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16. Abstract

This report focuses on the engineering practice of chemical grouting, summarizing the findings of a study to improve design and control techniques for chemical grouting in soils. Improved methods for the planning, control and evaluation of chemical grouting are now available. These include a better understanding of injection behavior, grouted materials, electronic process monitoring for better field performance and improved geophysical testing methods to measure grouting quality.

This report is the fourth in a four-volume series. The others in the series are:

Vol. No.	FHWA No.	Title
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BACKGROUND

Chemical soil grouting involves the injection of a chemical agent into the soil interstices to bring about specific changes in subsurface soil properties, either to consolidate or strengthen the soil or to reduce or stop the flow of water. The recent increased use of chemical grouting is largely due to its widespread application in the construction of several major subway systems. A variety of chemical grouting systems and applications are now available, indicating a vigorous technology.

The correct application of chemical grouting results in no visible changes from the ground surface. There is no accessible product which can be measured, weighed, or tested for adequacy. Evaluation of a grouting contractor's work must therefore be based on indirect measurements and inferences concerning conditions underground. Improved methods for the evaluation and control of chemical grouting are now available, including electronic process monitoring for better field performance and improved geophysical testing methods to measure grouting quality.

This report briefly summarizes the findings of a study to improve design and control techniques for chemical grouting in soils. The study provides a basis for improvements in "construction control" focuses on "materials descriptions concepts," and interprets the results in the content of "engineering practice." The complete findings of the study are reported in three volumes that deal with these three areas. This summary report focuses on the engineering practice of chemical grouting.

GROUTING OBJECTIVES

Chemical soil grouting is used to strengthen a soil mass (structural), reduce its permeability (water control), or both. The intended purpose of grouting on a job must be determined and clearly stated by the designer, since it is possible to accomplish either objective without the other or both together. For example, waterproofing a zone of potential running sand prior to tunneling may be done with a weak grout that will not impede tunneling progress. Conversely, a structural grout that will both waterproof and provide a strong cohesive zone around the tunnel to minimize lost ground and surface settlement may be used in the same situation. The intentions of the designer must be made clear to the specialty contractor and construction manager if the expected results are to be obtained in a cost-effective manner.

Structural Grouting

Structural chemical grouting is used when it is desirable to increase the strength and/or stiffness of a soil mass. Application examples range from the stabilization of running ground prior to tunneling to strengthening of dynamic machine foundations, where the soil stiffness must be changed to eliminate dynamic resonance problems.

Chemical grouts can be used in sand or silty sand containing up to about 20 percent material passing the No. 200 sieve. Less costly particulate grouts, such as portland cement or bentonite clay grout, can be used in very coarse sands and gravels. Fine soils, on the other hand, with high silt or clay contents cannot be grouted at all. The effect of chemical grout on sand depends somewhat upon the sand itself. The primary effect of chemical grouting is to add cohesion to the sand. Unconfined compressive strengths between 0.2 to 4.0 MPa (30 to 600 psi) can be obtained, depending upon the soil and the grout.

Concepts concerning the properties of grouted soils are now adequate for the design of civil engineering structures. Variability in soils from point to point in a given soil mass causes greater uncertainty in predicting the properties of the grouted soil mass than the lack of data on the characteristics of grouted sand. The designer should obtain soil samples from his site and have them injected with grout and tested. This process provides much better data than a review of typical published curves obtained by tests on nonrepresentative soils.

Structural grouting has been applied to a wide variety of problems. In recent years, structural grouting has been used extensively to protect fragile or important existing structures from movements during soft ground tunneling. It has also been used to stabilize dynamically loaded foundation soils to eliminate settlement caused by densification under vibration, and to stabilize liquefaction-prone soils to protect against earthquake distress. Structural grouting may be applied either before or after construction, and can be used to replace more traditional systems such as mechanical underpinning.

<u>Water Control Grouting</u>

Water control by grouting requires complete grout permeation of the treated zone, such that no "windows" of ungrouted soil remain. This is accomplished by injecting triple line grout curtains or blankets, always involving primary, secondary and tertiary grouting phases. Subjects appropriate for waterproofing are excavations, hazardous water disposal sites, leachate ponds, and any site where conditions require the cessation of groundwater flow. When using chemical grout for waterproofing, it is essential that full and complete coverage be obtained. If even small zones are left ungrouted, high pressure gradients across the grout curtain will develop significant flows of groundwater through the small ungrouted "windows." These may lead to piping and progressive failure of the grout curtain if allowed to grow. In especially critical cases, it may be desirable that the grouting contractor be available to treat such areas if they develop during excavation or later phases of construction. Grouts appropriate for waterproofing need not be as stiff as structural grouts. The use of softer grouts is often desirable if the treated zone will be excavated at some later date.

GEOTECHNICAL CONSIDERATIONS

For the rational design of chemical grouting, all of the available geotechnical information must be synthesized to define the technical and economical conditions for the accomplishment of the project purposes. The importance of obtaining adequate geotechnical data and the proper interpretation thereof cannot be overemphasized. Selection of the best injection materials and methods is directly linked to knowledge of the job ground conditions.

Important geotechnical parameters related to chemical grouting are shown in the table below, with methods employed in establishing their values and their significance.

IMPORTANT GEOTECHNICAL PARAMETERS

Geotechnical Parameter	Evaluation Method	Significance
Permeability	Estimate from grain-size analysis; calculate from in-place pump-in tests; and laboratory tests	Determines groutability and injection rates
Micro-stratigraphy	Semi-continuous sampling and visual inspection of samples	Relative shape of bulbs; shows preferred grout flow layers
Groundwater	Borehole groundwater readings; piezometers readings; chemical analysis; grout-groundwater gel tests	Influences injection sequences and grout selection
Porosity	Laboratory tests; correlation with density and grain-size data	Determines volume of grout required to impregnate unit volume of soil
Strength and Stiffness	Acoustic velocity profiling; pressuremeter test; SPT; laboratory testing	Deformations under load
Environmental History	Maps, construction excavation observation, inspection pits	Underground anomalies
Injection Fracturing Pressure	Estimate from soil density and permeability; correlate with pressuremeter data; define by injection test with acoustic emission monitoring	Establishes maximum production injection rates for controlled grouting

For a given sand and permeant, the coefficient of permeability decreases as the gradient increases; this effect appears to decrease as the effective grain size of the sand decreases. The effective grain size of a well-graded sand can be approximated by the D_{10} grain size. Empirical formulae developed by Hazen, Rose, Terzaghi were found to predict the permeability of fine sands to within a factor of three, but they overestimate the permeability of silty sands by about an order of magnitude.

