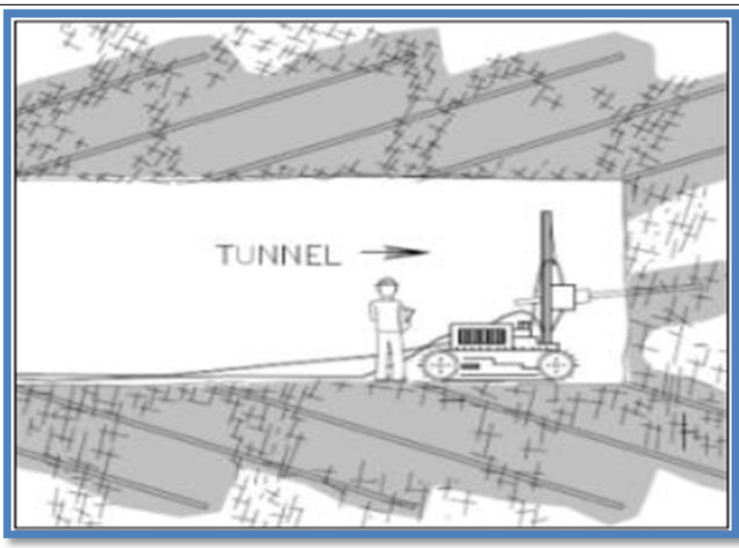


Figure 6-3. Pre-consolidation grouting ahead of tunnel excavation

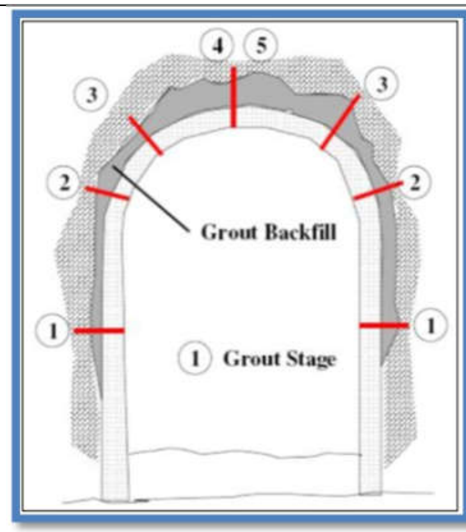


Figure 6-4. Sequence for contact grouting a horseshoe-shaped tunnel.

Chapter 7. Drilling and Grouting Equipment

Overburden Drilling Equipment

Introduction. Drilling holes for the purpose of injecting grout is a critical phase of a grouting program and one that can present numerous challenges. Often these challenges result from the materials that have to be penetrated, which can vary significantly across the project site in both the horizontal and vertical directions; to the terrain that the drilling equipment must traverse; to the environmental requirements of the drilling process; to the required accuracy and condition of the final grout hole.

General Considerations in Selection of Method. Typically, the decision about the type of equipment to be used is left to the contractor. However, it is imperative that the project specifications provide the requirements for the grout hole alignment, accuracy, and special restrictions on equipment to protect the in-place conditions of the dam embankment or other structure and underlying strata. Each of these requirements can significantly impact the selection of drilling method. There are many types of drill rigs and many options in selecting drill tooling. Some are developed for high production and require road-like conditions for access. Other types of drill rigs have been developed to maximize mobility, while others have been designed for unusual applications such as drilling on steep slopes or in confined areas. The size of drilling equipment varies from very large track- or truck-mounted drills to small hand-held drills for use in confined areas. On large grouting projects, specialized drill rigs or attachments might be designed and fabricated for a specific application.

(1) Critical Versus Non-Critical Applications. Holes that are drilled through existing dam embankments or other earthen hydraulic structures are considered critical because of the potential for damage to the embankment materials. This damage generally results from excessive pressure of the flushing medium, which can cause significant scour or erosion of the boring sidewalls or can cause pneumatic or hydraulic fracturing of the embankment. Air, gas, water, mud, or any other drilling fluid shall not be used in these critical areas, specifically, the impervious core of the dam, and the core trench or foundation soil under the core. In addition, drilling fluids shall not be used in portions of dams where contamination of filters or drainage features is possible. Holes that are drilled outside the limits of the embankment core footprint are often considered non-critical when there is no potential for damage to the embankment due to the drilling process. A common example is drilling in coarse shell zones.

(2) Influence of Differing Material Types. Materials typically encountered during drilling for

grout holes can vary from clay cores, random fills, and rock shells in dam embankments to boulders and running sands in natural deposits. Each of these zones or materials requires consideration of the equipment most suitable for penetration without damaging the material surrounding the hole.

(3) Sampling Requirements. Often samples are not required in the overburden since the primary purpose of drilling through the overburden is to gain access to the underlying rock that is to be grouted or to subsequently inject low-mobility or solution grouts into the overburden. In addition, the site investigation borings have normally provided sampling and characterization of the overburden materials in advance. However, if samples are required, this will influence the drilling method to be used. It is not possible to obtain representative samples with some drilling methods since the material is changed significantly by the drilling process, which may pulverize the material. Other methods permit sampling of the return flush, which is highly disturbed. Some methods allow for retrieval of relatively intact bulk samples.

Rock Drilling Equipment

a. Introduction. This chapter provides information on the basic requirements associated with drilling grout holes in rock and discusses the various methods for drilling. The selection of the drilling method primarily depends on the characteristics of the rock to be drilled, the hole depth, access to the hole location, and the requirement to drill a properly aligned clean hole at a reasonable cost and in a reasonable time.

b. Basic Requirements.

(1) Hole Diameter. Typically, the diameters of grout holes are in the range of 2–5 in. with the preference of 3-in. diameter in rock. Any specific requirements for hole size should be clearly stated in the contract documents. Depending on the application, such as drilling through a concrete structure and into rock, a maximum hole size provision might also be appropriate to minimize damage to the structure, such as cutting reinforcement. The selection of the minimum or maximum hole diameter requirements, which should be site specific, is based on the hole depths, the equipment access requirements for the subsequent grouting operations, and the need for any special treatments, such as telescoping casing through unstable strata within the rock.

(2) Hole Orientation. Proper orientation of the drill hole begins with an accurate layout of the hole locations at the surface. Proper alignment is enhanced by providing a stable platform for the drill

rig, an accurate setup of the rig, and monitoring of the continued correct orientation. This is accomplished by conventional survey equipment used to confirm the proper drill layout, electronic levels, or orientation equipment that can be attached to the drill mast. Electronic levels with accuracies of 0.1 degrees are readily available and should be used in the absence of other methods.

c. Selection of Drilling Method. There are two basic methods for drilling grout holes in rock: rotary drilling methods and rotary percussive drilling methods. Each of these basic methods has variations that may be used. Rotary methods can be subdivided into high rotational speed and low rotational speed. The rotary percussive methods can be subdivided into top-hole rotary percussion and down-hole rotary percussion.

(1) Rotary Methods. High-speed rotary drills apply limited torque and thrust and rely on the high-speed rotation of the bit to cut the rock. Low-speed rotary drills require large drills with high torque and thrust to destroy the rock fabric.

(a) High-Speed Rotary. The most common method of high-speed rotary drilling is diamond drilling. This method has long been used for drilling rock. In the past, it was considered to be the best method because it created smooth-walled holes that made setting packers easier, and it resulted in straighter holes. An advantage of the diamond rotary method is that equipment is readily available in smaller and lighter rigs, and they can easily drill to the depths generally required for grouting. Diamond rotary holes can be drilled using destructive or non destructive methods. If no sample is desired, plug bits can be used. With the advent of wire line drilling methods, plug bits are rarely used, as the area of rock requiring cutting is the total area of the hole. Coring is generally faster than plug bits and provides the advantage that the rock being grouted can be directly observed. Figures 7.1 through 7.3 show examples of high- speed rotary drills.

(b) Low-Speed Rotary. This drilling method employs large drills capable of installing larger-diameter holes to considerable depth. The large down-pressure and torque applied to the drill string and bit are used to penetrate the rock. The most common use of these drills is for water well drilling, where air is commonly used as the flushing medium. If water is used as the flushing medium, there is no reason that this drilling method would not be acceptable for drilling grout production holes. However, economics and drill rig accessibility issues generally lead to the selection of alternative methods.

(2) Rotary Percussive Methods. These drilling methods use a hammer to impart percussive energy to the bit while the drill head imparts slow rotation. For top-hole percussion, the hammer is

mounted on the drill, and the energy is applied to the bit through the drill rods. For down-hole methods, the hammer is installed just above the bit and is activated by the drilling fluid while the drill head rotates the string.

Figure 7.1. Truck-mounted high-speed rotary drill rig. (Courtesy of Gannett Fleming)

Figure 7.2. Track-mounted and hand-held high-speed rotary drills.

Figure 7.3. High-speed rotary drills for difficult access and confined spaces

Hole Washing Equipment

a. General. Holes must be thoroughly washed before grouting to maximize access of grout to fractures. At the completion of drilling the grout hole, the washing operation begins by raising and lowering the drilling tools several times a short distance and allowing the drill water to circulate. This removes the coarser cuttings that tend to settle at the bottom of percussion- drilled holes. However, drill water circulation alone is not adequate to properly clean the holes. A separate hole washing step is a standard requirement after drilling.

b. Equipment. Equipment used in the washing process includes washout bits, pumps, and hoses and pipes to inject the water. Typically hoses with a minimum diameter of 2.5 cm (1 in.) are used for injecting water. Hose is preferred to pipe since it is lighter and can be used to a greater depth because the washing process is often done by raising and lowering the wash equipment by hand. The insertion and retraction of the hose can also be done more quickly than pipe, which has to be added or removed in sections. A special washout bit is attached to the bottom of the hose. The diameter of the bit should be similar to that of the borehole, but small enough to permit rock fragments and cuttings to pass between the bit and the hole sidewall. The bit has closely spaced holes (approximately 3.2 mm [1/8 in.] in diameter) spaced around its perimeter to permit radial flow to be directed at the sidewall, in addition to the bottom discharge. Water pumps should be capable of supplying water at a minimum pressure of 100 psi and flow rates at a minimum of 30 gpm at the top of the hole. Depending on the formation being cleaned, the pressure may need to be limited to prevent damage to the rock. After a hole is completely washed, a plug should be installed in the hole collar to prevent debris from entering the hole.

Pressure Testing Equipment

a. General. Grout holes are pressure tested to provide information on the permeability of the formation to be grouted, to identify highly permeable zones, to help identify unstable zones that may require special grouting, and to evaluate the permeability reduction being achieved as grouting progresses. The equipment for water testing is generally the same as that used for grouting.

b. Packers. Packers are used to isolate a portion of a hole for the purpose of injecting water under pressure into the isolated area. Packers are essentially a length of pipe, smaller in diameter than the grout hole or casing, with expandable devices attached to the pipe to create a seal between the pipe and the grout hole. There are several varieties of packers, including friction, mechanical, and inflatable. The type of packer recommended depends on the expected uniformity of the hole size and whether the packer will be installed in the hole casing or directly in the grout hole.

(1) Friction packers can only be used where the packer is seated within a grout hole standpipe. It employs U-shaped cups or O-rings to create the seal (Figure 7.4). With the U- shaped cups, the pressure of the water acts on the inside of the U-shape to expand the cup against the casing. The O-ring packer creates the seal by a tight friction fit between the O-ring and the casing. Both of these can sustain high pressure, but are subject to high wear due to the tight fit and must be replaced frequently.

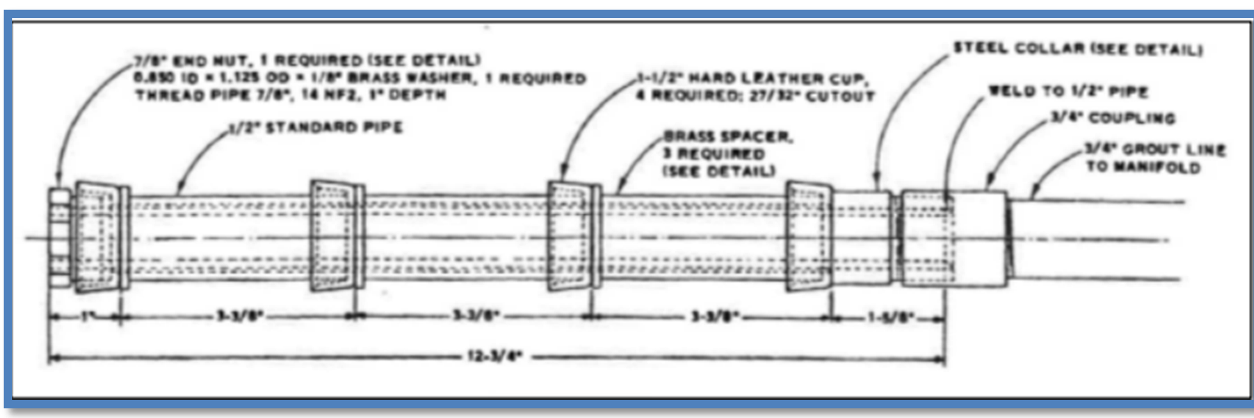


Figure 7.4. Cup-type friction packer. (Courtesy of U.S. Bureau of Reclamation.)

