COMPACTION GROUTING CONSENSUS GUIDE

Compaction Grouting Consensus Guide Committee
of the Geo-Institute of the ASCE

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ABSTRACT

Compaction grouting is a viable technique for densifying loose fills and native soils that permit adequate fluid pressure dissipation. The process involves injecting a stiff mortar-like grout into the ground to displace and compact the surrounding soil. During injection, the grout displaces the soil and forces the soil grains into tighter packing, expelling air and/or water out of the effected area, and reducing pore volume. At the end of injection the ground should contain stiff grout masses and densified soil. This Guide is specifically focused on applications of compaction grouting where densification of the soil surrounding the grout mass is a primary objective of the ground improvement.

This document is intended as a practical guide for those interested in specifying, designing, and/or undertaking compaction grouting. Field aspects of compaction grouting are discussed, including compaction grouting equipment, grout mix design, site investigation, and verification. The analysis and design sections of the Guide encompass a range of complexity from very simple through to more rigorous approaches suitable for very sensitive situations. An example specification is provided and typical applications of compaction grouting are presented at the end of the Guide.

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The provisions of this document are written in permissive language and, as such, offer to the user a series of options or instructions, but do not prescribe a specific course of action. Significant judgment is left to the user of this document.

This, the first edition of the Compaction Grouting Consensus Guide, has been written to promote good practice in compaction grouting. The authors of this Guide believe that compaction grouting is a reliable methodology for improving the density and strength of the soil. Similar to other grouting technologies, compaction grouting is a technology based on sound engineering principles, not a "black magic" that can only be understood by a chosen few. And, like all other soil improvement techniques, compaction grouting needs to be applied competently.

This Guide provides background for those interested in specifying, designing, and/or undertaking compaction grouting. As stated above, this Guide is not a manual and is not intended for use as a code of practice; hence it is not accidental that non-mandatory language is used throughout the text. But those involved in the development of this Guide hope that it will become a useful reference for all those interested in compaction grouting.

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SCOPE OF THE CONSENSUS GUIDE

Compaction grouting is a ground improvement technique that improves the strength and/or stiffness of the ground by slow and controlled injection of a low mobility grout. The soil is displaced and compacted as the grout mass expands. Provided the injection process progresses in a controlled fashion, the grout material remains as a growing mass within the ground and does not permeate or fracture the soil. This behavior enables consistent densification around the expanding grout mass resulting in stiff inclusions of grout surrounded by soil of increased density.

This Guide focuses specifically on *applications of compaction grouting where the increased strength and/or stiffness of the soil due to compaction is a primary element of the ground improvement*. Applications where a ground improvement design requires the injected grout to obtain a strength greater than that of the surrounding soil, although potentially a valid application of low mobility grout, are not considered to be compaction grouting for the purposes of this Guide, and hence are beyond the scope of this document.

Both practical and theoretical aspects of compaction grouting are discussed.

This Guide follows the guidelines of the ASCE and uses the International System of Units (SI) as the primary system of units; Imperial units are also provided in parentheses. Compaction grouting in North America typically uses Imperial units in the field, hence many of the SI units have been calculated from the original Imperial equivalents. In these cases an effort has been made to keep the "rule of thumb" values in their original form, and some loss of accuracy in the conversion between units may occur.

This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address the safety problems associated with its application. It is the responsibility of whoever uses this standard to establish appropriate safety and health practices and to determine the applicability of regulatory and non-regulatory limitation.

1. INTRODUCTION TO THE COMPACTION GROUTING GUIDE

1.1 What is compaction grouting ?

Compaction grouting is a ground improvement technique that improves the strength and/or stiffness of the ground by slow and controlled injection of a low mobility grout. The soil is displaced and compacted as the grout mass expands. Provided the injection process progresses in a controlled fashion, the grout material remains as a growing mass within the ground and does not permeate or fracture the soil. This behavior enables consistent densification around the expanding grout mass resulting in stiff inclusions of grout surrounded by soil of increased density. The process can be applied equally well above or below the water table. It is usually applied to loose fills and loose native soils that have sufficient drainage to prevent build up of excess pore pressures.

1.2 Short history of compaction grouting

Although grouting as an engineered process is not new with many records of grouting projects dating back before the 1800s, compaction grouting is one of the more recent grouting methods dating back only to the middle of the 20th century. Compaction grouting is also noteworthy as the only major grouting technology to originate in the United States. Today this technology is widely used worldwide. The development of compaction grouting is particularly interesting in that it appears to have come about serendipitously, and seems to have progressed through the efforts and innovations of many small independent contractors.

The first use of low mobility grout (i.e. grouts which have a consistency similar to very stiff mortar) for ground improvement is in the latter part of 1952, when a small contractor in Los Angeles, California named James Warner needed to fill some small voids under a structure (Warner, 2003). Filling of the void with a cement mortar seemed like the most expeditious repair, and “unable to find either established technology or equipment to pump the mortar, he constructed a "pump" which consisted of a length of six inch diameter steel casing about five feet long and positioned vertically in a wooden frame. It had a two inch hose attached to the bottom and a "piston" consisting of a wood disk fitted with a few layers of old carpet cut to the casing diameter to form a seal. The piston was attached to a push rod of 2” x 4” lumber”.

Fortunately for the progress of compaction grouting, Warner was unaware of the then well established rule of thumb in grouting "if you can't pour it, you can't pump it", and so he directed his efforts to pumping plastic consistency grouts. He was fortunate to meet others with the similar goal of pumping another low mobility mortar, Portland cement plaster, to elevated scaffolds. Success came two years later, in 1954, when due mainly to the efforts of Marvin Bennett a working pump was constructed. Marvin Bennett, along with his brother Richard, also went on to develop the first plaster pump ever in 1954 followed by the very first concrete pump in 1961. Warner however, continued his efforts to develop appropriate equipment and technology for grouting.