The presence of 5 percent to 10 percent fines in a graded sand reduces the coefficient of permeability by up to one-half an order of magnitude, whereas 20 percent fines will cause a decrease of one to one and a half orders of magnitude. Although one rule of thumb suggests that the permeability of a sand is reduced by about an order of magnitude for every 12 percent of fine material, the actual reduction depends on the nature of the fines.

PROPERTIES OF GROUTED SOILS

A grouted mass in the field is usually subjected to a three-dimensional state of stress and is frequently located below the groundwater table. The behavior of a saturated grouted mass under loading depends on the rate of loading and prevalent drainage conditions. Drained and undrained triaxial compression tests are considered to represent two extremes in the behavior of silicate grouted masses. In general, the grouted mass has a tendency to dilate for rates of loading higher than the rates of drainage; pore pressures decrease because of dilation of the sand and associated cavitation of the pore water, and temporary high effective confining stresses and shear strength develop. Eventually, as pore pressures dissipate, the behavior of the grouted mass is realistically represented by its behavior measured in a drained triaxial compression test. Every effort should be made to test saturated specimens to facilitate the interpretation of the results in terms of effective stresses. Drained triaxial tests simulate the long-term behavior of a grouted soil mass better than undrained tests.

Unconfined compression tests conducted under carefully controlled specimen preparation, handling, and testing conditions can be used when performing parametric studies, but should not be used to predict the behavior of grouted soils under more complicated stress fields. Appropriate consideration must be given in design calculations to the significant reduction in the creep strength of chemically grouted soils relative to the strength measured in a triaxial compression test conducted in a normal quick test. Creep or long-term strengths are generally only one-third to one-half of the conventional unconfined strength. If a grouted mass must support long-term loads, the allowable stress must be reduced to below the creep strength.

Dense sands display relatively little increase in stiffness (tangent moduli) when grouted, while loose sands become as stiff as dense sands upon grouting. However, acoustic velocity measurements indicate significant increases in micro-stiffness in both dense and loose grouted sands. This increased stiffness is substantiated by pressuremeter tests. Thus, the increase in modulus observed depends not only on the soil that is grouted, but also on the strain level that is used.

Chemically grouted soils are composite materials with mechanical properties that depend on the properties of the individual components (neat grout and sand) and the interaction between them. For practical engineering purposes, the following summarizes the behavior of silicate grouted sands: (a) the mechanical properties of sodium silicate grouted soils develop as a function of a grout curing time; (b) the observed mechanical properties of grouted soils depend on the type of test conducted; (c) Mohr-Coulomb failure criteria is a useful method of representing the strength of silicate-grouted sands; (d) every effort should be made to simulate field conditions during a laboratory investigation of grouted soils; and (e) time effects should be taken into account when describing the strength and stiffness of grouted soils.

PERFORMANCE PREDICTION METHODS

The rational design of chemical grouting requires some prediction of the project performance, including evaluation of soil stresses and strains. In the past decade, several large chemical grouting projects were carried out for American subway construction. With no analytical evaluation of soil stresses and strains, this resulted in apparently large but actually unknown degrees of conservatism, underscoring the fact that until recently, performance prediction procedures for structural chemical grouting around tunnels were not generally available.

A prediction of the performance of a chemically grouted structural soil mass requires the following:

1. A useful model of the construction environment and sequence;

2. A stress-strain-strength model of the grouted and ungrouted soils;

3. An understanding of the structural behavior of the chemically stabilized mass in resisting loads and deformations; and

4. Validation of the approach by comparison of analytical results with case histories.

The structural behavior of the chemically grouted zone is dependent to a large extent on the particular construction excavation procedures used. Consider, for example, the frequent case of chemical grouting underpinning of a conventional footing to permit adjacent excavation to several footing widths below the bottom of the footing. If the excavations is to be made in one lift with no lateral bracing to the footing or cut face, the role of the chemically grouted mass would be to provide total vertical support to the footing and lateral support to the retained soils. Because of the lower creep strength of chemically grouted soils, it is important to know how long the area will be left unsupported before final construction is completed.

On the other hand, if the footing is located within an area that will be laterally supported by conventional soldier piles and lagging, the role of the grouted mass may be reduced to providing limited vertical footing support near the cut face and to prevent any loss of ground (and associated loosening of formation support soils) during the actual lagging process. In this case, the amount of laterally unsupported ground would be limited to one lagging lift between soldier piles. Long-term strength would not be a factor. It is apparent that for this case the role of the chemically grouted mass is much less critical than in the former example. Designers can now use available finite-element analyses to predict the deformation response of chemically grouted soil masses during construction excavations.

INJECTION PROCESS PLANNING

Planning the injection program requires a fundamental understanding of how the liquid grout flows in the porous soil from the injection point.

Upon injection, silicate grout appears to flow progressively into the soil, with the fresher grout displacing the older grout toward the exterior of the grouted mass, even for grout with a short (5 to 10 minutes) gel time. Silicate grout can be pumped into a dry sand for a period as least five to six times longer than the design gel time before viscosity increases are sensed.

When pumping grout with a short gel time into a soil mass for long periods of time (more than five or six times the gel time), the agitation as the grout flows through the soil voids will decrease as the radial distance to the grout front increases, and this allows the older grout to become viscous; when this occurs, the new grout may develop preferred flow channels through the region where more viscous grout is present, thereby allowing the older grout to gel while the newer grout is bypassing it.