(2) Mechanical packers include a soft rubber or elastomeric sleeve that fits snugly over a

threaded metal tube (Figure 7.5). When a threaded coupler is turned, the sleeve expands laterally against the sidewall. The amount of expansion depends on the sleeve material, but is typically about 1.2 times the original diameter. Mechanical packers have some limitations. Due to their short length and limited expansion capability, there is a possibility that grout will bypass the packer because roughness in the borehole has caused an inadequate seal or because grout has flowed through the fractures and around the packer. This can cause the packer to become stuck in the hole and can cause loss of control of the flow of grout. Mechanical packers are commonly used when grouting the top stage through a grout cap if the length of an inflatable packer is greater than the thickness of the concrete.

Figure 7.5. Mechanical packers. (Courtesy of Palm Equipment, Inc.)

(3) Inflatable packers, also called pneumatic packers, consist of an expandable sleeve that fits over a tube attached to the grout pipe (Figure 7.6). The ends of the sleeve are sealed, and a fitting is incorporated so that air, water, or gas can be injected into the sleeve to cause it to expand. The sleeve is typically 0.9–1.2 m (3–4 ft) in length, but can be of any length. Longer packers provide additional bond length for successful seating and will resist higher pressures. The amount of pressure that the sleeve can sustain depends on the material, which is typically reinforced hose, but sleeves with allowable working pressures of 500 psi are readily available and are adequate for most grouting projects. Typically, the sleeve can expand about 1.3 times the initial diameter of the sleeve, with a maximum of about 1.5 times

the diameter. Sliding-end packers can achieve a maximum expansion of about 1.9 times the initial sleeve diameter.

Figure 7.6. Inflatable or pneumatic packer

Figure 7.7. Assembled double packer system.

(4) In downstage grouting, a single packer can be used. Upstage grouting normally requires a double packer system with a perforated delivery line between the packers to deliver water to the formation, as shown in Figure 7.7. It is important that the system performance characteristics be verified by pumping water and the grout mixtures being used through the system at various pressures to measure the volume the system is capable of delivering at each pressure and to measure head losses for calculating effective pressures.

c. Mechanical and Electronic Pressure and Flow Measurement Systems. Pressures and flow rates during pressure testing can be monitored either with mechanical systems or electronic systems. For pressure testing during the grouting phase, sufficient testing is usually performed to warrant the use of electronic pressure transducers and flow meters. Figures 7.8 and 7.9 show the measuring devices for a pressure testing system.

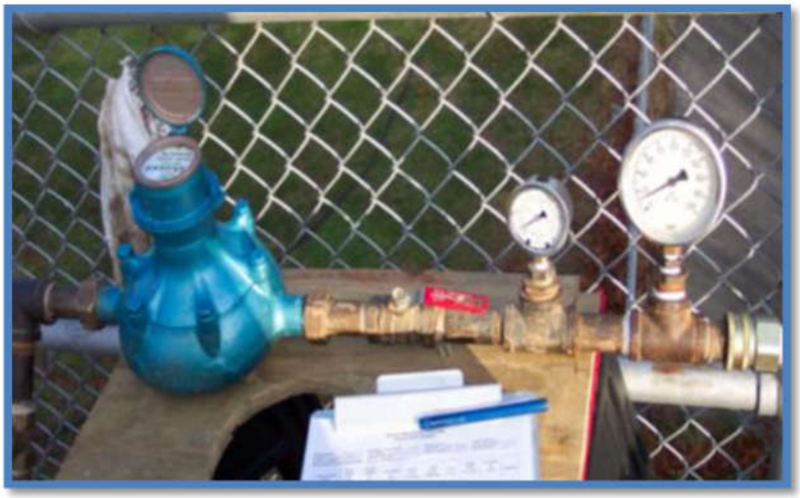


Figure 7.8. Manually read mechanical water meter and pressure gauges for pressure testing.

Figure 7.9. Electronic system for flow and pressure readings used in pressure testing.

Grouting Equipment for HMGs

General. There are many equipment variations available for each component of a grouting system. Likewise, there are several ways to assemble the required components, ranging from self-contained trailer or skid-mounted systems (Figure 7.10) that can be located immediately adjacent to the grout hole, to individual components that are distributed across the project site with the grout being pumped 250 m or more from a central mixing plant. Because the number of holes to be grouted, the accessibility of the holes, the site topography, the geology, the climatic conditions, and the size of the project will have major impacts on the selection and layout of the equipment and system(s) used, it is best to give contractors the flexibility to determine the best configuration and layout for their plant.

Figure 7.10. Mobile grout plant capable of being moved around a site near the injection point.

Grout Mixers. The grout mixing equipment must be capable of thoroughly wetting all of the particles of cement and other admixtures to create a homogeneous suspension. In the past, paddle mixers have been used for mixing grout on some projects. These employ slowly rotating paddles mounted horizontally or vertically in a tank. Paddle mixers alone are not satisfactory for producing high-quality HMG and should only be used for large backfilling or void-filling projects where incomplete dispersion of the cement particles and interruptions of the grouting are of little consequence. Current technology for high-quality grouting with HMG employs high- shear mixers. These are sometimes referred to as "*colloidal mixers*," although this name is not accurate since colloidal particles are generally considered to be less than 5 µm in size, which is smaller than most ultrafine cement particles. High-shear mixers generally consist of a vertical conical tank with a rotor located at the base rotating at 1,500–2,000 rpm. This imparts a high shearing force to the grout as the material is forced through the rotor housing by the rotor. The rotor then re-circulates the grout to the mixing tank. The grout re-enters the tank tangentially, which produces a vortex that aids in the thorough cement wetting process. Figure 7.11 shows a schematic of a high-shear mixer; Figure 7.12 shows a photograph of a rotor; and Figure 7.13 shows the vortex that forms within the mixing tank. Mixing with high-shear mixers is extremely efficient and can be completed rapidly (~1 minute) after all components have been added to the mixer. The high shear imparted to the grout generates substantial heat, which accelerates set time. Therefore, mixing time should not be excessively long and must be controlled. These mixers are capable of mixing neat cement grout mixes with water-to-cement ratios as low as 0.5:1 by volume or about 0.35:1 by weight. A minimum mixer size or capacity of 225–280 L is acceptable and appropriate for most rock permeation grouting projects. A mixer of this size can easily handle “two-bag” or “three-bag” mixes, which are common for most grouting projects. Mixer capacities that are too small result in an overworked mixer operator and interruptions in the grout supply. High-shear mixers on the order of 2 m^3 in size are available for projects requiring large volumes of grout, such as backfilling behind pre-cast tunnel segments or void filling. Paddle-assisted high-shear mixers provide even larger quantities, more than 5.6 m^3 per batch, and consist of a series of high-shear rotors surrounding a paddle mixer. Paddle-assisted mixers allow the rotors and paddle to operate independently, so that once the mix is batched, it can be agitated by the paddles until dispensed. Figure 7.14 shows a 500 L mixing plant.

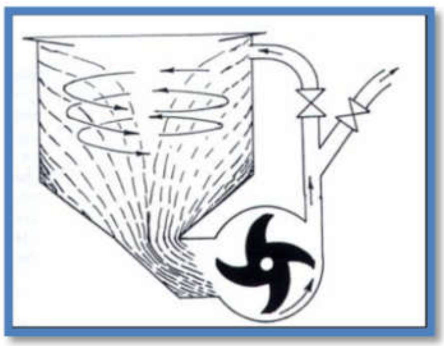


Figure 7.11. Schematic of a high-shear mixer. (From Houlsby 1990.)

Figure 7.12. Rotor of a high-shear mixer with the mixer cover removed. (Courtesy of Advanced Construction Techniques)

Figure 7.13. Vortex inside a high-shear mixer. (Courtesy of Gannett Fleming)

Figure 7.14. 500-L high-shear mixer with a 1,500-L agitator. (Courtesy of Gannett Fleming)

Agitators. The purpose of an agitator is to keep the grout mix in suspension after the initial mixing is complete. The mixer discharges to the agitator, which is a cylindrical tank with one or more paddles rotating at the speed necessary to keep the grout in suspension. The speed of rotation of the paddles is generally about 60 rpm. It is important to keep the speed just high enough to prevent settlement of the mix while slow enough that excessive heat is not generated, as the grout may remain in the agitator for an extended period of time. The agitator should have a capacity greater than that of the mixer to minimize the possibility of the agitator running dry. Tanks should be equipped such that they impart turbulent motion to the grout. The motor should be capable of turning the paddles at 100 rpm, and the tank should be equipped with baffles to prevent vortex formation. Specifications should require a minimum of four baffles and two paddles. One additional paddle should be required as near to the bottom of the tank as practicable to sweep the bottom of the tank. Figure 7.14 shows a typical agitator tank integrated on a platform with the high-shear mixer. Figure 7.15 shows an internal view of an agitator.

Figure 7.15. Inside view of an agitator tank with a bottom sweeper and other paddles.

Additive and Admixture Dispensers. Accurate measurement and dispensing of additives and admixtures is essential for proper mixing and quality consistency of multiple component grouts. While this is not a difficult issue, suitable measuring devices are required to measure and add precisely the correct amount of each additive or admixture. For manual batching of grouts, it is best that dry components be delivered in bags that are sized for each mix or that they be pre- blended with the cement, if possible. This cannot always be achieved, depending on the admixture being used and the concentration required. For fluid admixtures, admixture pumps are available that can be used to measure and add the correct volume of the additive directly into the mixer without the operator ever handling the fluid. Figure 7.16 shows an air-operated fluid admixture dispenser, and Figure 7.17 shows a gravity dispensing system.

Figure 7.16. Pneumatic additive dispensers. (Courtesy of Advanced Construction Techniques)

Figure 7.17. Gravity-feed admixture dispenser tanks re-filled via admixture pumps, with a 15-L polymer tank on the left and a 200-L bentonite slurry tank on the right with sight glasses for dosing. (Courtesy of Gannett Fleming)

Pumps. There are numerous combinations of pumps, speed and pressure controls, and power systems available for this important part of the grout injection system. The type of grout to be injected, the importance of pressure control during the injection process, and the serviceability of the pump are important considerations in selecting the correct pump. Pumps should be sized appropriately to match the expected pressures and flow rates required for the project.

a. The two types of pumps used most often in grouting are progressive cavity and piston pumps. Progressive cavity pumps output a nearly constant pressure throughout the grouting process. Piston pumps output cyclic pressures with a significant pressure difference between the maximum and minimum pressures as the valves open and close during the piston cycles. The standard practice is to require constant pressures to inject HMG for permeation grouting, which therefore requires the use of progressive cavity pumps. In contrast to the standard practice in North America, some grouters in Europe argue that cyclic pressures actually improve penetration. Houlsby (1990) dismisses this claim, and North American practice continues to require the use of constant pressures and a grout circulation line.

b. Progressive cavity or helical rotor pumps, also typically known by the trade names Mono or Moyno, consist of a steel, helical rotor that rotates inside a double-helix stator, which is made of a softer material such as wear-resistant rubber or nitrile. Figure 7.18 shows a cutaway view of a progressive cavity pump. Grout enters the pump throat from the agitator and is moved along in a screw-like motion with a positive seal between the stator and rotor. An advantage of the progressive cavity pump is the ease of servicing. The maximum pressure developed with a progressive cavity pump depends on the number of pump stages. As a rule of thumb, each stage of a progressive cavity pump will generate approximately 85 psi. Higher pressures are achieved when pumping higher-viscosity fluids. Lower-capacity progressive cavity pumps can be staged in series to achieve higher pressures.

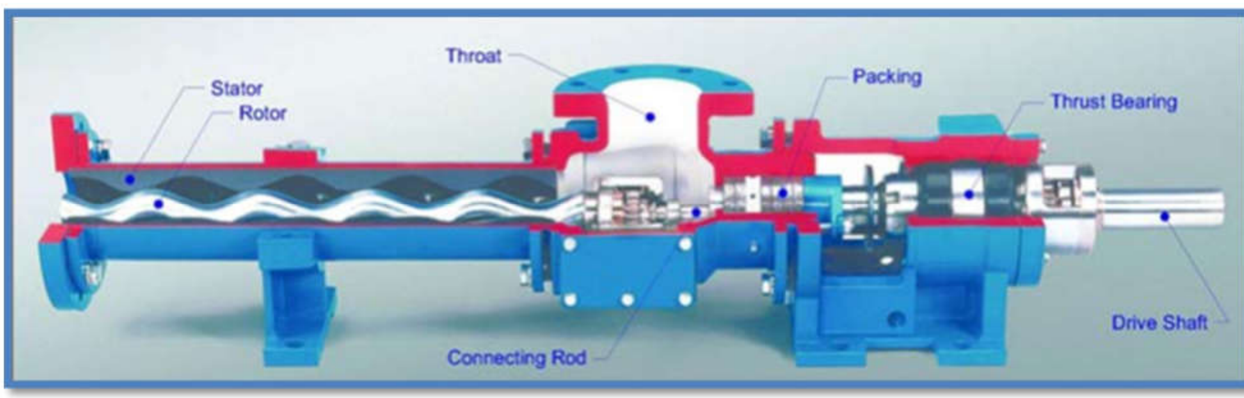


Figure 7.18. Cutaway section of a progressive cavity pump. (Courtesy of Moyno, Inc.)

c. Piston pumps have a piston or ram reciprocating within a close-fitting cylinder. The pumps can be single acting or double acting. Single-acting piston pumps only pump material when the piston moves in one direction, typically forward. Double-acting piston pumps pump material when the piston moves in both the forward and backward directions. Grout is pulled into the cylinder from one side and simultaneously expelled from the other end. This requires a combination of valves at each end of the cylinder that are actuated by the grout pressure to control the flow. Newer models of piston pumps have two pistons with a reciprocating power source located between the pistons (Figure 7.19). Piston pumps can generate very high maximum pressures in excess of several thousand psi. Some pumps also contain multiple cylinders so that quantities of grout pumped can be quite high. They are widely used for chemical solution grouting, in jet grouting methods, and on drills as booster pumps to increase the water flush pressures.