During the latter 1950s the use of low mobility grouts for void filling had become common. The use of these plastic consistency grouts was further extended to jacking of structures, using the important feature of such grouts; that they move as a globular mass and their movement can be controlled. However, compaction grouting for increasing the soil's strength was not yet a primary focus of the technology. The earliest mention of the use of stiff mortar-like grout, termed "compaction grout", was by Graf (1969) which described use of the Koehring Mudjack, a machine dating to 1934 for the purpose of pumping a clayey loam mixture under pavement for highway maintenance. He reported that some of the mudjack operators had found it useful to pump "zero slump" grout through pipes driven into the ground for raising structures and that larger than calculated quantities were sometimes used, concluding that the surrounding soil was being compacted. He referred to this as compaction grouting, and stated that "hundreds of jobs have now been successfully completed together with some failures" although no examples were provided. The term compaction grouting was further used by Mitchell (1970) as a method of foundation soil treatment.

The first reported use of compaction grouting to densify soil that the committee is aware of, and reported by Warner (2003), was in June of 1957 to remediate settlement of a swimming pool in a new apartment complex, and the densification was purely accidental! The pool was enclosed by a large building, preventing the use of large equipment. Additionally, it was located in what had previously been a basement boiler room. The bottom slab of this boiler room should have been perforated and the entire original basement filled with granular fill. However, this apparently had not been achieved. Instead the shallow end of the pool was founded on fine grained fill, resulting in cracking of the new pool, allowing water to leak and saturate the fill. One end of the pool had undergone significant settlement.

Paraphrasing Warner (2003), "For jacking, grout holes were placed on a grid of about four feet throughout the bottom of the pool (Figure 1-1). The geotechnical engineer had requested the grout holes in the shallow end be extended to the old floor slab. Though recognizing that fine grained soils couldn't be grouted, he reasoned a number of small holes filled with grout might provide needed support and prevent further settlement. For Warner (the contractor) the job was a disaster. As soon as injection started, water ran from the lower grout holes into the pool. It was removed with buckets but continued to inflow during the injection. The job required an amount of grout equal to more than ten times the calculated volume, before lift occurred. A horrible mess was made by the removal of the muddy water which had been spilled all the way from the pool, through the outside entry to a close at hand catch basin, for disposal".

Everyone involved was obviously upset and not happy, with but one exception, the geotechnical engineer, who exclaimed that "you have squeezed the water out of the fill, this is not supposed to be possible to do - it's wonderful!" Although at the time the process was referred to as *displacement grouting*, the term compaction grouting was adopted once the earlier papers were reviewed.

That project led to an extensive research program to better understand the mechanics, and develop optimal grout compositions and injection procedures. During this time period, interest in the methodology increased quickly, with several publications related to compaction grouting published in the Journal of the Soil Mechanics and Foundation Engineering Division of the ASCE. Graf's (1969) description of the procedure and basic concepts of compaction grouting was the first journal article on compaction grouting published. Shortly thereafter Mitchell (1970) compared this technology to other grouting methods. And Brown and Warner (1973) reported results of the research program along with some case histories of completed projects.

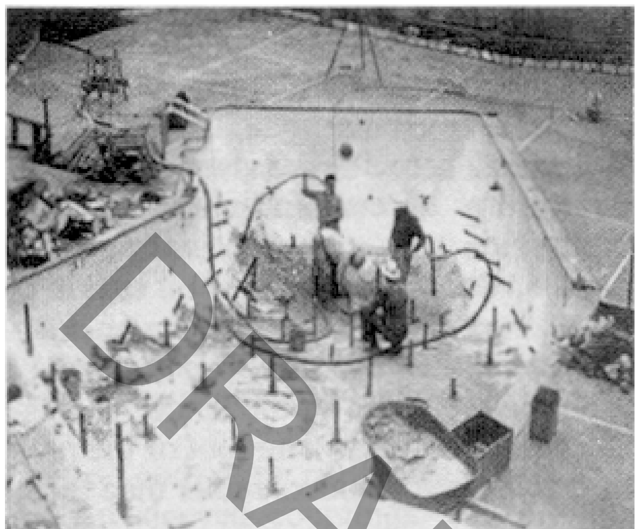

Figure 1-1 Water ran into the pool as fast as the grout was injected (Warner, 2003)

In the thirty plus years since these original papers the practice of compaction grouting has expanded greatly through the efforts of those working in this area. The technology is now widely used for densifying soils, most commonly to remediate settlement damage or reduce the likelihood of soil liquefaction during an earthquake.

1.3 Purpose and development of this Guide

This Guide has been written to promote good practice in compaction grouting. The authors of this Guide believe that compaction grouting is a reliable methodology for improving the density and strength of the soil. Similar to other grouting technologies, compaction grouting is a technology based on sound engineering principles, not a "black magic" that can only be understood by a chosen few. But, like all other soil improvement techniques, compaction grouting needs to be applied competently.

This Guide provides background for those interested in specifying, designing, and/or undertaking compaction grouting. This Guide is not a manual. It is also not intended for use as a code of practice; hence it is not accidental that non-mandatory language is used

throughout the text. But those involved in the development of this Guide hope that it will become a useful reference for all those interested in compaction grouting.

The Compaction Grouting Guide was commissioned as a *Consensus Guide* by the Geo-Institute of the ASCE, and hence to obtain the Consensus Guide designation certain rules have been followed in the Guide's preparation. A Consensus Guide is a non-mandatory technical document that is reviewed prior to publication to achieve a consensus on its content. A committee was formed to oversee the content of the Guide, comprising members of three interest groups, each group with between 20% and 40% of the total membership. The three groups were Producers, Consumers, and General Interest. In compliance with the ASCE Rules for Standards Committees, Producers include "representatives of manufacturers, distributors, developers, contractors and subcontractors, construction labor organizations, associations of these groups and professional consultants to these groups". Consumers include "representatives of owners, owners' organizations, designers and consultants retained by owners, testing laboratories retained by owners, and insurance companies serving owners". The third category, General Interest members include "researchers from private, state, and federal organizations; representatives of public interest groups; representatives of consumer organizations; and representatives of standards and model code organizations". Additionally, to prevent undue commercial bias, organizations should normally only be allowed one member on the committee.

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2. MECHANICS OF COMPACTION GROUTING

This chapter describes the basic mechanics of compaction grouting, including the types of soil conditions in which it is appropriately used.

2.1 Basic mechanics

Compaction grouting is the process of injecting a stiff mortar-like grout into the ground to displace and compact the surrounding soil. During injection, the grout displaces the soil and forces the soil grains into tighter packing, expelling air and/or water out of the effected area, and reducing pore volume. Compaction grouting is a viable technique for densifying loose fills and native soils that permit adequate fluid pressure dissipation. The soil is displaced and compacted as the grout mass expands. Where the injection process progresses in a controlled fashion, the grout material remains as a growing mass within the ground and does not permeate or fracture the soil. This behavior enables consistent densification around the expanding grout mass.