No clear evidence of a "break-through" or flow inversion phenomenon was found for silicate grout. Flow inversion is interpreted in the sense that fresher grout breaks through an external shell formed by older grout that has gelled in place. This is in contrast to some earlier evidence of such a flow inversion phenomenon for sudden-gelling acrylamide grout. Under cylindrical flow conditions, the pressure decreased in a generally logarithmic manner with distance from the injection pipe for silicate-water mixtures. The head loss with distance was much more rapid for the more viscous permeants, but pressure data during grout injection were inconsistent. General quantitative agreement in the pressure distribution as a function of distance from the injection pipe was noticed from results obtained from the cylindrical laboratory model and field data. Both results showed a sharp decrease (50 percent to 60 percent) in the injection pressure within the first foot or so, and the pressures in the next few feet were about 10 percent to 15 percent of the injection pressure at the grout pipe.

With an understanding of how the grout will flow into the ground, the planning aspects for the actual injection portion of a chemical grouting program involve the following four major steps: (1) definition of the shape and size of the grouted zone; (2) estimation of the total liquid grout volume required for injection of the grouted zone; (3) definition of the grout pipe payout, including location, spacing, and pipe installation scheme; and (4) establishment of an injection staging and sequencing procedure, including the indication of the order in which the various pipes and grout ports will be injected and the partitioning of the estimated grout volumes among the individual grout pipe ports.

Fluid chemical grout injected into pervious granular soil under pressure will permeate the soil following the paths of least hydraulic resistance. This means that grouted three-dimensional masses form radially around each injection point. Their shapes are irregular spheroids or ellipsoids (called grout bulbs) for the first stage of grouting. Where a very pervious channel is intercepted, a much larger proportion of grout will be found there. Moving water will also displace the grouted mass in the direction of flow. The most important factors affecting the location of the grouted zones are the locations and arrangements of injection points, which in turn are a function of the grout pipe location and type. Grouting sequence, i.e., the order in which the various grout points are injected, can also be very important in determining where the grout goes.

The final grouted soil mass is produced by the geometric arrangement of small, contiguous grouted masses. Second and third stages of grouting are often performed to fill in the small ungrouted zones between the original grout bulbs. Gel time, grout viscosity, pumping pressure, water flow, and soil anisotropy all affect the eventual grout distribution. Injection below the groundwater table must be done in such a way that escape locations are always provided for groundwater to be pushed or "herded" ahead of the advancing grout front. Injection grouting must proceed methodically either from one side completely across to the other side of a grouted mass, or from the center outward, from the top down, or any such sequence that will finally expel any groundwater from the interior of the grouted mass. If injection sequencing is improperly done such that water is trapped in the center of the grout zone, then increasing grout pressures will incorrectly indicate complete grouting, without the full use of the anticipated grout volumes.

Planning steps before actual grout injection include:

1. Establishment of grouted zones in idealized but realistic shapes.

2. Establishment of preferred sleeve-port grout pipe arrangement to cover idealized shape.

3. Adjustment of idealized shape to reflect actual grout pipe locations.

4. Adjustment of sleeve-port spacing for soil anisotropy and layering effects.

5. Calculation of soil volume to be treated and estimation of total required grout take using estimated soil porosities and grout loss factors.

6. Distribution of grout volumes between separate sleeve-ports and injection stages.

7. Establishment of grouting sequences to avoid trapping groundwater.

8. Adjustment of design grout volumes in the field during initial grouting according to observations, including indications of injection pressure increase, grout refusal, heave, and fracturing.

MONITORING AND EVALUATION

The most rationally designed chemical grouting plan is eventually subjected to the reality of field injection practice. The real time verification of the field injection activities is termed Quality Control. After injection, typical questions arise concerning the boundaries of the grouted zones, the completeness of treatment, and the properties of the injected soils. Post-injection evaluation of the grouted soils is termed Quality Assurance.

Recent developments in electronic grouting procedural controls provide for much improved quality control for chemical grouting of soils, and recent applications of geophysical profiling techniques to chemically grouted soils permit more comprehensive quality assurance programs. These improvements permit designers to take a more confident approach to the achievement of design objectives and should result in both reduced costs and superior technical results. Through improved quality control and quality assurance, both the designer and the owner/client can be assured that construction is satisfactory and that design objectives have been achieved.

Quality Control

The designer can reasonably require that a competent specialty chemical grouting contractor provide the following:

1. Grout pipes are accurately placed and properly installed.

2. Grout components are properly formulated and thoroughly mixed to give the required neat grout mix and gel times.

3. Grout volumes are accurately injected as planned to the specified grout ports, in a logical sequence and with acceptable flow rates and pressures.

4. Injection process data are recorded and used as feedback to determine that grout is where and in the condition it is expected to be.

5. Through final quality assurance testing performed after completion of the injection work, grouted soil acceptance criteria are satisfied.

The above specific items should be verified in the quality control plan.

The accurate measurement of grout flow rates, injection pressures and total grout volume with time per injection location are fundamental quality control requirements of any chemical project. In conjunction with the known geometrical array of grout port locations, these data can be used to infer the location and behavior of the grout underground. Grouting flow rates, pressures and volumes should be used in real time by the grouting technicians to decide whether to reduce or increase flow and pressure at any given moment and to decide when to end injection altogether at a given port. In addition, if properly documented and displayed, the flow rate, injection pressure, and grout volume histories can be used to review the contractor's activities and responses to dynamic field conditions at a future date. Thus, any adjustments to the design program can be based upon a clear picture of what has been accomplished to date. It is clear that any quality control test can be used as a quality assurance test, given appropriate documentation. For example, a strip-chart recording of injection pressure and flow rate versus time, annotated to show injection point and date, and properly filed, is both a quality control and a quality assurance tool.

Grout Pipe Verification

The accurate location and correct placement of sleeve-port grout pipes are so critical to the success of the injection process that special efforts should be made to verify this work. As a minimum, selected grout pipes should be plumbed to confirm that they are being installed to the depths shown on the as-built drawings. Selected water injection tests should also be performed to verify that the sleeve-ports are located at depths anticipated and that cracking pressures and injection pressures are as anticipated. Finally, grouting and inspection personnel should be very observant during the actual injection work to notice any surface leakage that may occur around grout pipes, indicating improper installation and sealing of the annular space around the pipe. This improper sealing problem can sometimes be solved by letting the leaking grout gel, thus reestablishing the seal.