Figure 7.19. Piston pump with a reciprocating power source.(Courtesy of Gannett Fleming)

Valves. A variety of valve types are used in grouting. Valves are used at multiple locations in the grout distribution system, including between the agitator and the pump, at the grout hole to control grout flow and pressure into the hole, on the return side of the circulation line, on the hole so the grout pressure on the hole can be maintained after grouting is completed, and at the hole so that the hole can be bleed of grout or excessive pressure during grouting. Some of the valve locations require operation in various settings, while other locations only require the valve to be fully open or closed. Typical valves include diaphragm, ball, and plug cocks. Each type has characteristics that make it suitable for specific applications.

a. *Diaphragm valves.* This type of valve operates by pressing a diaphragm, via a screw mechanism, against a raised ridge in the flow path (Figure 7.20). The advantage of this valve is that fine adjustments can be made in the flow, which is important during times when precise control of the flow and pressure is required. They can be fitted with a lever or a wheel-type handle. Diaphragm valves should be specified as a requirement on the grout return line and at other locations where required to accurately control grout injection pressure. Closing the return line valve decreases the flow back to the agitator and increases the pressure down the hole. Opening the return valve lowers the injection pressure. In some circumstances where the pressure in the circulation line is too high and cannot be controlled solely by the return line valve, the diaphragm valve leading down the hole must also be used to limit the injection pressure. Using the down-hole valve to control the injection pressure should not be a standard practice and should only be used as a last resort. The disadvantage of diaphragm valves is the time required to go from fully open to fully closed. Therefore, a ball or plug cock valve is generally placed just downstream of the diaphragm valve on the line of fittings leading to the hole. Diaphragm valves are typically limited in pressure to approximately 300 psi due to the flexible internal diaphragm. When higher pressure ratings are required, more expensive valves designed specifically for flow control must be obtained.

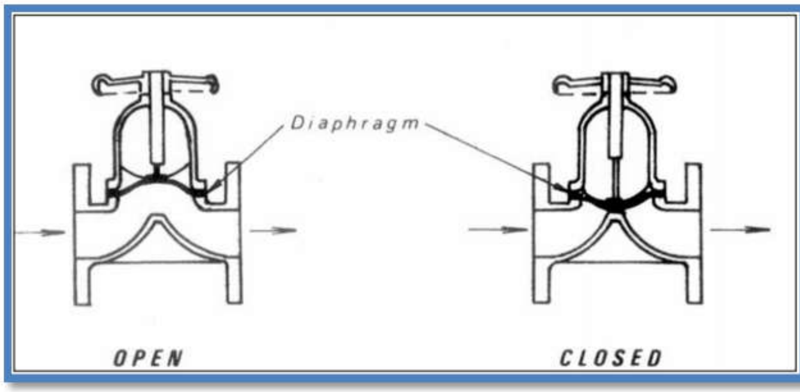


Figure 7.20. Schematic of a diaphragm valve. (From Houlsby 1990)

b. *Ball Valves.* This type of valve consists of a sphere with a hole through it, with the sphere able to rotate in its seat (Figure 7.21). The hole in the sphere should be the same diameter as the grout line so that there is no obstruction to flow when the valve is fully open. The ball is controlled via a handle and can be rotated 90 degrees from fully open to fully closed. Ball valves can become clogged when operated in a partially open position because of the restricted flow. The ball and seat are also subject to higher wear when operated partially open. These valves should only be used in applications where they are to be either fully open or fully closed. Ball valves should never be used to control the grout injection pressure.

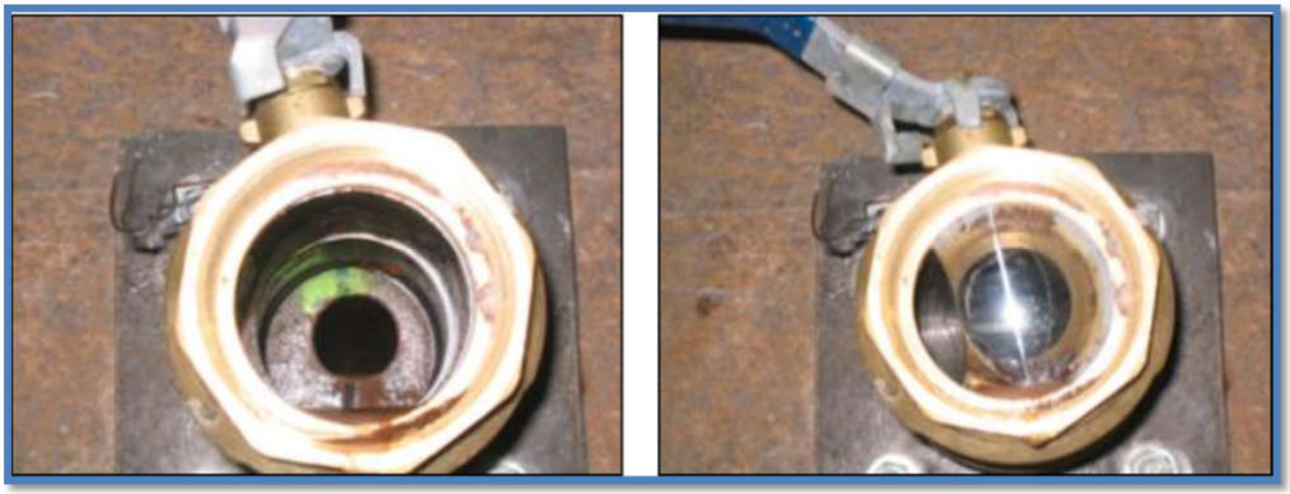


Figure 7.21. Ball valve fully open (left) and partially open (right).

Grout Headers.

a. Grout headers include an arrangement of valves and pressure gauges used to control the quantity of grout that flows to the hole, control the pressure of the grout applied to the hole, bleed fluid off the hole during grouting, and seal the hole after grouting is completed. Figures 7.22 typical arrangements of the fittings on common grout headers. The header consists of a pressure gauge or pressure transducer to monitor the injection pressure, a flow meter if electronic monitoring is being performed, a diaphragm valve on the return line to control the injection pressure, a diaphragm valve and a ball or plug cock valve on the injection line, and sometimes a blow-off or bleed line with a ball or plug cock valve.

b. **Circulation Lines and Equipment Arrangement.**

c. Circulation Loop System. Figure 7.23 shows a typical arrangement of the circulation lines and equipment for a circulation loop system. The grout is pumped from the agitator to the header. Grout not needed to satisfy the demands of the hole is returned to the agitator tank. Additional headers can be inserted in the loop if multiple hole grouting is permitted or for treating connections between holes. The use of a return line allows excess pressure in the circulation line to bypass the hole, eliminates wasted grout when a hole is completed, and maintains the velocity of the grout at a high rate in the circulation line during times of low flow at the grout hole.

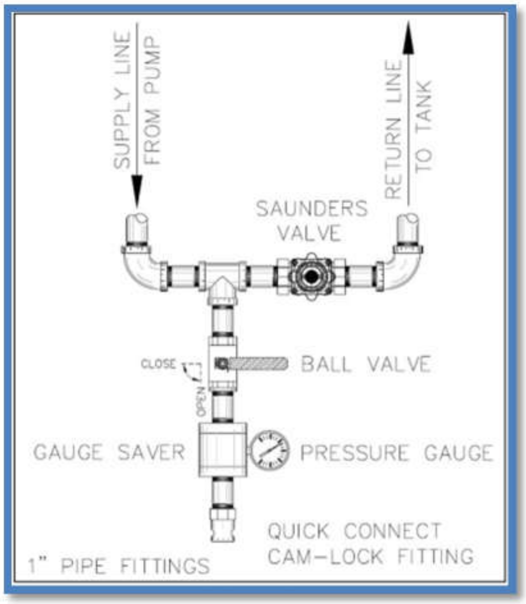


Figure 7.22. Typical Grout Header.

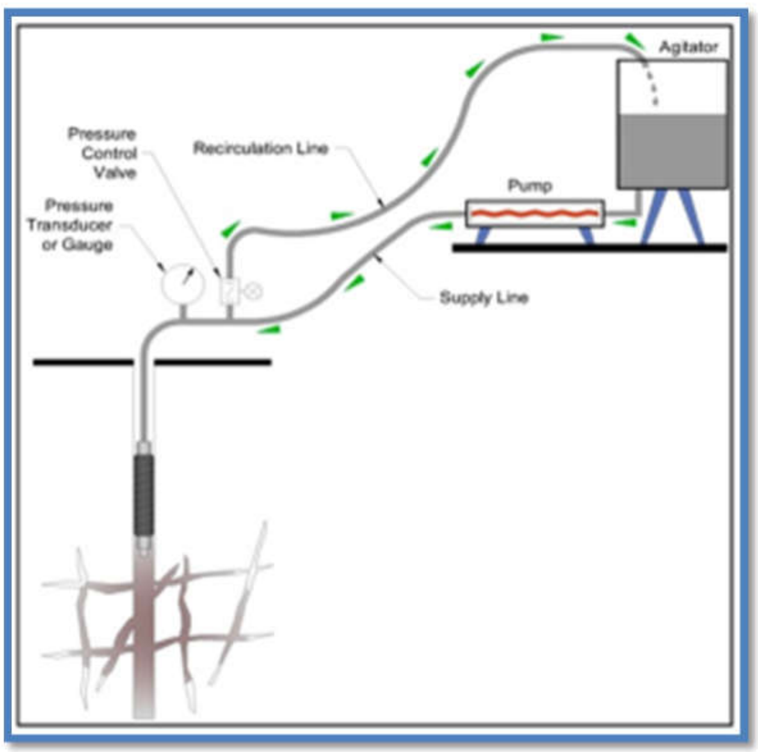


Figure 7.23. Grout circulation system with return.

Chapter 8. Monitoring of Grouting Operation

General. The raw data collected during water pressure testing and grout injections are pressure and flow measurements as a function of time. Processing of these data on a real-time basis using other known parameters, such as hole depth, static elevation heads, depth to groundwater, system head loss, and specific gravity of injected fluids, is necessary to:

(1) Determine and control the effective pressures being applied to the stage

(2) Evaluate the nature of the stage's response to mix changes and applied pressures

(3) Verify that the required refusal criteria are reached

(4) Determine the cumulative volume of injection.

a. Data Compilation. The compilation of both the raw data and the calculated data provides the record of water pressure testing and/or grouting for the stage and is normally the basis for at least a portion of the measurement for payment activities.

b. Data Processing. The necessary real-time processing of the data required for controlling the injection can be performed either manually or semi-manually by individual inspectors at each hole, or it can be performed automatically by computer systems that are centrally located and capable of managing multiple headers simultaneously.

c. Records. After completion of the stage, the stage records are analyzed to evaluate the effectiveness of the grouting program.

Water and Grout Injection Measurement Equipment

a. General Recommendations.

(1) Table 8-1 lists a summary of the types and characteristics of available measurement equipment, including both systems that have historically been used and more advanced equipment now readily available and commonly used. For dam safety projects, this ability can be extremely valuable and necessary for managing construction risks.

Table 8-1. Summary of measurement equipment and accuracies.

Parameter*	Monitoring Equipment or Technique	Accuracy	Comments
Water and/or grout take (volumetric flow)	Agitator dipstick reading	< ±0.25 CF or 7 L per volume measured	Accuracy depends on diameter of the agitator and plant operator's attention to detail. Requires averaging total flow over test time to acquire rate.
	Agitator riser tube	Slightly better than dipstick	Allows easier confirmation of readings by inspector. Lessens operator attention factor. Requires averaging total flow over test time to acquire rate.
	Nutating disk water meter	±1.5% of rate when new	Significant loss of accuracy at low- flow rates. High wear rate of measurement components can require frequent meter rebuild/replacement.
	Magnetic flow meter	±5% for flow rates greater than 0.25 L/min. ±25% for lesser flow rates (depends on line size)	Zero reading is zero flow. Requires power supply at header or remote system with signal and power cables. Easy to check calibration on site.
Water/ grout gauge pressure	Dial-type mechanical gauges	Accurate to 1% of range. Visual observation required. Pressure spikes and fluctuations often missed or ignored in manual calculations	Various gauge ranges required. Gauge calibration should be checked weekly against master gauges. Weekly calibration requirement often missing or not enforced. Gauges routinely go out of calibration and require correction or replacement.
	Electronic pressure transducers	<0.5% of full scale	Calibration on site possible, but cumbersome. Requires power supply at header or remote power with cables.