As the grout mass expands, the surrounding soil is subjected to an increase in the total average or mean stress and is also subjected to shear. The increase in mean stress compresses the soil. Shearing the soil causes looser soils to contract as particles reorient themselves and fill void spaces within the mass. Shearing of a dense material will result in an increase in volume, termed dilation, as the particles shear, since particles must move over the tightly packed adjacent particles to pass. Hence, compaction grouting is typically used to densify loose soils.

In order for the particles to achieve a denser packing, air and/or water must be expelled from the initial pore space. As with any compaction effort, the moisture content is a factor in the overall success. Where materials are excessively dry, additional efforts will be required for shearing. As moisture levels increase, they provide lubrication of the particles allowing shearing to be achieved at lower energies. However, in low permeability saturated soils it is difficult to move water from the pore space thereby preventing effective compaction. Non-saturated high-moisture content soils can become saturated during grouting as a result of the reduction in void space.

Compaction grouting is a strain controlled process. The rate and volume of grout injected is controlled and pressures are measured to determine the ground's resistance to grout injection. Injection rates are typically on the order of 30 to 60 liters per minute (≈1.1 to 2.1 ft^3 per minute) although slower rates are requisite in sensitive applications. Higher rates may be used in certain conditions; however faster injection rates may make the grouting harder to control. Excessively high rates of injection may lead to undrained soil behavior (associated with excess pore pressure generation), when the water near to the grout bulb is unable to flow beyond the stressed soil during injection. This significantly reduces densification and will greatly increase the injection pressure. A rule of thumb for determining the optimal injection rate is to control the rate of pressure increase to not exceed about 55 kPa (8 psi) per minute, once grout flow has been established. An injection rate of 30 to 60 L per minute (1 to 2 ft^3/min) has been found to

be optimal for most production work. Slower injection rates are appropriate in finer grained and slower draining soils, and instances to obtain improved control such as in sensitive areas as described in Chapter 9.

Injection of the grout mass is a localized pressurization event. When permeability rates are high enough and injection rates (loading) are slow enough, the pore pressures can dissipate as water flows out of the pore space of the soil near the point of injection, facilitating successful compaction. Where the rate of injection is not balanced with the rate of pore pressure dissipation and pore pressures elevate excessively, hydraulic fracturing in lieu of the desired shearing may occur. Hydraulic fracturing is highly undesirable. Although a volume of grout is still injected into the ground taking up space, the benefits of controlled granular shearing and thus densification in the vicinity of the injection point does not occur.

Densification is also more effective if there is confinement such as a stiffer zone of soil adjacent to, or above, the expanding grout mass. The confinement enables the development of higher local stresses forcing the particles closer together during shear, which in turn results in better compaction. For this reason compaction grout holes are usually drilled and grouted in sequence on a grid pattern. Perimeter holes are grouted first to provide the necessary confinement for those on the interior. Often, unsuccessful (or inefficient) grouting programs can be traced to methods where the work is completed from the inside out. Thus there is less reaction or limitation to movement to permit the development of stresses high enough to produce effective compaction during soil shearing.

Confinement during grouting is optimized by using a method known as "split spacing" whereby the holes are grouted in an alternating pattern. In this way grouting is performed at locations between previous injections where confinement is maximized. The initial holes are termed "primary" holes and subsequent locations between those are termed "secondary" holes. Subsequent additional split spacing may be used if necessary.

This similar logic will also apply to injection at various depths. Where injection occurs at significant depths, there is a much greater level of resistance than at shallower depths. As such, greater pressure can be used and larger volumes injected to influence larger soil masses without causing heave of the ground surface. However, as the injection point approaches the ground surface, lower pressure and smaller volumes of grout will lift the ground surface, negating further densification. This is the reason bottom up injection is not very effective at shallow depth. Although some contractors provide shallow bottom up holes with greater injection controls use of top down staging is more effective at shallow depths as are significantly slower pumping rates. This can be critical where the goal of a program is to improve conditions at shallow depth.

Compaction grouting is less effective near the surface than at depth because the overburden pressure at shallow depths provides relatively small surface restraint. This behavior is a function both of the grout volume injected and the resisting pressure. As grout is injected the projected area of the grout mass increases. As the soil is compacted,

the pressure in the grout mass rises. The limiting depth of grout injection can be calculated based on a force balance model of a truncated cone similar with that used for computing the limiting capacity of soil anchors. The grouting pressure is applied over an area equal to the projected area of the grout mass to obtain the uplift force. The mass of the soil in the cone and frictional resistance on the sides of the cone act as resisting forces.

Chapters 6 and 7 of this guide will detail the analysis the engineer and contractor can go through to assess these and other issues critical to designing and implementing a successful compaction grouting program.

2.2 Soil conditions

As with all grouting, the goal of the engineering is to first understand the scope of the problem and the soil conditions. Only once these elements are understood, can the goals of the grouting be defined. Then the means and methods necessary to complete the grouting can be established.

Site conditions dictate how to proceed. Determining the nature and scope of the problem is often the most difficult issue. Adequate field exploration including test borings, test pits, in situ testing, laboratory testing, visual reconnaissance, and surveying will all add to the information database of a project. Sufficient sampling must be completed to identify the nature of each of the subsurface materials that will have to be treated, as well as the vertical and lateral extent of each material. The investigation should also note the presence of obstructions such as boulders or debris that could complicate the drilling and grouting. The investigation must extend to sufficient depth to define the bottom of the problem area and any compressible zones that could consolidate under the increased weight of the compaction grouted soil. Note that layers of looser, denser, or cohesive material may have a strong influence on both the efficiency of grouting and the volumes of grout required. Gradation analysis, water content and index tests are necessary to obtain information on the basic properties needed. In situ density is usually estimated from the standard penetration test (SPT), but should be measured directly where possible. Permeability information is needed to assess the dissipation of pore pressure and should be measured for fine-grained soils. Consolidation behavior may be important for cohesive soils, particularly if compaction will produce conditions near saturation.