Grouting Systems

Grouting systems are distinguished by the particular combinations of grout mixing methods (batch vs. continuous) and grout injection methods (open pipe vs. grout ports) employed. Because control and evaluation depend upon the particular grouting method used, these factors should be considered when establishing the Quality Control and Quality Assurance plans.

Chemical grouting by continuous mixing uses metering or proportioning pumps and totalizing meters for grout components. Continuous mixing systems permit better control over the injection process since short gel times can be used. Typical gel time used with batch systems are 45 to 90 minutes, whereas gel times used with the continuous mixing systems are usually 10 to 30 minutes. Silicate grout gel times are lengthened by agitation in the ground when high injection flow rates are used. Combining the continuous mixing system with short gel time avoids the formation of large pools of ungelled grout in the ground or loss of grout migrating downward away from the design zone.

The importance of short gel time can be illustrated by a project that required grouting in loose material behind a tunnel lining. Grouting was used to stablize the loose material to permit removing the existing lining. The configuration is shown in Figure 1. The sandy material immediately behind the temporary lining was injected with grout having gel times of 15 to 30 seconds. Despite these short gel times, some liquid grout rained through the wooden lagging, but the job was successful in sealing the lining and stabilizing the loose material. The tunnel lagging was subsequently removed, and the grouted soil was self-supporting during relining.

Further argument for short gel time grout is provided by Karol who conducted laboratory tests in samples subjected to lateral flow of groundwater. Tests using short gel times produced balls of stabilized soil around the injection point, but long gel time grout was diluted and washed away before it could gel. It is probable that batch mixing can be used without difficulty in many soil grouting projects, but greater control is afforded by the use of continuous mixing and short gel times.

Injection Measurements

Volume. Accurate volume measurements of individual grout components are required to confirm proper grout mix proportions and to calculate total grout volumes for pay items. For both batch and continuous mixing type grout plants, positive displacement meters should be used for this purpose. Conventional water meters or waffle-plate meters cannot provide required accuracy for the variable flow rates and viscosities involved. Meters should be provided with filters and be protected from overpressuring.

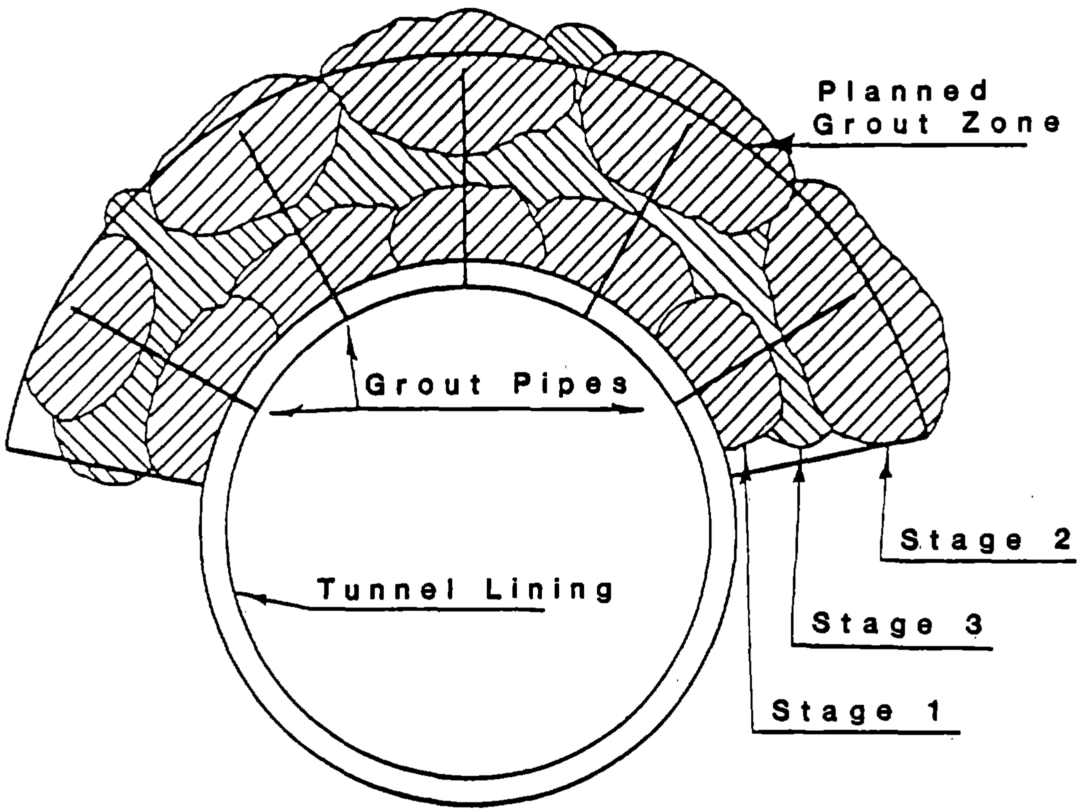


Figure 1 - Crown Grouting With Short Gel Time

Pressure. Electronic transducers convert liquid pressures to electrical analog or digital signals for use with electronic recording systems. Tranducers accurate to 3 kPa (0.4 psi) and rated to 3,000 kPa (440 psi) are available so that overpressuring is not a problem.

Where continuous electronic recording is not done, pressure measurements should be made by bourdon tube pressure gages. Indicated pressures should be recorded periodically on a data sheet. Bourdon gages will not register below about the lowest 5 percent of their range. Thus, high pressure gages must not be used to measure low grouting pressures. Positive gage protection against plugging by gelled grout and against overpressuring during grout port cracking must always be provided.

Flow Rate. Grout flow rates at individual grout ports must be measured in an easily interpreted form. This preferably involves an electronic direct reading device such as an acoustic or magnetic flowmeter that permits strip-chart recording.

Also used for this purpose are flow-column meters, mechanical turbines, or positive displacement meters. Back calculation of flow rate based on the rate of liquid drop in chemical tanks is not considered accurate enough for good control. Flow rate measuring devices must be constructed so as not to have dead spots where grout can gel and be trapped, to later break loose and jam flow paths.