*After Wilson and Dreese 1998.

(2) In general, the advantages of using the latest measurement system technologies (pressure transducers and electronic flow meters) are so great that their use is recommended for all projects, regardless of size and regardless of selection of the real-time processing and post- processing methodologies and systems, which might vary by project size and application.

Automated Monitoring Systems

All contractors capable of a sophisticated grouting program have proprietary automated monitoring systems that differ widely in their capabilities; however, it is possible to design one with off-the- shelf hardware and software with relative ease. Two key factors that make this possible are advances in computer monitoring systems, and GISs that facilitate the final display of the grouting data that has been organized into a usable database. Common elements of all systems include pressure transducers and flow meters, power and signal cables or wireless data transmission, analog-to-digital converters, computer hardware, and monitoring software (Figure 8-1).

Figure 8.1. Centralized automated system for real-time processing and display for actively monitoring and controlling injections. (Courtesy of Gannett Fleming)

Injection Pressures

a. General. The radius of spread of grout is controlled by the fracture size, the cohesion (actually Bingham yield point) of the grout, and the injection pressure. The rate of flow of grout into the fracture is controlled by the size of the fracture, the viscosity of the grout, and the injection pressure. Both the radius of spread and the rate of flow are directly proportional to the injection pressure, so higher grouting pressures are beneficial in increasing the extent of the zone of treatment and in decreasing the time to accomplish that treatment. The only issue, therefore, is establishing safe grouting pressures to be used in treatment. Other activities, such as pressure washing and water pressure testing, have the potential to damage the embankment by using pressures that are too high and should always be performed at pressures less than the established safe grouting pressure.

b. Uplift vs. Dilation. Safe injection pressures for rock are pressures that will not lift or separate fractures to the extent that they are irreversibly locked into a more open position. This "locking open" of fractures is termed "uplift," although it could conceivably occur on fracture planes other than the nearly horizontal planes that are normally visualized. Dilation is similar, but is reversible. Dilation might or might not occur as a first indication of uplift.

(1) Uplift. Uplift is to be carefully avoided, both during water pressure testing and during grouting. By definition, it permanently increases the permeability of the rock mass by resulting in an irreversible movement of rock. If it occurs during water pressure testing, as a minimum it will require

repair by more extensive grouting. Depending on the horizontal and vertical extent of the rock movements, which will generally not be known except by installing numerous check holes, it may damage already completed portions of the work. Similarly, uplift during grouting may damage adjacent areas of work already completed and will require extensive effort to determine the extent of damage and the amount of regrouting necessary to repair the damage. It is easier to cause uplift during injection of water than during grouting because water injection can generate larger forces at an equivalent pressure. One of the greatest concerns in grouting is causing uplift that is undetected and therefore not repaired, resulting in unsatisfactory performance.

(2) Dilation. Dilation is the temporary and reversible opening of fractures by fluid forces. Dilation can be the first stage of uplift developing, but it can also be a separate phenomenon representing elastic deformation of the rock mass. The fractured and ungrouted rock mass has a bulk modulus of elasticity affected, in part, by the presence and nature of the fracture system. It is possible to cause detectable and recoverable deformation of that rock mass by applying pressure. In European practice, many consider dilation to be highly desirable because it can improve penetration of grout into very fine fractures, resulting in better fracture filling when the pressures are reduced and the rock closes on the grout that has been placed. The most serious issues are the practicality of monitoring dilation effectively and ability to absolutely differentiate it from uplift. United States practice has, in general, not embraced the concept of intentional dilation of fractures. Even if the deformations are recoverable, they may still damage previously grouted sections and potentially any overlying existing structures. Dilation may have valid application in specific situations, such as for formations containing numerous, but very fine, fractures, which preclude entry of normal grout mixes, requiring the use of low viscosity, but more expensive solution grouts or extraordinary long amounts of time at very slow injection rates. However, dilation should only be undertaken on a production basis after being carefully evaluated and proven in a full-scale, highly controlled test section.

(3) Monitoring Uplift and Dilation. Until recently, monitoring the occurrence of dilation and uplift has been neither practical nor effective. Surface monitoring for uplift is cumbersome, time consuming, and, in general, insufficiently accurate and/or timely to be of much practical value. Detection of dilation has not normally even been considered. Currently, with the advent of extremely accurate pressure transducers and flow meters, balanced stable grouts, and computer monitoring, both dilation and uplift are easily detected on each stage on a real-time basis within seconds of initiation. Figure 8.2a shows an example of a stage record that exhibits the opening of a fracture under pressure followed by closing of the fracture after the pressure is reduced. The dilation,

which in this case was interpreted as the beginning of uplift (as opposed to elastic dilation within the rock mass), occurred 25 minutes into the grouting under a relatively minor pressure increase. As the pressure was gradually reduced, the dilation gradually closed, followed by abrupt closure at about 55 minutes.

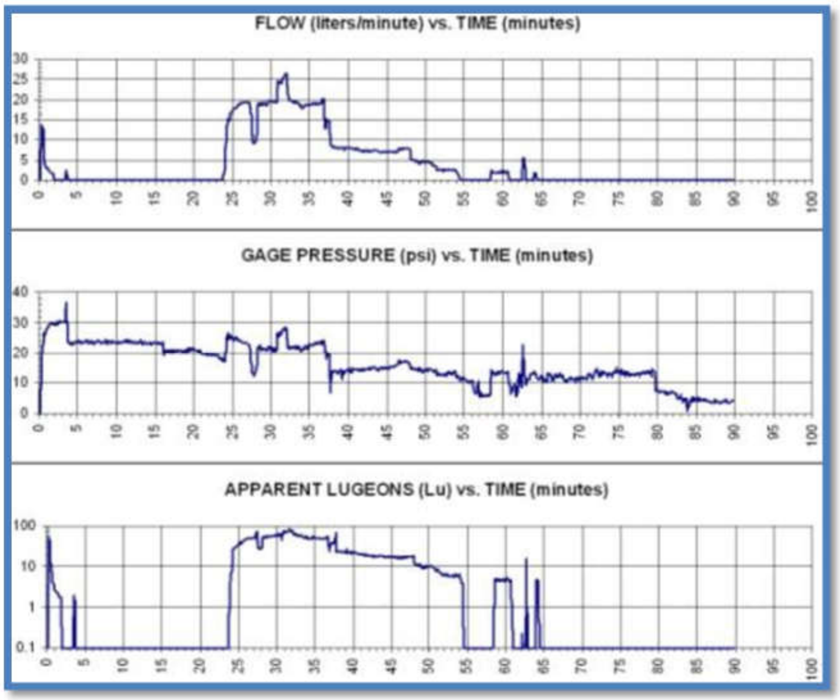


Figure 8-2a. Grouting record with dilation that closed on reduction of pressure.
(Courtesy of Gannett Fleming.)

Figure 8-2 b and c shows upheaval gauges provided in bore holes to monitor uplift of formation during the grouting operation.

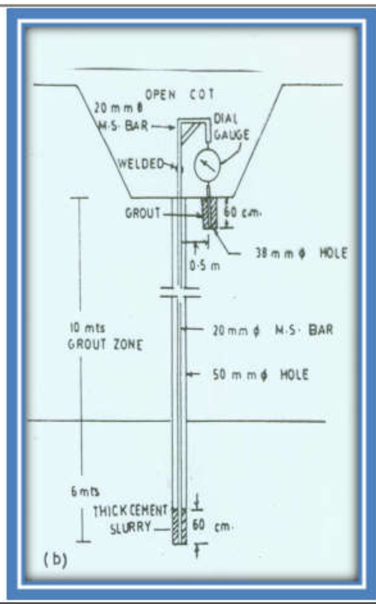


Figure 8-2b Typical Upheaval gauge for earth dam

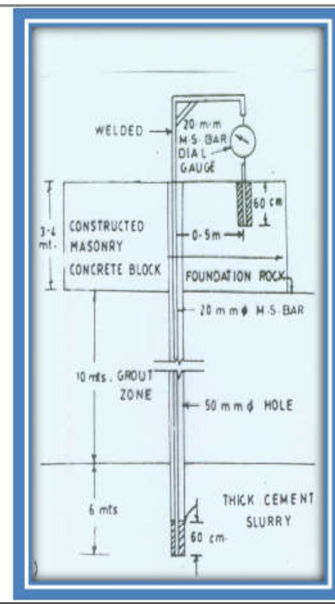


Figure 8-2c Typical Upheaval gauge for concrete dam.

c. Effective Pressure. Regardless of how safe injection pressures are determined for a project, it is important to accurately know the actual pressure that is being applied to a water pressure testing or grouting stage. For that reason, the effective pressure that is being applied should be calculated for each stage. In the past, it has been common to simplify the calculations and not account for every factor that enters into the calculation. The widespread use of computers in grouting projects now makes that simplification unnecessary, and it is recommended that calculations include correction for all factors to bring the accuracy into the same range as the accuracy of other operations. The effective pressure is usually calculated at the midpoint of the stage, but for long stages it may be necessary to calculate and check the effective pressure being applied at both the top and bottom of the stage. The effective pressure applied at any point in the hole at any given time is calculated as:

Effective Pressure = Transducer or Gauge Pressure + Static Head of Grout or Water

-Static Head of Groundwater – Dynamic Losses

and is illustrated in Figure 8-3.

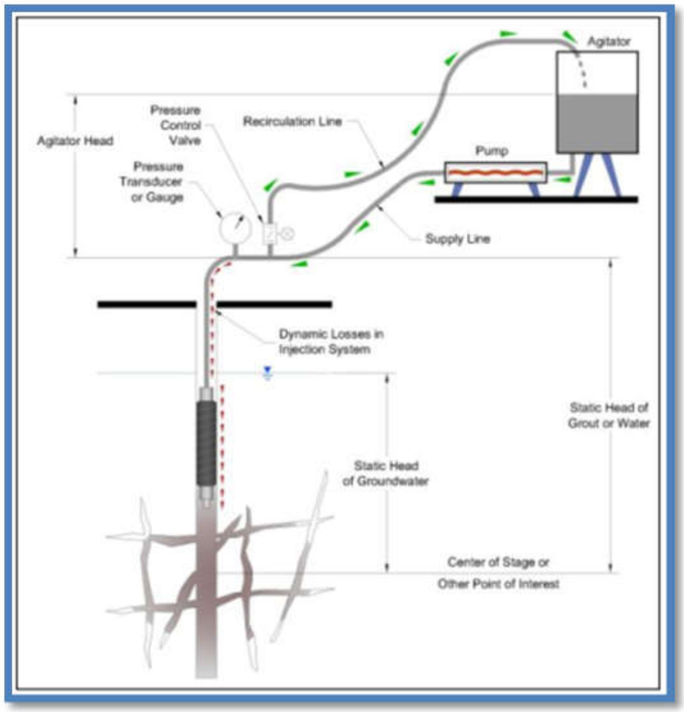


Figure 8-3. Schematic illustrating effective pressure calculation

Rules of Thumb. "Rules of thumb" have been established for safe grouting pressures in soil and rock. Weaver (2000) presents a good summary of the rules of thumb. On recent USACE projects, maximum safe grouting pressures have been established as 0.5 psi/ft for the overburden soil thickness and 1 psi/ft for depth into rock. These rules of thumb were developed based on experience. The weight of the material over the zone being grouted was the primary consideration when developing the rules of thumb (USACE 1984). If these guidelines are followed, then the pressure applied to the grouting stage will be less than the weight of the overlying materials, thus preventing lifting or "heave." An additional margin of safety is afforded by the strength of the rock. However, factors such as depth to the water table, sloping ground conditions, discontinuities that cause lower in-situ ground stress, and defect connections to the soil were not considered.

Blindly using rules of thumb can be dangerous, especially when grouting through existing embankment dams where defects in the rock are connected to the foundation soils and low confining stress conditions are present. A review of numerous past grouting projects performed by USACE and the Bureau of Reclamation (Patoka, Mississinewa, East Branch, Wolf Creek, Hop Brook, John Martin, Norfolk, Allatoona, Hartwell, Oologah, Alvin Bush, Abiquiu, Efaula, Dworshak, Libby, Clarence Cannon, Longview, Morrow Point, Flaming Gorge, Hoover, Heron, Kortes, Hungry Horse) indicates that these rules of thumb have not been applied consistently and were often misunderstood. The grouting pressures ranged from 0.5 to 2.0 psi/ft of depth. On some projects, the guidelines were interpreted to be the required pressure rather than the maximum. On other projects, only the gauge pressure at the top of the hole was used, with no regard for the additional pressure from the static head of the grout column. Sherard (1973) documents numerous cases where dams were damaged from drilling or grouting operations. USACE grouting projects with incidents of damage or hydrofracture include Red Rock Dam, Kentucky Lock, Patoka Saddle Dam, Center Hill Dam, Wolf Creek Dam, Addicks Dam, and Barker Dam.