The grouting engineer should review all available data, including borings, test results, historical site plans, geologic maps and other pertinent information to define the nature and extent of the problem. Definition of the problem, based on the data, allows the engineer to focus on the next step; finding a remediation technique that resolves the problem. This definition of the problem will also be the key to determining when the problem is fixed. Without a clear definition of purpose, we may be able to determine whether the grouting was carried out as specified, but we may not know whether the grouting was successful in achieving the desired outcome.

Although compaction grouting has been applied in situations involving almost all soil types, compacting soils by grout under pressure is most effective in soils that can be readily densified by squeezing water and air from the void spaces. Thus, fine grain soils such as high plasticity clays, particularly below the water table, are not well suited to compaction grouting. Mixed granular soils are the most suited to this method. Sandy soils, silt, and even clayey and gravelly soil can generally be compacted effectively with compaction grouting.

The lower the initial density, the more improvement can be achieved through grouting. In fact, dense soils may be loosened by the shearing induced during compaction grouting. In practice, a standard penetration blow count (N) is often used to determine the practical limit for improvement by compaction grouting methods. However, the value of N corresponding to the practical limit whereby denser soils are not densified by compaction grouting is soil specific. This limiting N value can be slightly higher if the improvement is being performed at significant depths. Hydro-collapsible soils, such as loess or debris flow deposits, common in some areas of the United States, yield high standard penetration blow counts but collapse upon wetting. It is often of benefit to wet these soils prior to, or during, injection.

2.3 Field evidence on compaction grout behavior

Full scale injection, followed by excavation and visual observation, as well as testing of several hundred full scale injections, has occurred since the mid 1950s. These visual observations have allowed greater understanding of the effect of grout mix and injection rate on the shape of the grout mass. This section of the Guide provides a summary of the findings.

A report by Brown and Warner in 1973 described a large scale research program where injection and extrication of more than 100 test injections was made, as well as several actual case histories where the grout mass was exposed through excavation. The test injections were all at the same site which consisted of silty sand underlain by clean fine to medium sand. Different sizes of holes as well as many different methods of advancement including drilling and driving were tried, and a variety of different grout mixes, as well as injection rates, were evaluated. They concluded that top down staging through casing cemented into oversize holes, although more expensive, provided the best results at the relatively shallow depths of 1.2 to 4.9 m (4 to 16 ft) considered. Maximum grout take, interpreted as the greatest increase in density, was experienced at an injection rate of about 30 L/min (1 cu ft/min). In this investigation it was found that clay included in the grout mixture was found to act negatively; having clay in the grout reduced the amount of grout that could be injected prior to hydraulic fracture and/or leakage to the surface. A photograph of successfully injected masses is reproduced as Figure 2-1.

Figure 2-1 Grout masses from two test injections (Brown and Warner, 1973)

Figure 2-2 Injection made in tidal zone bay mud

Experimental work has been carried out in South Korea to form grout columns in bay mud deposits, and again shows the typical columnar shape of a successful grout injection. The grout consisted of aggregate falling within the gradation envelope of Warner and Brown (1974) with about 10% cement. It is injected at a constant rate of 57 L/min (2 ft^3/minute). Some work has been accomplished at low tide within the tidal zone, Figure 2-2, while other injections have been made underwater. Figure 2-3 shows a typical grout column being recovered with a derrick barge. The column actually penetrated deeper into the mud seabed than the piece being removed which broke off upon extraction. The grout is apparently displacing the highly plastic but extremely soft mud deposits equally in all directions, resulting in the regularly shaped grout masses shown.

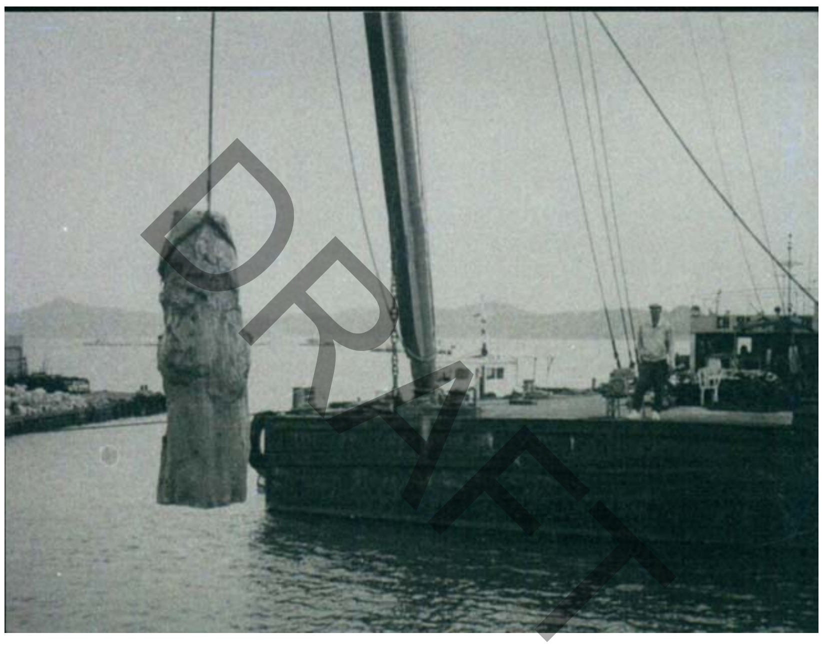

Figure 2-3 Grout mass resulting from underwater injection

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3. COMPACTION GROUTING MATERIALS

3.1 Introduction

Compaction grouts are a type of low mobility grout, typically comprising stiff soil-cement and/or cement mortar type mixtures. The term mobility is a measure of how easily a material flows and was defined by L'Hermite (1949) for concrete to be inversely proportional to the internal resistance. Warner et al (1992) used the ratio of maximum radial travel of the grout from the point of injection to the minimum radial distance to a grout-soil interface (termed the travel index) as a measure of the mobility of the injected grout. Lane and Best (1982) found that water:cement ratio and fine aggregate content affect the pumpability of concrete. The mobility of a soil-cement mortar grout also changes between the confined high pressure conditions within the pump and lines, and the lower pressure after exiting the delivery line; to be effective, the grout mobility must be limited (i.e. the internal friction of the grout must increase) as the grout leaves the injection pipe and, still under pressure, enters the soil.