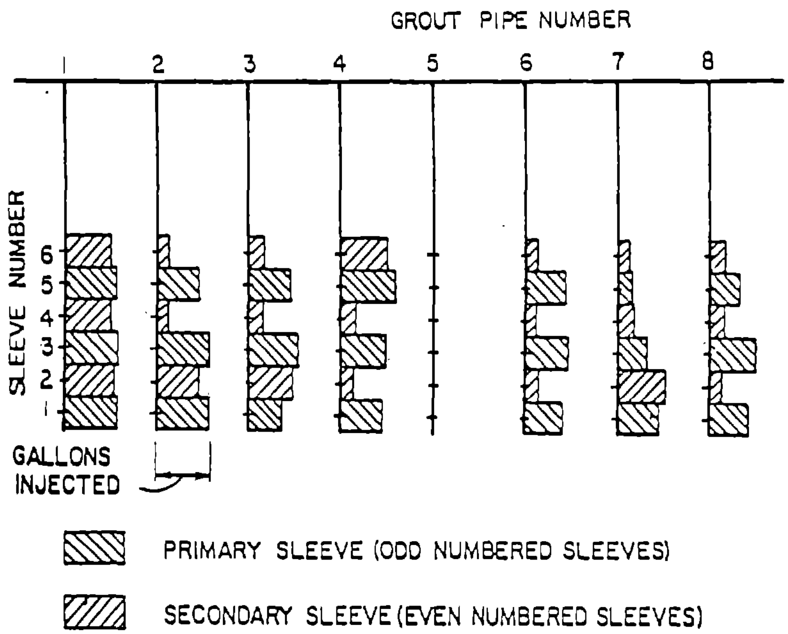
Continuous Monitoring. Injection pressures and flow rates should be continuously monitored. The grouting technician should not have major duties other than monitoring the injection process itself. When manual systems are used, pressure and flow rate records are made for each grout port whenever injection pressure changes more than 25 kPa (3.6 psi) or flow rate changes more than one liter per minute occur, or at least every 10 minutes. For simultaneous multiple hole grouting, special automatic recording equipment should be used.

Date Recording and Evaluation

The accurate measurement of grout flow rates, injection pressures and total volume with time per injection location are fundamental quality control requirements of any chemical grouting project. In conjunction with the known grout port locations, these data are used to infer the location and behavior of the grout underground. Grouting flow rates, pressures and volumes are used in real time by the grouting technician to decide to reduce or increase flow and pressure at any given moment and to decide when to end injection altogether at a given port.

Specifications usually require that a detailed grout monitoring program be submitted by the grouting contractor for approval by the Engineer. The detailed methods for measuring grout flow rates, pressures and volumes and recording these items are usually left up to the specialty grouting contractor.

Graphical Grout Take Log. An important adjunct to field record keeping is the use of a graphical grout take log, showing grout volume injected at each injection point. Upon a cross-sectional display of injection pipes and ports, a graphical representation of actual injected grout volume is drawn at each injection point. Linear, logarithmic, or circular representations of grout volumes have been used. Color coding can be used on the graphical grout take log to highlight areas of serious over and under grout takes, making it an excellent tool for contractor and inspector alike for visualizing project progress. By referring to such a graphical log at the job proceeds, variations in injection conditions can be observed and any unusual situations spotlighted. A typical log is shown in Figure 2. Grout volumes are drawn at each grout port proportional to the volume injected. It is clear that grouting of pipe 5 has not been completed and that the upper primary grout port at pipe 7 was undergrouted.



Note : 1 gallon = 3.785 litres

Figure 2 - Graphical Grout Take Log

<u>Secondary-Tertiary Grout Port Test</u>. An important tool used to test the adequacy of grouting is the secondary-tertiary grout port test. Grouting is traditionally conducted in stages in the same zone, with primary, secondary, and somethimes higher level injection points.

If the secondary stage injection points produce a rise in pressure and reduction in flow as the projected volumes are reached, this is taken as an indication of nearing complete grout saturation and that the primary grouting is satisfactory. Figure 3 shows typical injection records. For the primary stage grouting curve, the flow rate/pressure curve is about constant, showing no grout saturation "closure." For the curve displaying a strongly decaying flow rate pressure ration with time, grout saturation or "closure" was inferred and injection was terminated when designed secondary grout volume had been injected, with good confidence in the grouting effectiveness in this particular example. If the flow rate pressure ratio does not drop off during the second stage, a third stage of grouting may be necessary to verify the completeness of the second stage. This response is not typical of a single row grout pipe array, or grout ports on the perimeter of the grout zone.