(1) Safe Pressures for Soils. Grouting pressures should be maintained lower (with a margin of safety) than the pressure that could cause unwanted damage or hydrofracture. There are many theories and models proposed in the literature to estimate borehole fracture pressure in soils and rocks. For soils, a review of measured data in the published literature from field and laboratory studies indicates that the borehole fracture pressure (P_f) can be approximated by the sum of the minor principal total stress (σ_3) plus the undrained strength.

(2) Safe Pressures for Rock. In situations where there is no overburden or existing structure over the rock being grouted, or where the rock has been reliably isolated from the soil, the 1.0-psi-per-foot-of-depth rule of thumb is likely a safe guideline to use for most intact rocks. Massive formations provide few avenues for rock block movement due to minimal fracture frequency. Highly fractured and weak rock obviously warrants more conservative pressures. For conditions where the risk of damage is minimal and the rock is massive, higher effective injection pressures can be used with confidence. Trial values for bedrock can be established at the higher end of published guidance (i.e., in the range of 1.5–3.0 psi/ft, depending on the characteristics of the rock), and the suitability of those values can be evaluated on every stage. It is recommended that caution be used in grouting the uppermost stage and those pressures be limited to approximately 1.0 psi/ft in that zone.

Limiting values of pressure for each zone may be established initially on the basis of the categorization of rock as suggested in Figure 8-4 should be taken as initial values to be confirmed by trial and observations.

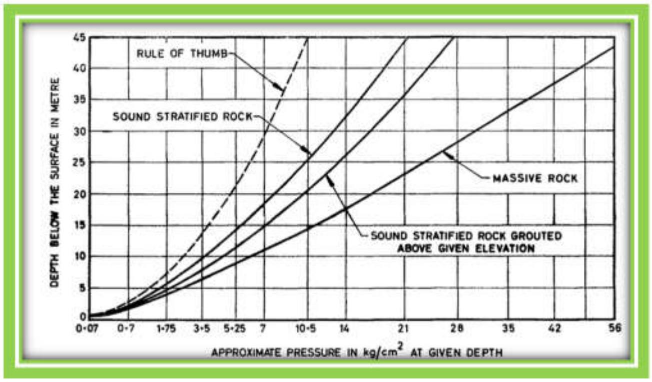


Figure 8-4. Guidelines for grouting pressure (Ref. IS 6066-1994)

(3) Advance Evaluation Programs. If a full-scale test section is performed as part of the design process, the program should include testing to determine the actual limiting pressures for dilation, uplift, and/or hydrofracturing, which then can be used to establish safe injection pressures for production work. The advantage of this approach is that, if high pressures are found to be workable, it presents the opportunity to either increase the hole spacing or possibly terminate some series of holes at reduced depths.

Grouting Operations

a. Starting Mixes. The starting mix depends on the geology and the objective of the project. Grouting of each stage should, in general, be started with the thinnest mixes that are being used on the project. They are the appropriate mixes for the finer fractures, and it should always be assumed that fine fractures exist within the stage being grouted. Assuming pressure can be built up in the hole, using the thinnest mix allows grout to be injected into these fine fractures for a period of time before considering thickening of the grout in response to the presence of coarser fractures.

(1) Unstable Grout Mixes. Starting mixes for unstable grout mixes, composed of neat cement grouts or grouts that have additives, but are not stable throughout all mix consistencies, should have a volumetric water/cement ratio of 2:1 or 3:1, with the choice being based on early experience at the site. If a 2:1 mix is readily accepted, then it is suitable as a starting mix. If trial injections of a 2:1 mix result in refusal in 30 minutes or less, then typically a 3:1 mix should be used as a starting mix. Historically, starting grout mixes as thin as 5:1 have been used successfully in certain geologic conditions.

(2) Balanced Stable Grouts. There is no standard convention for designating balanced stable grouts at this time. A suite of mixes will be developed that cover a range of marsh funnel flow times. Normally, the thinnest mix has a 1-L marsh flow time of 35–40 seconds. This is the mix that should be used as the starting mix in all stages. Water, by comparison, has a marsh flow time of 28 seconds.

b. Management of Grout Injection.

(1) Initiation of Grout Injection. After the grout has been mixed and is in the agitator, it must be circulated through the entire system to ensure complete filling of the lines and to allow checking of the system for leaks or other problems. After circulation is established, the control valve on the header is gradually opened and adjusted until the pressure value is stable. Operators should check for surface leaks and connections to other holes and detect any other problems.

(2) Observation of Injection Behaviour and Typical Conditions and Responses. The goal of grouting, under ideal conditions, is to inject the grout smoothly and continuously. The reality of grouting is that the time it takes to reach refusal is highly variable. The grouting is actively managed by the geologist or engineer in control of the injection operation based on a review and interpretation of data being obtained and plotted while injection is in progress. Grouting of the stage is actively managed by changing mixes and/or other factors to produce the desired result. The information gathered during drilling and pressure testing of the stage should be used in the decision making process while managing the injection. The following paragraphs summarize typical behaviours commonly observed while grouting and typical responses to those behaviours.

(a) Gradual Decline in Rate of Injection. When the rate of grout injection is declining, however slowly, it is normal to continue injection with the same mix since the stage is moving in the direction of refusal. Thickening of the mix under this condition may result in rapid and premature termination of grouting without filling of the fractures. A similar interpretation —that grouting is proceeding satisfactorily under the current mix— applies when grout is being injected at the maximum rate and the pressure is gradually increasing toward the maximum target pressure.

(b) Constant Rate of Injection. When the rate of grout injection continues for an extended period of time without decreasing, it generally indicates the grout mix must be thickened. The point at which the decision to thicken is made will vary, depending on the rate of grout take. In a stage with a slow rate of injection, it may be appropriate to inject for an hour or more before changing mixes. In a stage with a relatively high rate of injection, the decision to thicken the mix may be made after three or four batches of the initial mix are injected.

(c) Sudden Decrease in Take. A sudden decrease in take typically indicates either that the grout was too thick initially (if the sudden decrease occurred with the initial mix) or that thickening of the mix was not appropriate for the fractures. There are two possible remedies for this event: an attempt can be made to inject water to revive the stage, which requires wasting of grout in the agitators and lines and switching to water injection; or, as an alternative, noting the location and adding extra holes on either side to remedy the zone where premature termination occurred. Geological factors causing a sudden decrease could include displacement of water from a void through fine fractures; the sudden decrease in take would indicate that the void is completely filled with grout, and subsequent injection at the reduced rate represents grout permeation of the fine fractures.

(d) Sudden Increase in Take. A sudden increase in take could indicate one of the following types of conditions: (1) dilation or uplift of the rock, (2) breakout of surface leaks or connections to other holes, (3) or hydrofracturing through infilled materials. Assessment of the most likely event and determination of the appropriate response are made based on knowledge of the conditions of the zone being grouted. For example, the proper response for suspected uplift may be to reduce pressures without changing mixes. An appropriate response to leaks or connections may involve special measures at those discharge points with or without subsequent thickening of the mix. Hydrofracturing through infilled materials might require no change in operations. However, if the grouting program is being performed in an earthen embankment dam or levee, the suitable response could be quite different. Figures 8.4 through 8-12 show examples of grouting records that illustrate various time behaviours of the injection and the points of mix changes.

c. Mix Changes. Grouting references frequently contain extensive tables for thickening and thinning grout mixes. These tables are normally applicable for unstable grouts composed of only cement and water. In using these tables, it is necessary to know whether they are based on weight or volume relationships. The tables do not apply to balanced stable grouts. In general, it is not very common to alter a batch of grout that has already been mixed. Normally, thickening is performed when a fresh batch of grout is mixed rather than by adding materials to an existing, partially used batch. Thinning, if used at all, is typically performed only when there is a substantial amount of grout remaining in the agitator after completion of a stage and it is time to begin another stage with a thinner starting mix. Depending on the age and the amount of grout left from the previous stage, it is not uncommon to simply waste that grout and mix a fresh batch of the starting mix. Regardless of which procedure is followed, the injection lines and pump must be fully flushed of the thicker mix before filling them with the thinner starting mix.

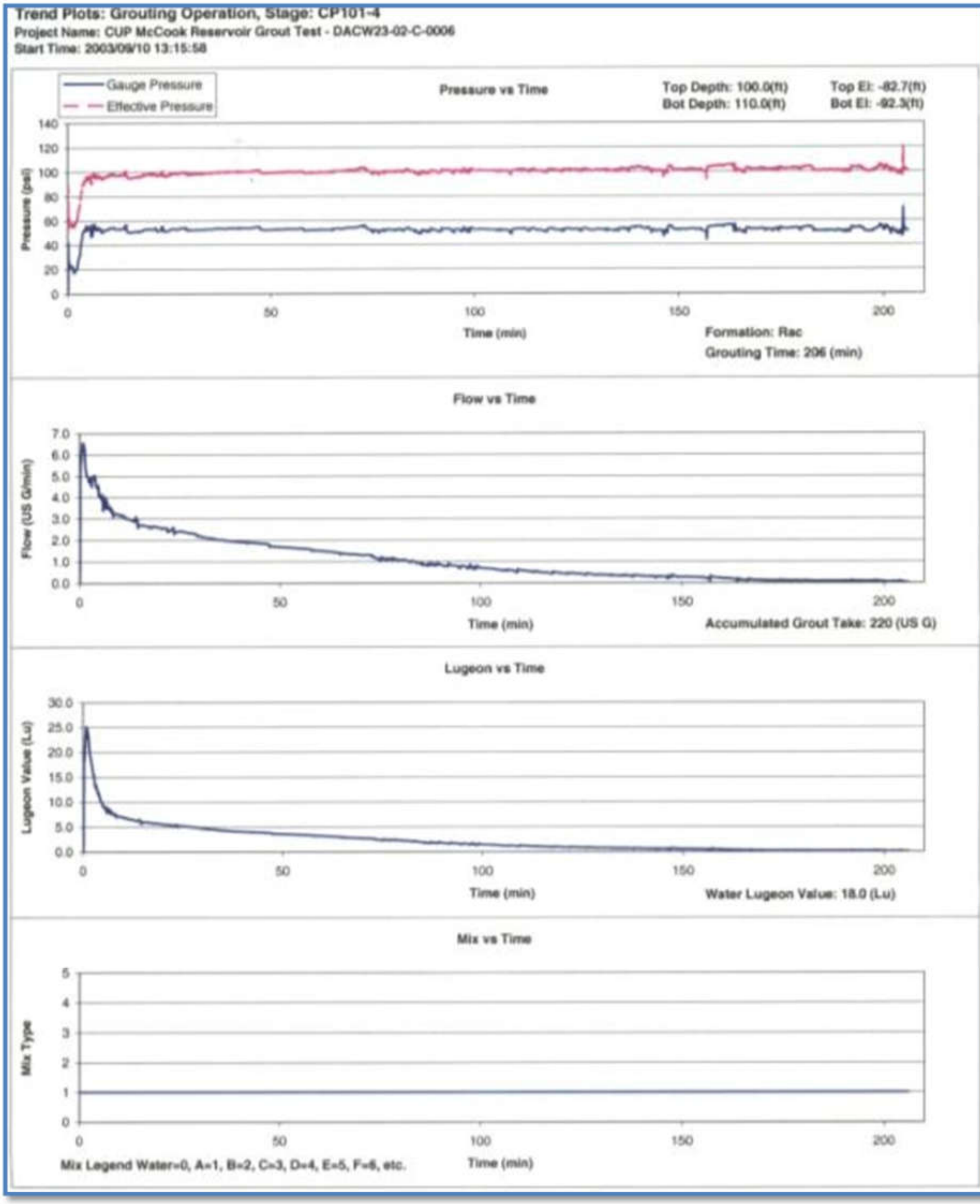


Figure 8.4. Grouting to refusal under a single mix, with a gradual, steady decline of grout take and Apparent Lugeon value. (Courtesy of Gannett Fleming)