The grout flow properties, or rheology, are dependent on a great many factors. Some of these include: grout permeability (Borden and Ivanetich, 1997), aggregate gradation (Warner, 1992), grout filter criteria (Bandimere, 1997) and injection rate (Byle, 1997; Warner, 2004). Contractors involved in compaction grouting by experience know the proper grout consistency by feel. Many grouters describe the grout "body" when talking about this consistency and squeezing the grout in their hand. This is far from a scientifically repeatable test, but to date is the only way of actually evaluating grout rheology in the field.

The ASCE Committee on Grouting defines compaction grout in their “Glossary of Grouting Terminology” (ASCE Committee on Grouting, 2005) as “*Grout injected with less than 1 in.(25 mm) slump. Normally a soil-cement with sufficient silt sizes to provide mobility* <u>*together with sufficient sand and gravel sizes to develop sufficient internal friction……*</u>” (emphasis added). In the past many practitioners have noted the one inch slump requirement but failed to appreciate the equally important dictum for development of “internal friction”. Although no particular slump test was specified in the Glossary, the ASTM C 143 test prevails as it is the most well-known, and is widely used with concrete. However ASTM C 143 is not ideal for use with compaction grout. This test requires the mold to be filled in three increments with each rodded 25 times. Such rodding of typical cohesive compaction grout will leave voids in the specimen. Even when used with concrete, for which the test was developed, ASTM in their Special Publication 169C states it is not appropriate for “very dry” mixtures, which includes most common compaction grouts. Because appropriate mixes are cohesive and oftentimes sticky and thixotropic, the level of shear stress required to start movement can exceed the force of gravity upon which slump is based. When acted on by the greater force of a grout pump however, many of these mixtures will flow readily and in some cases actually behave as fluids. Thus, even though a mixture displays low slump in the test, its actual behavior when pumped can be quite different.

Although acceptable compaction grout mixes will be of relatively low slump, this property alone cannot qualify a mix. The best assurance of adequate performance is prescription of the grout aggregate gradation, which will be discussed in detail later in this chapter.

3.2 Factors affecting grout mobility

Seemingly contrary characteristics are required for compaction grout. It must be sufficiently workable to be pumped, yet be relatively immobile once it leaves the end of the injection casing. Making a pumpable grout has never been a problem. Adding more fines, water, cement, or other fluidifying agent can generally produce a grout that can be pumped. However, if the grout behaves as a fluid, it can cause the undesirable effect of hydraulically fracturing the ground, known as hydro-fracturing.

Grout mobility is affected by the ability of the ground to absorb excess pore water from the grout and the grout's ability to lose pore water. This in turn is affected by the pressure gradient between the grout and in situ pore pressure, and the permeability of the grout and surrounding soil. Hence, one effective approach to controlling grout mobility is to use a mix that relies on its own internal permeability to allow water loss once it enters the ground. In this case the grout is pumpable under the conditions of pressure and flow within the pump and lines, but loses pore water to the ground to become less mobile once it leaves the injection casing. This approach offers a measure of control not afforded by stiffness alone, but relies upon the grout-soil interaction to work properly.

The grout pump and injection system must obviously be capable of operating at the required high pressures, and be very durable to withstand the abrasiveness of the grout material moving under high pressure. An appropriate material can be difficult to mix, has high line friction, and a high potential to plug the lines should water be lost through joints or fittings.

The pumping rate determines the injection pressure in any given soil and must be carefully controlled to assure that the internal pore pressure of the grout can dissipate once it enters the soil. Otherwise, the grout will remain excessively mobile, resulting in a loss of control and a tendency to hydro-fracture.

3.3 Composition

The grout usually consists of a mixture of silty sand, cement and water to form a mortar-like material with a slump less than 2 inches. Cement is usually included, but is not a requirement and can be omitted. Depending on material availability, the silty sand may be obtained by adding appropriate fines to available sand.

Addition of highly plastic clay such as bentonite, or concrete pumping additives, has generally been found unacceptable and should only be considered under very rare circumstances as they have been found to cause the grout to behave as a fluid in the ground. High plasticity clay, in particular, is not recommended for use in compaction

grouts (even 1.5% by weight of mix of bentonite can cause a loss of control). Where clay is considered in the grout full scale test injections into the actual soil to be treated should be made to confirm the behavior of such special mix designs. These tests should include excavation of three or more injected masses to confirm acceptable grout behavior.

3.4 Design of the grout mix

Design of the grout mix must strive to fulfill three competing objectives:

1. Sufficient pumpability to enable the grout to be injected, and
2. The grout must remain as a growing mass in the ground.
3. Any bleed water must be able to dissipate into the ground (i.e. no water around the bulb).

These three considerations are primarily controlled by the amount and properties of the fine particles which are defined as particles of size less than 0.074mm (equivalent to a #200 sieve). The amount of water in the grout mix and the aggregate gradation are also extremely important.

Figure 3-1 shows an acceptable grout circulating back to the pump hopper. The granular surface of the breaks (i.e. no slickensides) are indicative of good grout rheology.

Figure 3-1 Grout circulating back to pump hopper: note the granular surface of the breaks which indicate good grout rheology.

The particle distribution envelope for the aggregate presented here (see Figure 3-2 reproduced from Warner et al., 1992) is well graded and contains particle sizes ranging from silt to gravel. Aggregate falling within the gradation envelope provides a satisfactory grout, with the larger gravel sized particles resulting in greater injection control and resistance to hydraulic fracturing of the formation. Round grained natural deposits should be used, especially for the finer fraction. As an example, substitution of crusher run dust for the silt sizes generally does not produce a satisfactory grout. Where round or semi-round grained materials are not available, trial batches should be made to confirm pumpability of the resulting grout mix. The grout should be stiff enough that it exits the delivery line as an extrusion as shown in Figure 3-1. Pieces that break off of the main body should possess a granular texture as shown. An indication of inappropriate rheology would be the grout exiting without breaking apart, or with any breaks that occur possessing a slick surface.