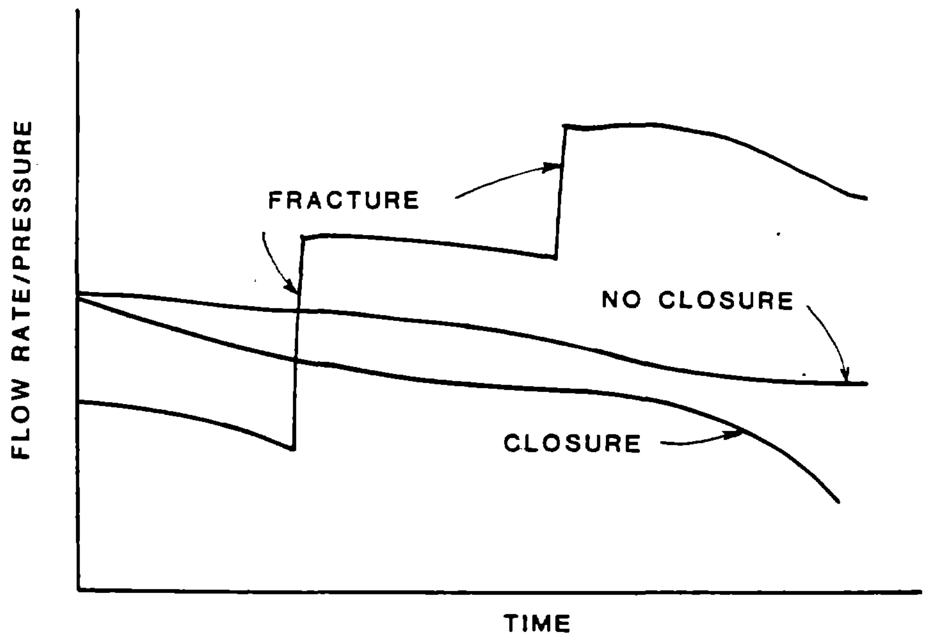


Figure 3 - Typical Flow Rate-Pressure Ratio Curves

Hydrofracturing of Grouted Soils

Hydraulic fracture is indicated by large increases in flow rate with only small pressure increases. That is, the flow rate/pressure ratio curve is concave upward or discontinuous with time. Though relatively easy to diagnose during injection into impermeable materials or previously grouted materials, hydraulic fracture is more difficult to identify in permeable soils that have been grouted. Figure 3 shows a typical flow rate/pressure curve where fracturing occurred on two occasions.

In the past, the traditional opinion held that hydraulic fracturing of ungrouted or grouted soils during injection should not be permitted. In contrast, current opinion holds that hydrofracturing of grouted soils is not necessarily detrimental, but is necessary to obtain complete grout impregnation. Recent Corps of Engineers studies showed that hydrofracturing of previously grouted soils due to reinjection of the same grout port will occur at pressures as low as one-half the overburden pressure, or may not occur until pressures reach three or four times the overburden. Thus, limited hydrofracturing of grouted soils is a necessary feature of effective grouting practice.

Hydraulic fractures will run through previously grouted sand until an ungrouted volume is intersected, and then permeate normally into the untreated sand. Thus, access to adjacent small ungrouted zones may only be possible by limited hydrofracturing of previously grouted zones. This feature may be used to promote thorough grouting. Used carelessly, it can result in grout traveling outside the grout zone and being wasted. Hydraulic fractures usually initiate in the plane of the borehole, and may exert considerable force by virtue of the hydraulic pressure distributed over the fracture area. Since hydrofracturing causes some horizontal precompression of the ground, a nearby basement wall or lateral retaining structure for an adjacent excavation may be endangered by hydrofracturing. There is little risk of initial fractures causing heave of the ground surface unless the grout holes are horizontal or fracturing occurs between layers of different soil types. Overgrouting will eventually cause ground heave. It is not known what effect fracturing has on the strength of grouted masses. On being excavated, a grouted soil mass will sometimes break along the fracture, other times across the fracture.

Acoustic Emission Monitoring of Injection Pressure

Acoustic emission (AE) monitoring, a relatively new geotechnical monitoring tool, may be used to detect structural distress in geotechnical materials. In grouting, it may be used to detect hydraulic fracturing and therefore allow for control of this phenomenon. Indications of fracturing are bursts of microseismic noises "heard" by the system, denoted by increased acoustic emission count rates.

High grouting pressures and the high flow rates can reduce grouting cost to the owner's benefit. The critical pressure at which fracturing is initiated can vary by a factor of three or more at points less than a meter apart. The common rule of limiting injection pressure to one psi per foot of depth (20 kPa/m) will not completely eliminate the risk of fracturing, and the use of higher and more efficient injection pressures might be completely safe over much of a grouting site. What is required is not a rule of thumb, but instrumentation that will detect fracturing immediately as injection pressure is raised. Acoustic emission monitoring can be used to detect the grout pressure causing hydraulic fracturing and therefore allow for control prevention of this phenomenon.

An effective AE sensor is a hydrophone placed in a water-filled grout pipe. Placing the hydrophone underground reduces surface noises which otherwise would cause spurious alarms. The AE system should have adjustable filters that can eliminate frequencies below 1,000 hertz, which includes most construction noise.

The time of integration of the AE system is usually between 10 seconds and 1 minute. The AE system should have an annotatable strip chart output recorder, visible to the grouting technician, so that he will immediately see any large pulses in the AE output. An audio output (earphones) may be used so that any noise sources detected may be more readily identified in the field and noted on the AE strip chart. AE monitoring procedures usually include the following steps:

1. At the start of grouting, set the filters on the AE system so that construction on other cultural noise on-site will not be recorded.

2. In a noncritical area of the grout zone, conduct a hydro-fracture grout injection test. Set the threshhold and gain controls so that only hydrofracturing is recorded. Typically, the sound of hydrofracturing is several thousand times more intense than background noise levels if the AE sensor is placed at the grouting depth in a nearby grout pipe.

3. During grouting, set the AE system so that the grouting technician can see the recorded output. He can then increase the injection pressure at each injection point until fracture begins, and then back down to a comfortable safety margin.

4. If fracturing occurs during grouting, the grouting technician can reduce the pressure on the several injection points one at a time to identify the one causing structural distress.

The AE system controls should not be changed frequently. They should be set so that little if any cultural noise is heard, but fracturing is. It is a great temptation for the operator to increase the gain until extraneous construction or background noise is detected. This produces confusing data and should be avoided. Acoustic emission systems should be operated by experienced personnel. The array of controls and indicators on the face of an AE monitor is confusing and intimidating to the untrained construction worker. However, individuals having some experience in instrumentation or electronics can be quickly trained to use AE equipment.

GEOTECHNICAL QUALITY ASSURANCE TOOLS

Quality assurance methods include those systems of measurement and documentation that are useful in proving that the specified project objectives were or were not accomplished, since one cannot "see" the grouted ground. This section discusses those systems which are strictly quality assurance tools, and are not used for quality control purposes. In addition to conventional site exploration tests, selected geophysical tests are now being used to evaluate grouted soils. These include borehole radar and crosshole acoustic velocity, which can be used to determine the grout location and condition underground.

Attempts are frequently made to evaluate chemical grouting effectiveness using conventional site exploration tools. Tools that may be applied include the standard penetration test, borehole pressuremeter, undisturbed sampling, and the excavation of test pits. These systems are useful under some conditions, but under other conditions, they are ineffective or even misleading.