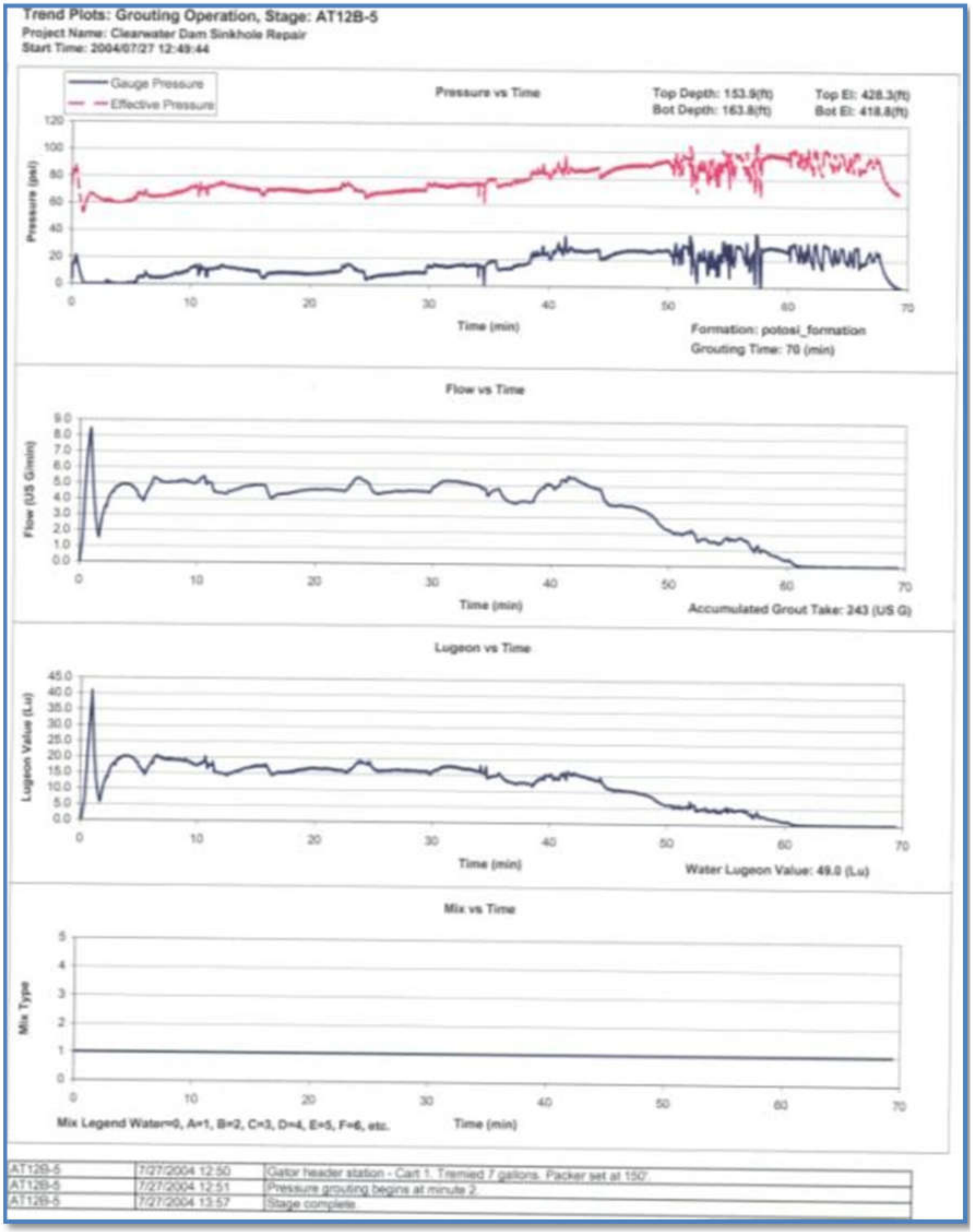


Figure 8.5. Grouting to refusal under a single mix. The mix was not thickened because injection at the maximum rate showed that the pressure was building to desired pressure. (Courtesy of Gannett Fleming)

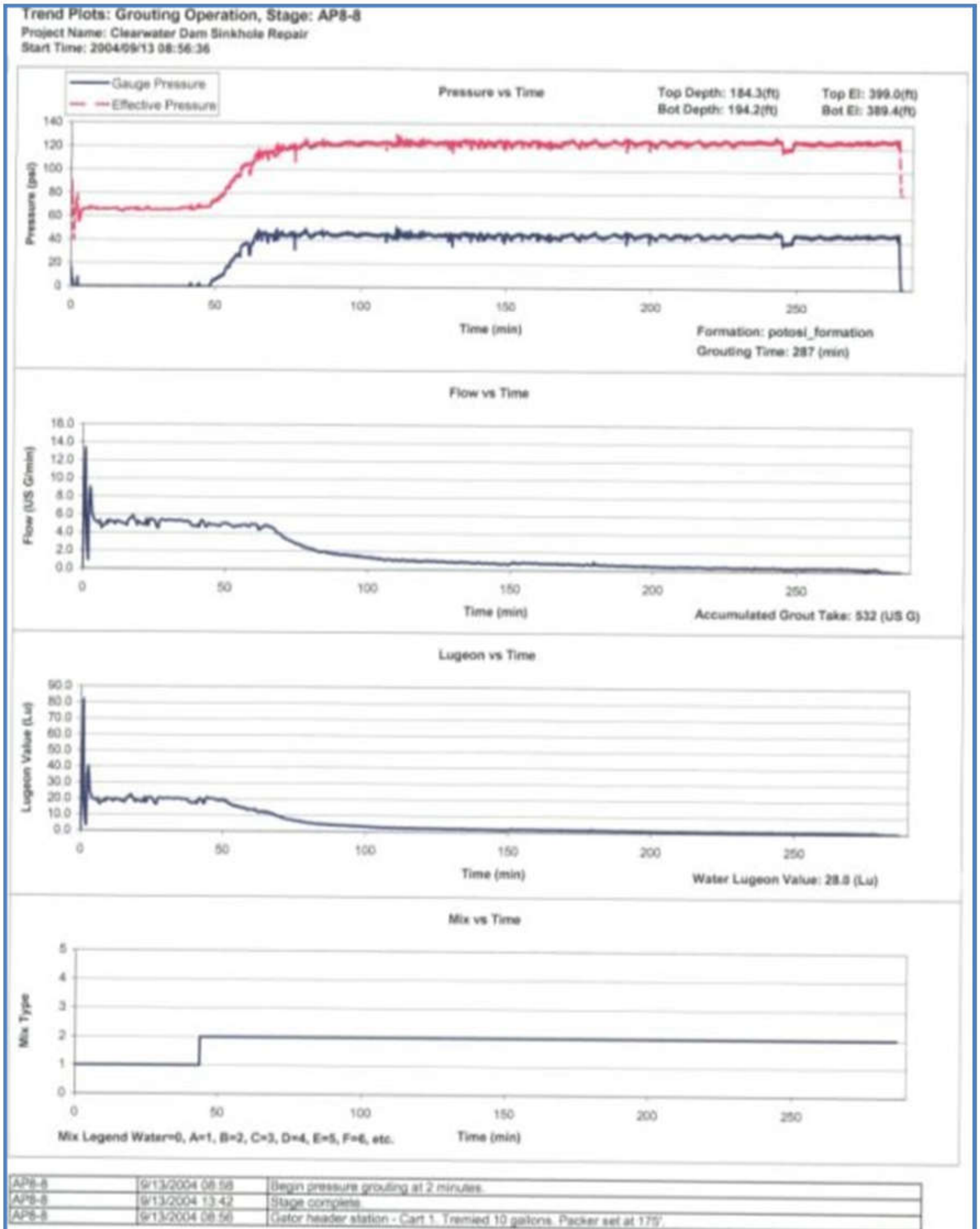


Figure 8.6. Gradual refusal after one mix change. The mix was changed after there was no pressure buildup at the maximum rate of injection. (Courtesy of Gannett Fleming)

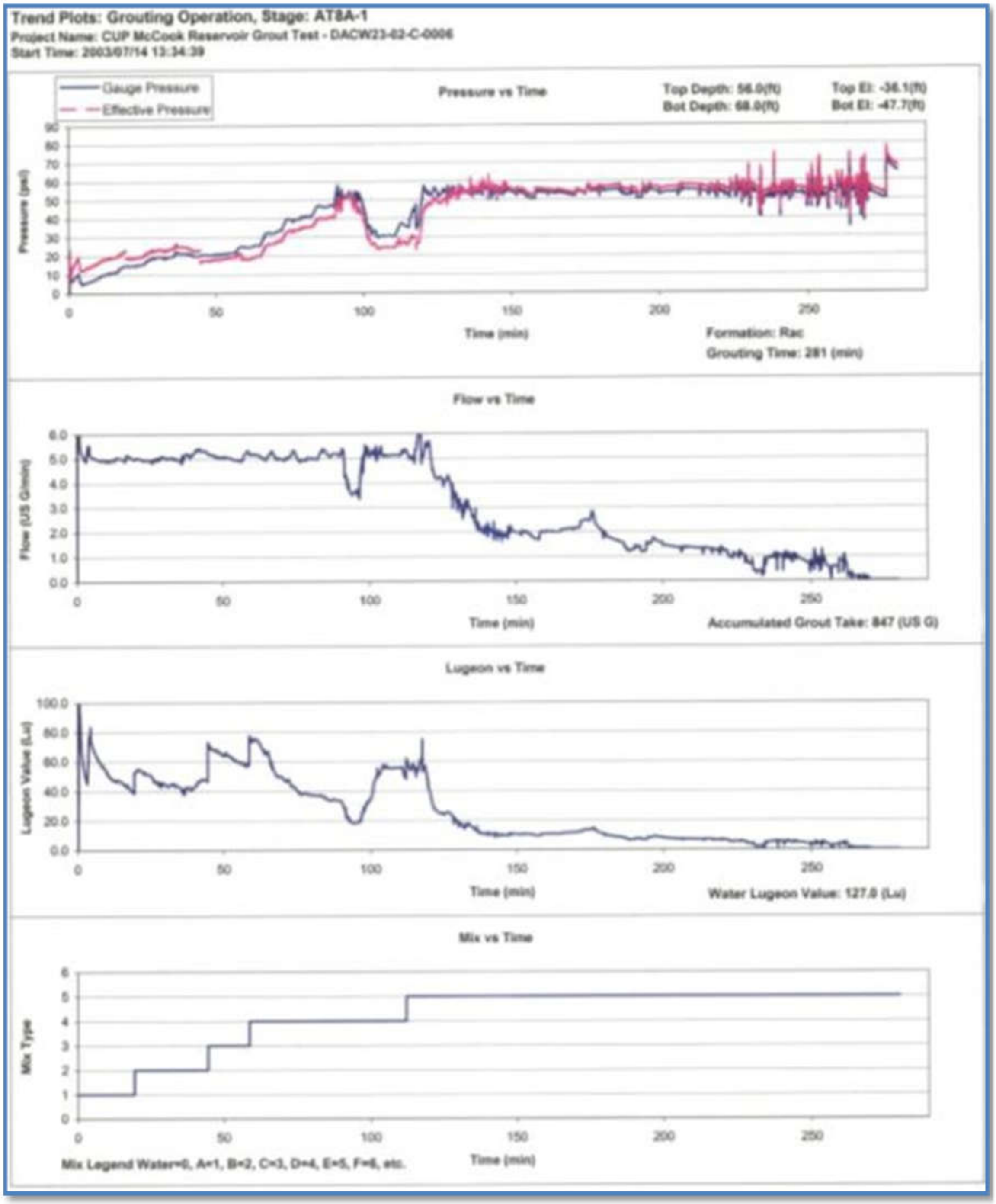
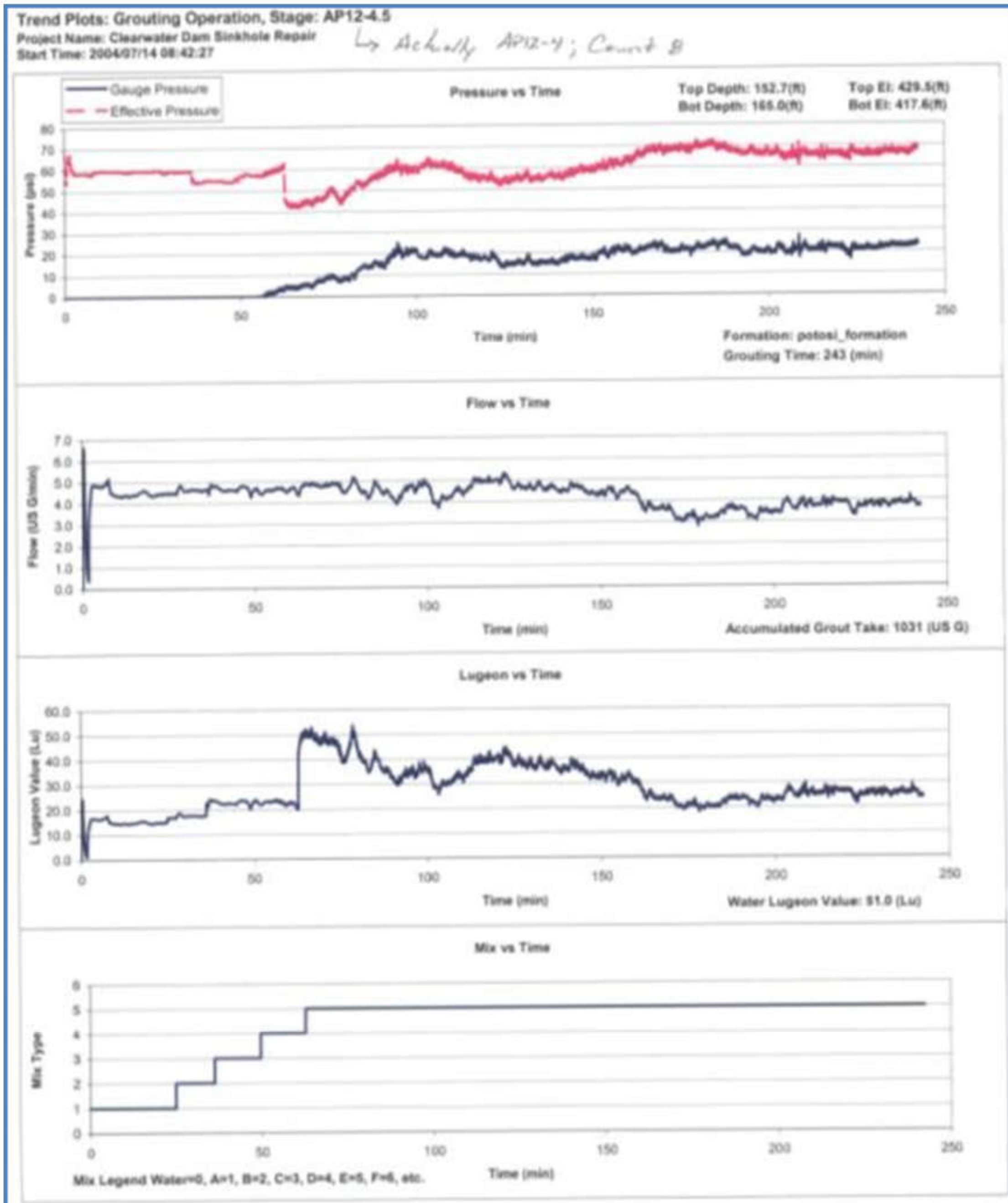