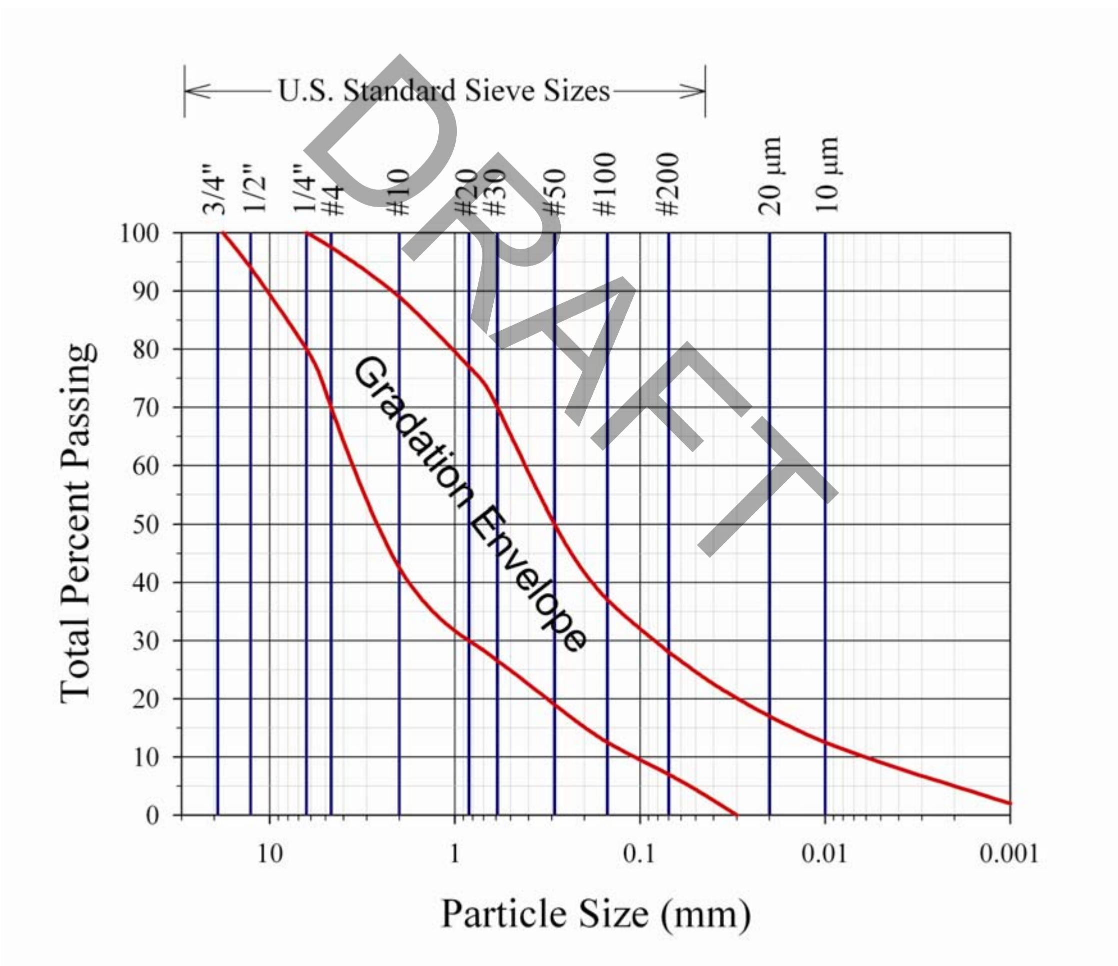

Figure 3-2 Updated envelope of preferred aggregate gradation (Warner et al., 1992)

Mineralogy of the aggregates used in the mix will also affect the behavior. It has been found (Bandimere, 1997) that limestone aggregates require a much smaller fines content to make them pumpable. Hence limestone aggregate grouts are generally easier to control. They also typically have greater strength, although for most compaction grouting applications the strength of the grout is only required to exceed or meet that of the in situ soil.

As stated previously, great care should be exercised when introducing additives, clay sized particles, or high plasticity clay to the grout mix, as they may cause the grout to behave as a fluid in the ground, leading to loss of control which may result in hydrofracture. The effect of concrete additives, although potentially very useful to improve pumpability, is not yet well understood for grouting. Most research has focused on their use in concrete where "control" of the grout mix after leaving the grout line is not required.

The amount of water added to the mix should always be the minimum required to enable the mix to be pumped.

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4. GROUTING IN THE FIELD

This chapter addresses how compaction grouting is typically conducted in the field. It provides guidance on the types of commonly used equipment and grouting procedures.

4.1 Methodology

The grout material is pumped into an open segment of borehole termed a "stage". Each stage is typically on the order of 0.3 to 0.6m (≈1 to 2 ft) , although up to about 1.8m (6 ft) stages have been used successfully at greater depths. A casing is installed tightly in the borehole, with little or no annulus, so that grout will be forced to expand radially and is restrained from traveling upward along the pipe.

Mobility of the grout is dependent on the grout mix and the rate of injection. The grout must behave essentially as a growing solid when it enters the soil. It must have sufficient internal friction so that it will behave as a continuous mass and not induce hydraulic fracturing of the soil. The rate of injection is important to allow dissipation of pore pressures

The degree of densification produced by compaction grouting is improved by grouting in a predefined pattern to provide resistance and confinement. The most commonly used arrangement for the compaction grout holes is a rectangular or triangular grid. Injections are made at alternating holes by a method known as "split spacing". By this method, the holes are grouted in an alternating pattern using a system of primary, secondary, and occasionally tertiary or higher order injections. Secondary holes split the distance between primary holes and are spaced midway between them as depicted in Figure 4.1. The alternate rows containing the all of the primary grout holes should be grouted first. In Figure 4-1 grouting begins around the perimeter and progresses inward to the center so that the initial injections serve as a reaction for the subsequent injections, improving the densification as the soil becomes more contained. The sequence of completing the holes can be varied to adapt to specific site conditions, but generally working from outside in toward the center of the treated area works best.

Grouting may be accomplished by either the "stage-up" or "stage-down" method. The process of stage-up grouting is shown in Figure 4-2. As the name implies, stage-up grouting is accomplished by installing the casing through the full depth of the zone to be grouted and grouting from the lowest stage upward toward the ground surface. For each stage, the casing is withdrawn a distance equal to the desired stage length and grout is injected until the established refusal criteria are reached. In cases where a larger stage length is being used it may be desirable to add a short stage length for the initial stage. The casing is then raised up and the next higher stage is grouted. This process is repeated until the grouting reaches the top of the zone to be improved, or a shallow depth (1.5 - 4.6 m $\approx$ 5 - 15 ft) which provides insufficient confinement for further injection.