The Standard Penetration Test (SPT) is a favorite site exploration tool in spite of its crudeness. The primary advantage of the SPT appears to be the wide familiarity geotechnical engineers have with it. Unfortunately, it is a dynamic test and grouted soil is an easily shattered brittle material. These factors combine to increase the already large variability of the SPT when it is applied to grouted soil. While it is usually apparent in the blow counts that there has been an increase in soil strength after grouting, the increase in blow count is not commensurate with the anticipated increase in strength.

The borehole pressuremeter can be used effectively in grouted soil where drilling does not disturb the adjacent soil and where a smooth clean borehole can be obtained. This is presently not possible in grouted gravelly sand. The borehole pressuremeter can be used in clean fine sands having no gravel if the hole is drilled using a "fishtail" or drag bit rotated under tight pressure and with a heavy drilling mud. Having obtained a smooth clean hole, the pressuremeter tangent modulus can be measured. Often, the strength of the grouted soil is greater than the pressure capacity of the conventional pressuremeter. Interesting data might be obtained by pressuremeter creep tests, but this has not been attempted.

Occasional attempts are made to obtain undisturbed samples by core drilling. Shelby tube or split-spoon sampling is out of the question in grouted soil. Rotary drilling with a core barrel is often unsuccessful, due to small gravel particles or broken pieces of grouted sand working their way into the core barrel and abrading the sides of the sample, usually breaking it in flexure. Even if a sample is recovered intact, it is of questionable value because of the rough handling it undergoes during the coring process. It is difficult to hand trim an undisturbed specimen from a block sample in the lab, much less to drill one in the field. Undisturbed samples can, however, be obtained by trimming block samples recovered at tunnel headings or from test pits.

The most effective traditional grout evaluation method is the excavation of test pits. One can then enter the grouted zone and recover undisturbed samples, conduct plate bearing, CBR or wall reaction tests in-situ, and generally evaluate the grouted soil by personal inspection. If it is difficult to detect the grouted soil either by odor or color, however, an acid/base indicator such as phenothalene can be sprayed on the soil to detect the presence of high pH silicate grouts. While test pits are both destructive and expensive, they are most effective conventional grout evaluation methods.

To summarize, some conventional site exploration tools can be used to obtain a qualitative idea of the grout location and condition, but even with them it is difficult to obtain quantitative data. In most cases, even intuitive judgments based on extensive experience with the particular tool in question can be misleading because of the sensitive nature of grouted sand.

GEOPHYSICAL QUALITY ASSURANCE TOOLS

General

The geophysical tests that have proven most useful in evaluating grouted soils include cross-hole acoustic profiling and ground probing radar. These geophysical methods are well suited to defining increases in soil stiffness and grout presence and are being used increasingly to monitor soil grouting.

Borehole Radar

Borehole radar profiling involves the transmission of microwaves through the ground from one borehole to another. Silicate grouted sand becomes opaque to the microwave transmission, such that loss of signal is interpreted as a sign of good grout penetration. Recent development of small-diameter (35 mm) down-hole transmitters and antennas now permit economical use of plastic sleeve-port grout pipes as monitoring holes. This eliminates the need for expensive special instrumentation holes and greatly reduces the cost of radar profiling of grouted masses. Data processing equipment is needed to allow on-site interpretation of the before- and after-grouting radar logs by non-specialist technical personnel.

Borehole radar may be used in either transillumination mode or transmit/receive mode. In transmit/receive mode, a single borehole instrument is used which transmits a pulse, and then listens for the reflected signal. Because both portland cement and silicate are "lossy" materials, they are typically poor reflectors, and are difficult to see using transmit/receive mode. In transillumination profiling, a transmitter is lowered down one borehole, and a receiver down the adjacent borehole, both to the same level. The instruments are then raised simultaneously, so that the signal path between them is level, and the received signal is recorded as a "radar profile." By taking radar profiles before and after grouting, the effects of grouting can readily be seen in the comparison of the profiles. Transillumination radar is best used to determine the grout location, and to obtain an indication of the amount of grout present. Figure 4 shows a typical before- and after-grouting radar profile image pair.

Equipment. Earth probing radar is available in a variety of forms. For effectiveness in grout monitoring, the radar and grouting systems should have the following features:

1. The grouting system should use plastic grout pipes through which the radar can see, and which are available for radar surveys before and after grout injection.