Figure 8.7. Gradual refusal after four mix changes. The mixes were changed in response to pressure plateaus while injecting at maximum rate. The sudden decrease in pressure near minute 100 could be interpreted as hydrofracturing through clay in fracture. (Courtesy of Gannett Fleming)



AP12-4.5	7/15/2004	Tremied 4 gallons from time 0 to to 1 minute. Inflated packer and started to Re-Grout at 2 minutes.
AP12-4.5	7/15/2004	2 tablespoons of welan gum per 20 gallons of grout was added to the E-mix to create a mix with a
		higher viscosity.
AP12-4.5	7/15/2004	Stage NOT Complete.
AP12-4.5	7/15/2004	Gator-Yellow Header Station - Cart 1.
AP12-4.5	7/15/2004	After completion of grouting on 7/14, lost water during washing operations. Hole measured open to 154'
		using packer.
AP12-4.5	7/15/2004	Stopped after approximately 1,000 gallons for the day.

Figure 8.8. Termination of grouting without reaching refusal at a predetermined maximum stage injection quantity of 1000 gallons. There were four mix changes without any indication of approaching refusal. The rapid thickening was based on early stage response. (Courtesy of Gannett Fleming)

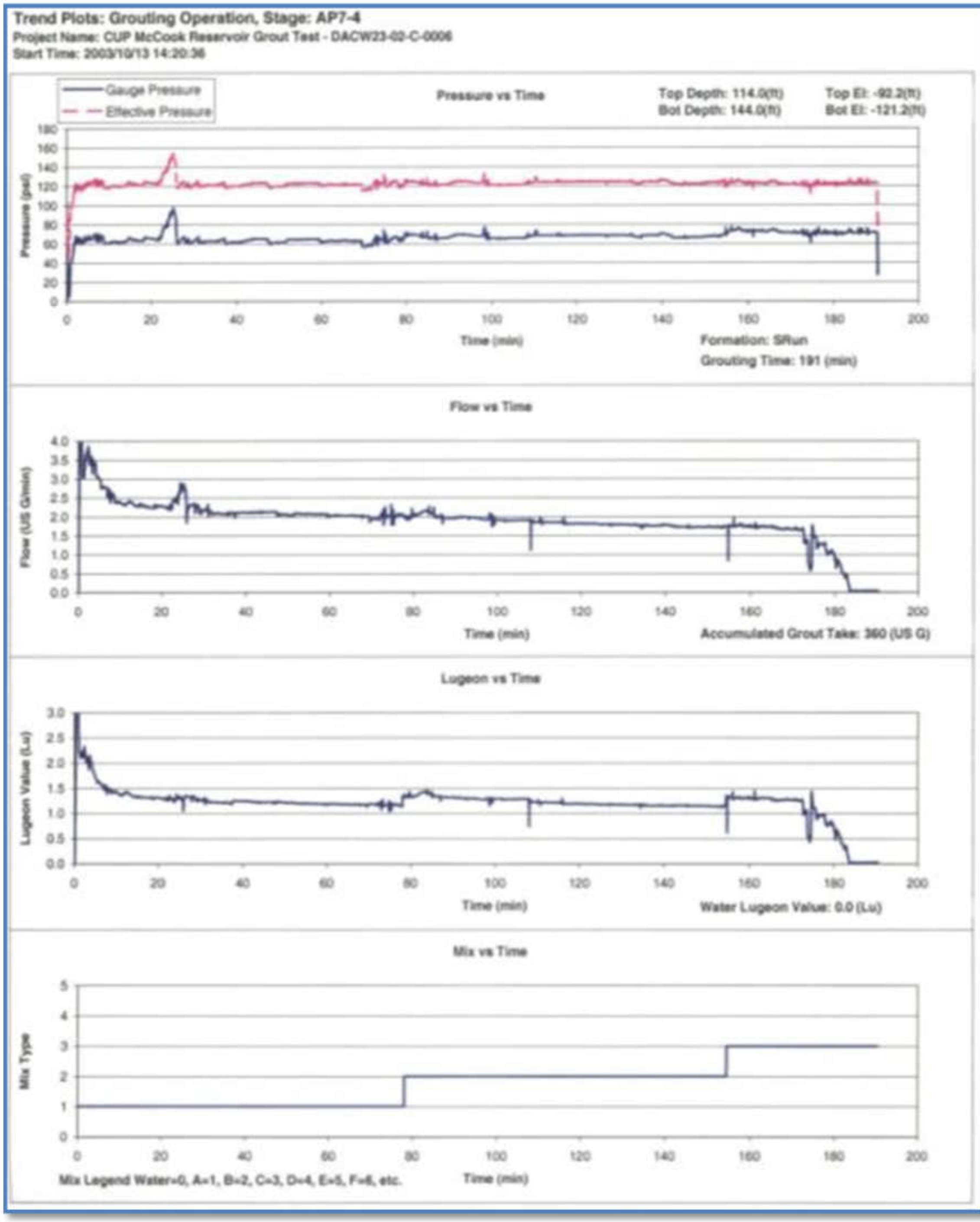


Figure 8.9. Abrupt refusal of a low Lugeon stage after a second mix change. The decision to thicken was based on time management of the stage and the extremely slow rate of approaching refusal under Mix 2. (Courtesy of Gannett Fleming)

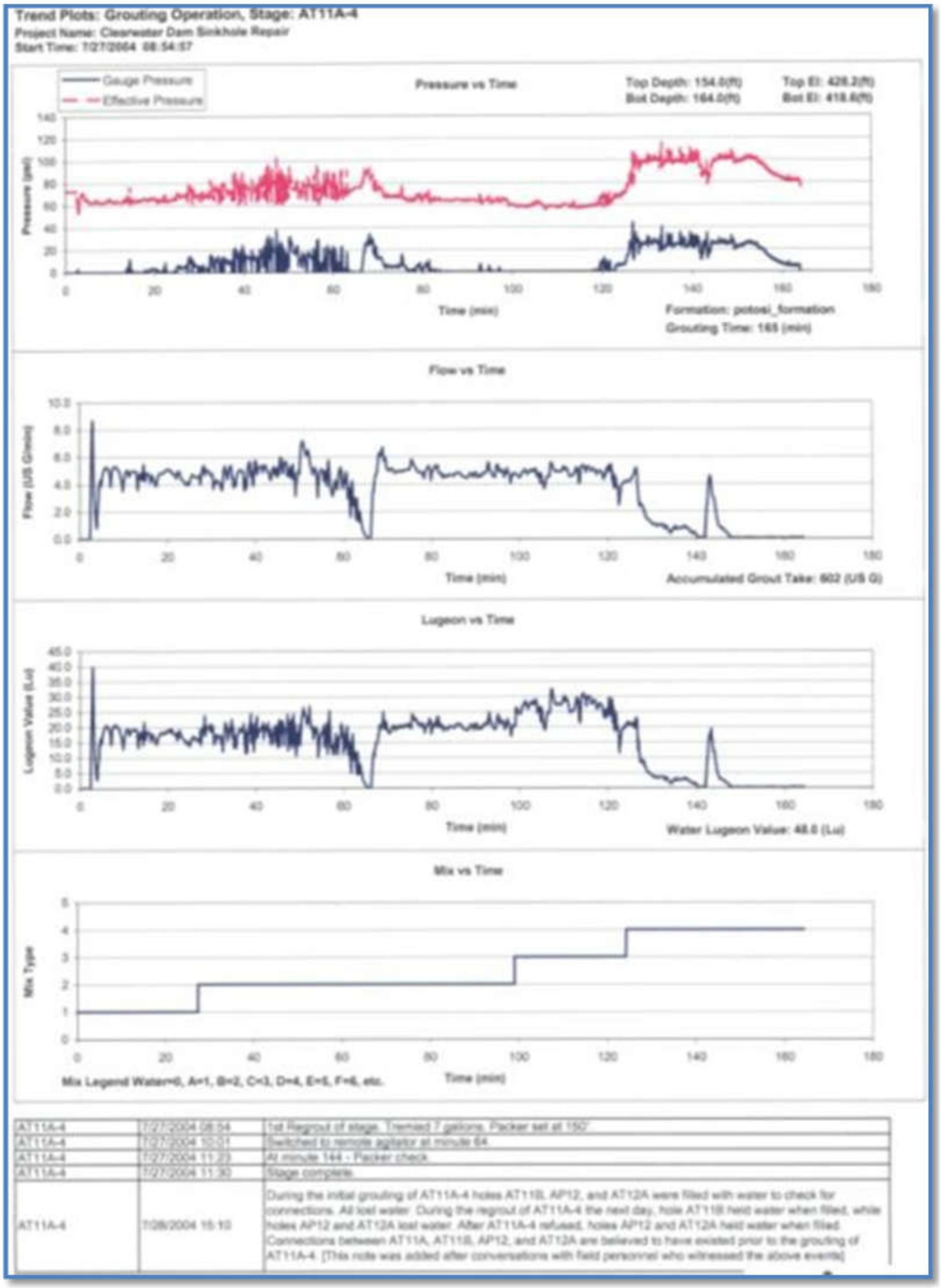


Figure 8.10. Abrupt refusal of a moderate Lugeon stage after a third mix change. The decision to thicken to Mix 4 was based on no indication of progress toward refusal under Mix 3. (Courtesy of Gannett Fleming)

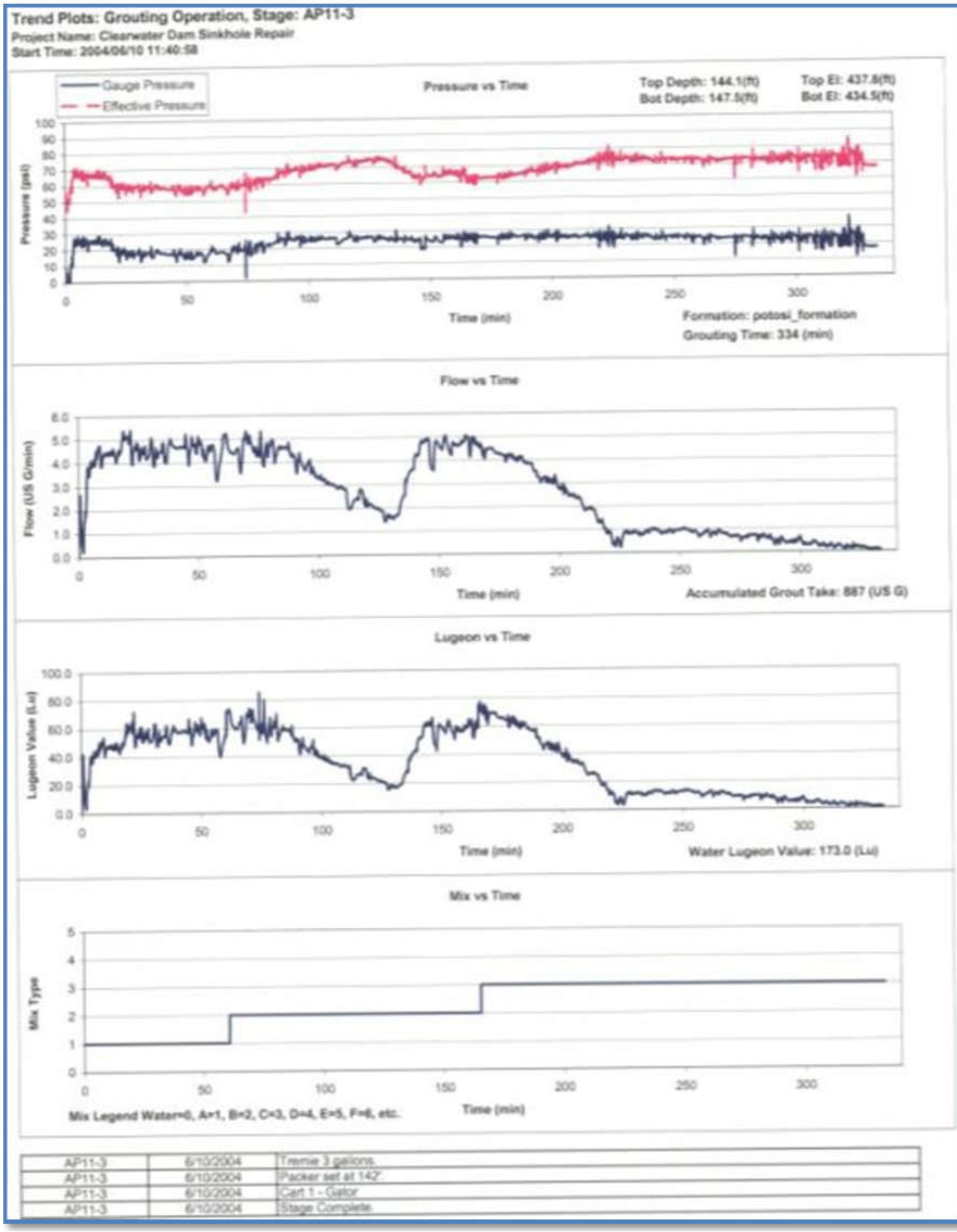


Figure 8.11. Sudden increase in grout take as the desired pressure is first approached at 130 minutes in karst geology, interpreted as hydrofracturing through infilled materials. Refusal was reached after extended grouting with Mix 3. (Courtesy of Gannett Fleming)