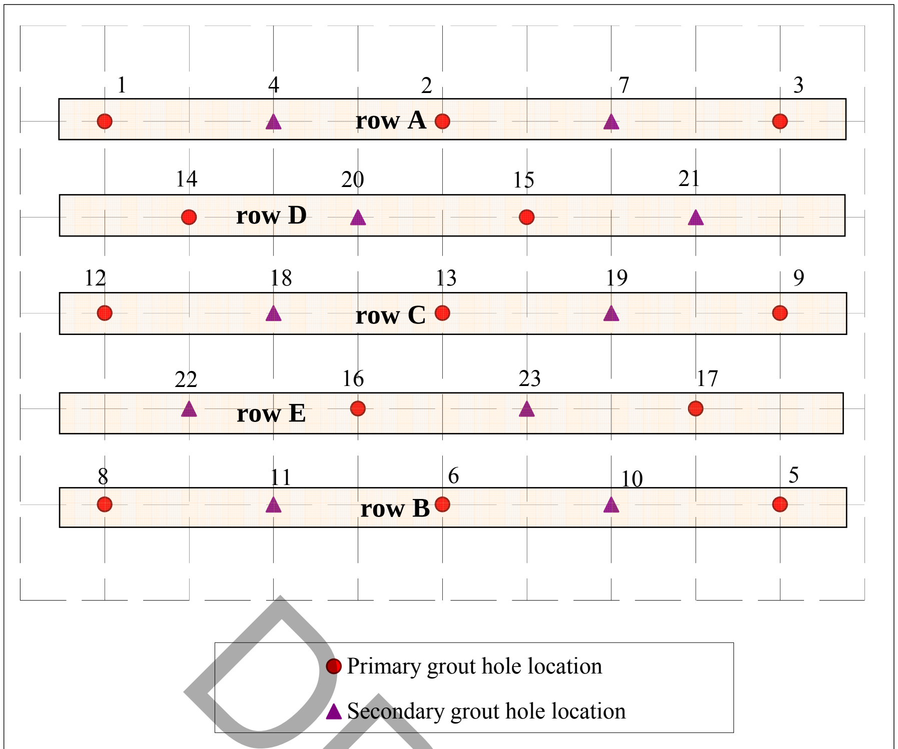
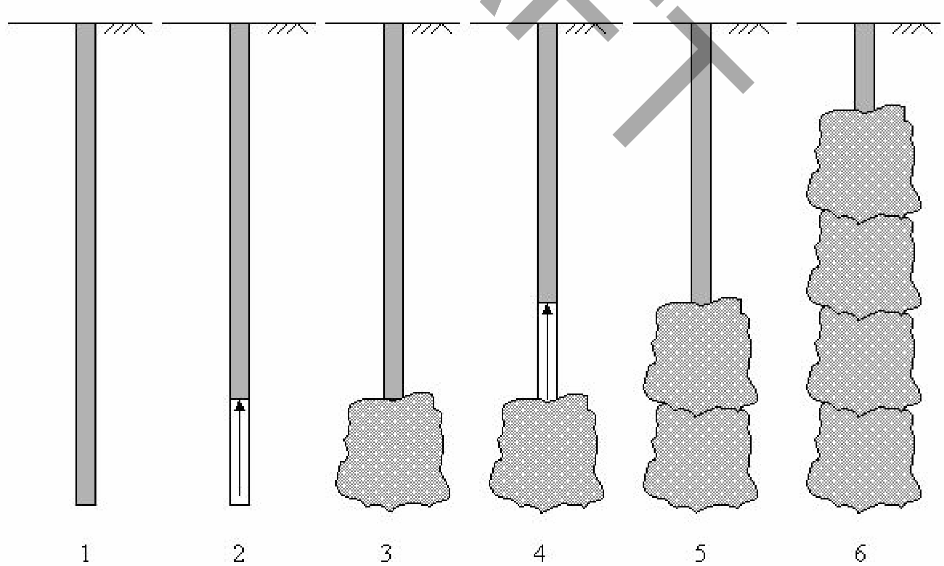


Figure 4-1 Typical split spacing hole pattern

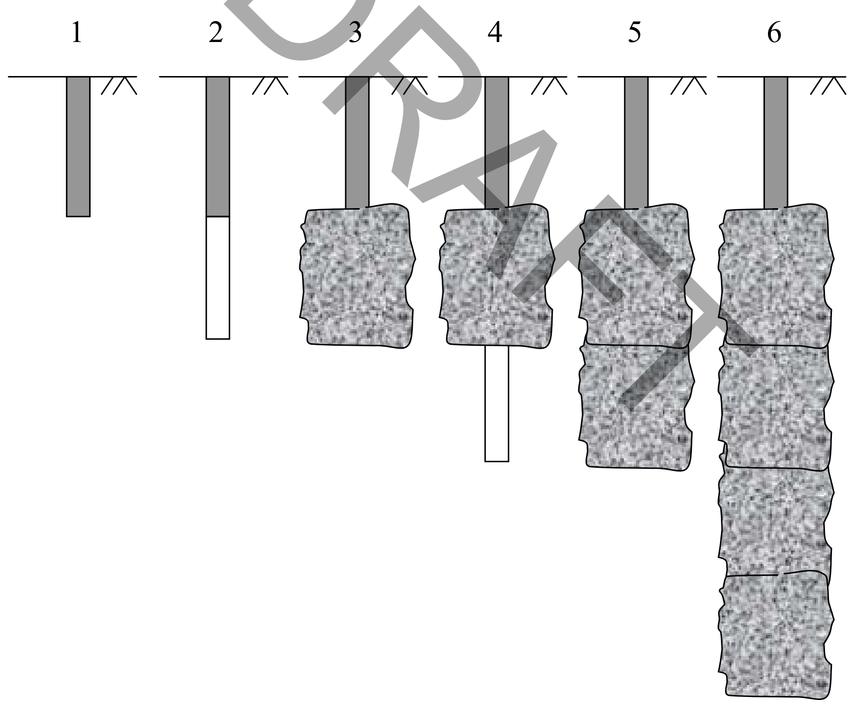


Stage-up Process: 1) install casing 2) retract casing to top of deepest stage, 3) grout 1st stage, 4) raise casing to top of next stage 5) grout next stage, 6) repeat steps 4 and 5 to top of improvement zone

Figure 4-2 Stage-up grouting procedure

Upstage grouting has substantial advantages in that it is the simplest, fastest, and least costly method. However, when grouting is used as a means of lifting foundation elements from relatively shallow (1-3 m) depths, the stage-up process can be difficult to control, especially when near-surface soils are particularly weak. An alternative grouting method termed the “stage-down” method may be used in cases such as these.