2. The radar system must have borehole antennae which fit in the grout pipes. Surface radar is ineffective.

3. Transillumination radar, which has a transmitter in one borehole and receiver in another, must be used.

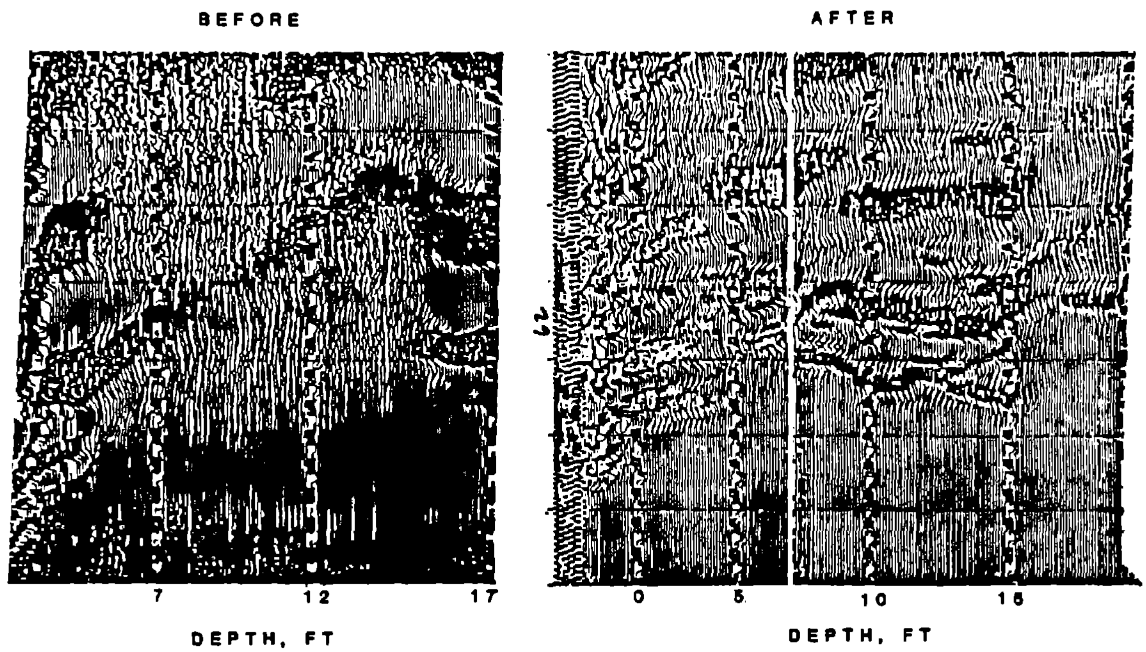


Figure 4 - Before and After Grouting Cross-Hole Radar Images

Criteria 1 and 2 above insure that radar surveys are possible in existing grout pipes without the expense of extra boreholes intended specifically for the radar surveys. Transmitting and recording equipment manufactured by Xadar Corporation and Geophysical Survey System, Inc., have been successfully used. Small-diameter antennae suitable for use in 40 mm (1.5 inch) diameter PVC grout pipes are not yet commercially available and must be custom manufactured.

Operation. Borehole radar can see through ungrouted soil, but not through well-grouted soil. Interpretation of single run borehole radar survey results is difficult. When the system is used before and after injection, the changes caused by grouting can be readily discerned, even by inexperienced personnel. Use of borehole radar equipment should be supervised by technical personnel with geophysical experience. Properly used, it is capable of determining whether the area between two grout pipes has been grouted. The recommended sequence of steps is as follows:

1. Prior to grouting, conduct borehole radar surveys of selected PVC grout pipe pairs, noting operational parameters on the radar system. The survey should extend the full depth of the boreholes, starting with the antennas in the air above the borehole. One pair of "calibration holes" should be established outside the grouting area.

2. After grouting, repeat the surveys in the same boreholes, using the same settings on the radar controls. Confirm that the radar equipment is adjusted and operating properly by surveying the "calibration holes" and verifying that the "radar profiles" are similar.

3. Make side-by-side comparisons of the before and after radar surveys. Areas which were grouted will show much reduced signal strength, while the areas not grouted should show similar geologic features on both surveys.

When the surveys extend from the bottom of the grouted zone to the ground surface several feet above the grout, the before and after radar profiles should be similar near the surface. This is evidence that the before and after surveys were in the same pair of boreholes and that the radar was working well. The top of the grouted zone should be clearly delineated by decreased signal strength. With such data, even those who are not familiar with borehole radar can understand and appreciate the results.

Cross-Hole Acoustic Velocity

Geotechnical acoustical velocity measurements involve the evaluation of the rate of travel of mechanical pulses through the ground. The acoustic pulses are distinguished as either compression (P)-waves or shear waves. Work reported in this study was limited to compression (P-wave) measurements. At the time of this writing (1982), actual job applications have shifted to the use of shear waves, thought to be more independent of groundwater levels.

Cross-hole acoustic transmissions are used to measure acoustic velocity and a spectra of received signals. Profiles are obtained between grout holes in much the same fashion as in transillumination radar profiling, except that the signal is a mechanical rather than electromagnetic pulse and a 3-hole profile line is required. The acoustic system is set so as to determine whether a significant increase in acoustic velocity occurred upon grouting, and whether the transmitted spectrum indicates an improved acoustic medium after injection of the voids with grout. Attenuation of acoustic energy in soil is highly dependent upon the stiffness of the ground. Structurally, grouted sands are known to increase in microstrain stiffness, and thus show two to ten-fold increases in acoustic velocity.

Cross-hole acoustic surveys are used to determine qualitatively the strength of the grouted zone. Like radar, it is used before and after grouting, and the ratio of flight times is compared to indicate relative changes in acoustic velocity. Thus, distances between test holes are not measured. The acoustic sounder and receiver are used in grout pipes, so that special survey holes are not required. Acoustic velocities through ungrouted soils typically are several hundred meters per second (600-1,400 ft/sec). After grouting, velocities as high as two kilometers per second (6,600 ft/sec) may be observed. This factor of two to ten increase is diagnostic of change from soil to weak rock, and indicates well grouted material.

Requirements for cross-hole acoustic tests in grout are as follows:

1. Grout pipes are available for cross-hole surveys prior to and following grouting.

2. The acoustic tools are sized to pass through the boreholes.

3. Cross-hole acoustic velocity profiles are run the full length of the grout pipes.

4. The after survey should be long enough after grouting to permit full gel formation of the grout, say 48 hours.

SPECIFICATIONS

Specifications for chemical grouting differ from conventional construction specifications in that the desired final results require the unusual field expertise of a specialty grouting contractor skilled in chemical grouting. This special expertise is needed for the following steps: (1) development of a grout pipe layout scheme and installation of sleeve-port grout pipes in a precise pattern; (2) development of a rational injection sequence plan with proper allocation of grout volumes to the various grout ports; (3) proper operation of the grout mixing and injection system in harmony with the actual ground response; (4) continuous recording (preferably automatic) and graphical display of the injection data; and (5) quality assurance acceptance testing. The integration of the technical and mechanical skills required by the above is so complex as to preclude the design engineer from directing the exact details of the work.

Specifications for chemical grouting should be written to require the grouting contractor to bring the necessary expertise to the job and to perform and organize his work according to the above five-step outline so as to accomplish the established purpose. Done in this way, the work can be easily monitored by the construction management staff on the job, and performance problems will be quickly highlighted and more easily corrected. Accordingly, specifications should define the intent and extent of the work, establish specialty contractor qualifications, set criteria for grout selection, describe acceptable pumping equipment types and operating procedures, specify grout pipes, define injection procedures and quality control, and establish the basis for acceptance and payment. For important projects, automatic electronic recording of injection data should be required. The detailed equipment and methods for measuring grout flow rates, pressures and volumes and recording these items are usually left up to the contractor; however, they should be measured, recorded and analyzed continually during grouting and must not be optional.