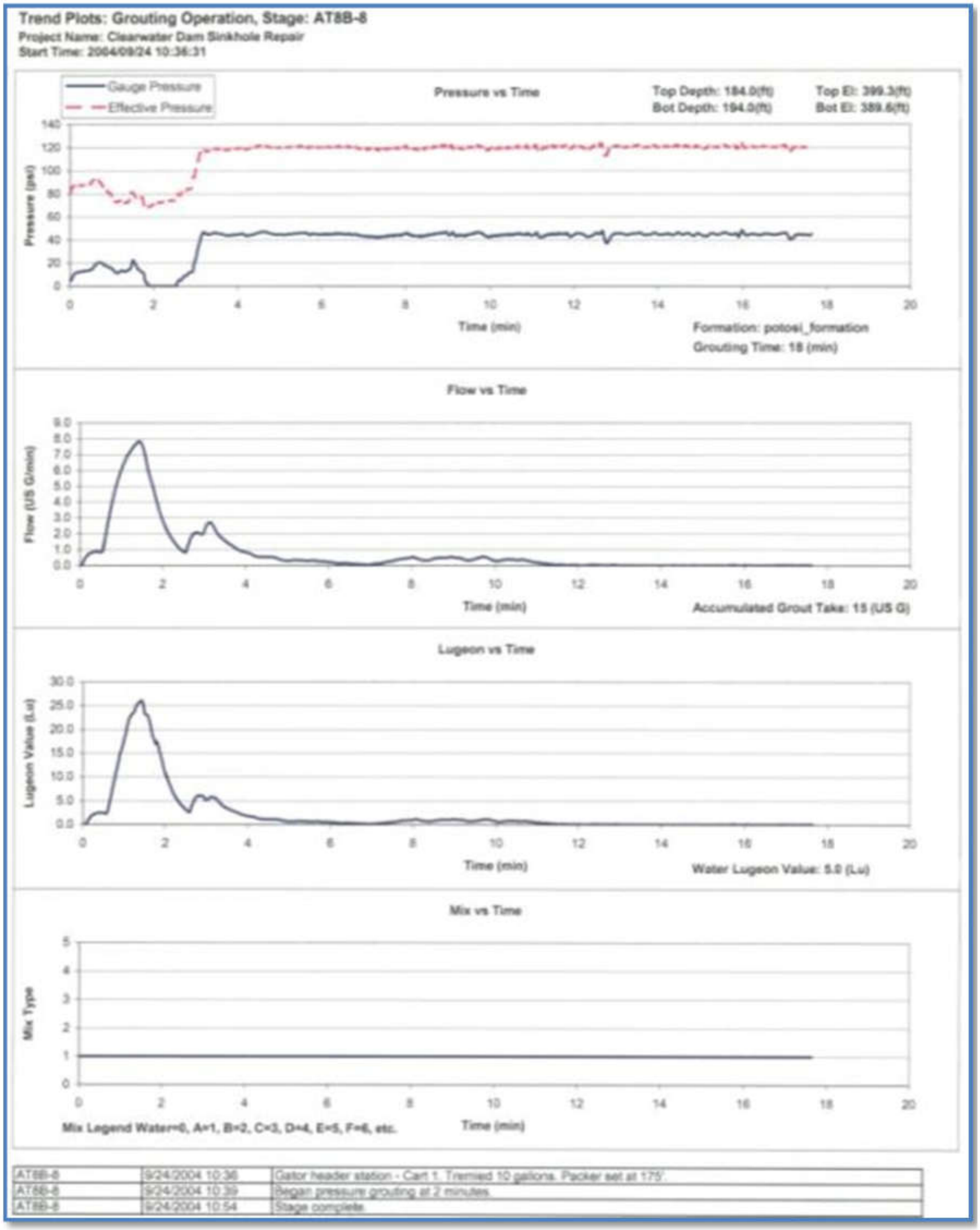


Figure 8.12. Rapid refusal on a tertiary hole. (Courtesy of Gannett Fleming)

Time Pressure Consumption Graph:(TPC Diagrams – Figure 8-13)

The behavior of a hole has been classified in six broad categories based on time- consumption and time-pressure data (Mistry, 1988, Shroff, 1999).

Interpretation of standard curves:

1. Consumption drops and pressure remains constant after peak. After reaching the maximum pressure, a few minor cracks might open out which are again filled up. The pressure curve is approximately parallel to the time axis while the consumption at the nearly constant pumping energy goes on decreasing. This is the ideal pair of curves.

2. Pressure increases and consumption remains constant after peak. This pair of curves shows that the pressure slightly falls due to opening of the cracks. After filling in the cracks, the pressure rises and the rate of consumption remains constant. If the rate of consumption is within permissible limits, the grouting may be stopped. If the pressure achieved is more than specified, the operation may be continued at a suitably reduced pump speed. This is also an ideal pair of curves.

3. Pressure and consumption remains constant after peak. At the peak pressure, the grout continues to ravel in the cracks unchecked. In this case the grouting operation may be stopped after injecting a certain quantity of grout, say 50 to 75 kg of cement/meter. The injected grout left to set. Grouting may then be resumed after a lapse of about 48 hours, when the cracks will have been partly sealed by the setting grout.

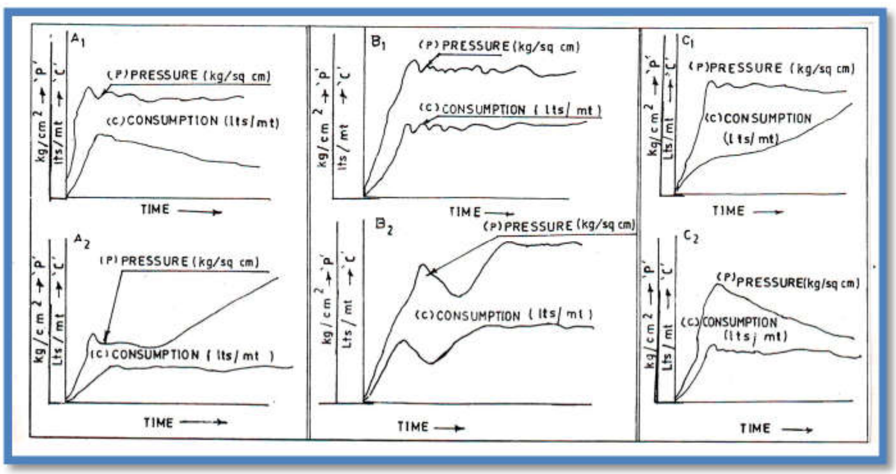


Figure 8-13. Time-Pressure-Consumption (TPC) Monitoring Diagrams-Behaviour of Grout Holes

4. Pressure and consumption rise to some value and then fall rapidly. This pair of curves indicates the opening out of new cracks at peak pressure. On filling of these new cracks, the pressures and consumptions remain constant throughout, indicating that at the second peak pressure the grout travel is continuing uncontrolled. In this case also, the grouting operation may be stopped after injecting a certain quantity of grout and then resumed after 48 hours.

5. After a rise in pressure to a certain value, the pressure remains more or less constant, while the rate of consumption goes on rising. This pair of curves reveals abnormal behavior in the hole. They indicate that there may be leakage of grout through natural strata or along the hole or some upheaval in the rock strata. Immediately on locating the leakage point, it

should be plugged by excavating a small pit around it an filling this with lean cement/concrete. If there has been any upheaval; grouting should be stopped forthwith and grouting resumed after 48 hours with pressure sufficiently reduced.

6. After reaching to a certain value, the pressure quickly drops while rate of consumption remains constant. It also shows abnormal behavior of hole. There may be leakage of grout through natural strata or along the hole or same upheaval in rock strata. The procedure outline in (5) should be followed.

Refusal Criteria

General. Specification of a refusal criterion must be carefully considered when preparing bid documents. Items to be taken into account include: What is the purpose of the grouting? Is it to be standalone or supplemental to subsequent barrier wall construction? What is the desired resulting permeability? How variable is the geology (for example, will close-order holes be necessary regardless of the grout takes on more widely spaced holes)? How many grout lines are planned? How large is the grout job? What are the consequences of a “less-than-perfect” grout job? Additional factors may also be considered. Given all this and the inherent variability of geology, this task is not easy or straightforward. Equating any refusal criterion, no matter how stringent, to a resulting permeability during the planning and design phase is rough at best. In practice, a specified refusal criterion must be coupled with the judgment of the construction staff gained during actual execution of the work on a hole-by-hole basis.

Refusal Criteria Recommendations.

(1) Low-Tech Monitoring and Control. For those relatively few projects still using low levels of technology for both grouting mixes (i.e., unstable grouts) and for monitoring and control of injection (i.e., dipstick and gauge technology), Houlsby (1990) offers a simple yet effective solution in which he recommends that refusal be defined as the point at which there has been no measurable take at the desired pressure within a 15-minute period. He also recommends that the full pressure should then be maintained for an additional 15 minutes, which, in effect, provides an additional 15 minutes of grouting. After grouting is terminated, the injection valve is closed and the pressure is maintained until excess pressure naturally bleeds off. Assuming that measurements are as accurate as possible for the equipment being used, the flow rate at the defined point of refusal is probably in the range of 0.10–0.15 gpm. Since grouting is specified to continue for 15 minutes beyond that point, the actual rate of take at completion is often less than that value. Based on information interpreted from a

variety of sources, it is estimated that multiple-line curtains grouted with this criterion can routinely achieve a grouted zone permeability of less than 5 Lugeons, provided all other aspects of the design and execution are of high quality.

(2) High-Tech Monitoring and Control. Aside from the many other benefits of using state-of-the-art monitoring and control technology, the use of pressure transducers and flow meters substantially improves the accuracy of measurements while allowing much earlier detection of when designated refusal points are reached. Therefore, the technology permits grouting to lower refusal criteria with confidence, and the additional time required to reach refusal is largely or completely offset by more rapid detection. Figure 8-13 and 8-14 shows High-Tech monitoring control equipment.

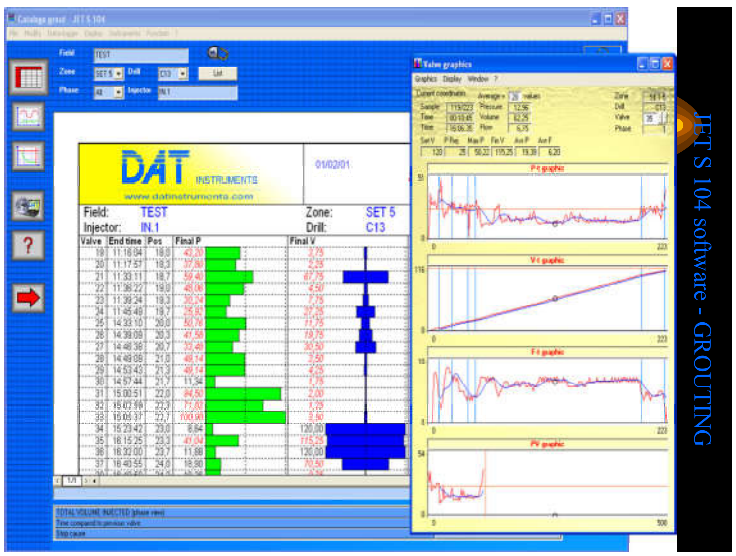


Figure 8-13 High-Tech monitoring system

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