The process of stage-down grouting is shown in Figure 4-3. The stage-down method is based on casing only to the top of the first stage. The hole is then extended by drilling through the casing to the bottom of the stage, followed by grout injection. The next (deeper~~)~~ stage is then established by drilling through the casing and previously placed grout. The process is repeated for subsequent deeper stages. The stage-down method has several advantages in that each stage is verified by drilling through it, and the upper stages provide some additional confinement for the deeper stages, allowing shallow injection and providing a means of limiting surface uplift to a smaller, or more “focused” plan-view radius surrounding the point of injection. Because it requires more drilling, it is slower, and hence more costly.



Stage-down Process: 1: cement casing into oversized hole that extends to the top of the 1st grout stage, 2): drill through casing to extend hole to bottom of intended stage, 3): grout first stage and allow grout to set (usually overnight), 4): drill through 1st stage and extend hole to bottom of second stage, 5) grout stage and allow grout to set, 6) repeat steps 4 and 5 until hole bottom is reached (usually indicated by low grout take or high pressure).

Figure 4-3 Stage-down grouting procedure

The result of compaction grouting is a densified mass of improved soil that contains discrete masses of grout which might form continuous columns. The strength of the grout is usually not a factor where compaction is the objective, although the grout will usually provide some additional support as it typically has a strength greater than the surrounding soil. Structural applications of this kind of grouting fall into the larger classification of limited mobility displacement grouting which is beyond the scope of this document. For compaction grouting, the grout strength at the completion of injection need only be as strong as the improved soil. Strength beyond that of the surrounding soil is neglected in the evaluation of compaction grouting effectiveness.

4.2 Equipment

The equipment used in compaction grouting consists of a mixer, a pump, hoses, pipes and gauges. Additional components are the drilling equipment and casing extraction apparatus. The general arrangement of two typical mixing setups is shown in Figure 4-4 and Figure 4-5. It is important for all the piping and fittings to be tight and all changes in diameter to be gradual. Leakage in the fittings will result in water loss from the grout that can lead to blockages in the lines (dry-packing). All equipment must be rated for pressures in excess of those that are to be used, typically about 1,500 psi (10.3 MPa).

Figure 4-4 Batch mixing setup using pump with “horizontal paddle mixer”

4.2.1 Mixing

Grout mixing may be accomplished in individual batches (Figure 4-4), or by use of a continuous mixer as illustrated in Figure 4-5. Grout is commonly mixed on-site using batch or auger type continuous mixers. Obtaining grout from standard batch plants in

ready mix trucks is sometimes contemplated for large projects. Concrete plants, however, do not stock the special aggregate used for compaction grouting, and even if they did, due to the fines content it may not batch properly. Off-site mixing requires special measures, as stiff compaction grout does not mix or readily flow easily from the drums of typical mix trucks. Also, unless multiple pumps are operating, the grout must be delivered in relatively small quantities and possibly a retarder added so that it does not set during the relatively slow injection process.

Figure 4-5 Auger type continuous mixer commonly used in compaction grouting.

4.2.2 Pumps

Positive displacement piston pumps are used for compaction grouting~~.~~ They must be capable of pumping stiff grout at pressures up to about 10,350 kPa (≈1500 psi) at variable rates from 0 to 57 L/min (0 to 2 ft^3/min). Most compaction grouting is accomplished with conventional small line concrete pumps with material cylinders four inches in diameter or less. Use of concrete pumps with larger cylinders has been attempted, but not found to be very suitable due to non uniform output when operating at the very slow pumping rates required for compaction grouting.

4.2.3 Hoses and fittings

Either high pressure hose or a combination of hose and rigid steel delivery lines are used. They are most often 50 mm (2 in.) inside diameter although both 40 and 75 mm (1.5 and 3 in.) are sometimes used. Because the grout flows as an extrusion, all couplings and fittings should be the full inside diameter of the line. Wide sweep bends should be used rather than standard pipe elbow fittings. Clamp type couplings, as used in concrete

pumping, are generally used. To assure fresh grout at the grout hole, a reasonable velocity of grout through the delivery system is required. Use of delivery lines larger than 50 mm (2 in.) inside diameter should generally be avoided, especially where long lines are used and/or the environmental temperature is high.

A problem unique to compaction grouting is swelling of flexible hose lines when under sustained high pressure. The hose typically used is that manufactured and marketed for concrete pumping. In that use, the outlet end is always at zero pressure whereas in compaction grouting a positive head pressure always exists. Further, compaction grout flows through the delivery line as a stiff extrusion. A large pressure loss thus occurs when the expanded extrusion encounters the more rigid couplings and fittings in the delivery lines.

4.2.4 Safety on site

All construction sites are potentially dangerous. Compaction grouting has additional challenges because the process involves high pressure positive displacement pumps, small high torque hand held drills, large drills with casing handling equipment, both air and liquid hydraulic equipment, high pressure hoses and couplings, high pressure air compressors, sometimes rated at 400 psi (2.76 MPa) or higher, high capacity cement grout mixers (stationary and truck mounted), welding equipment, and all manner of large tools and smaller items. As stated previously, this standard does not purport to address the safety problems associated with compaction grouting. It is the responsibility of whoever uses this standard to establish appropriate safety and health practices and to determine the applicability of regulatory and non-regulatory limitation. However, safety is important and a few safety hazards that relate specifically to compaction grouting are highlighted in this section.

- High pressure hoses in poor repair
    - Hoses and fitting should be inspected prior to every use.
    - Worn hoses, defective fittings and any other defective equipment should be removed from service.
    - Care should be taken to keep hoses as straight as possible to minimize wear and back pressures.

- Handling heavy materials
    - Grout crews shall be trained in appropriate lifting techniques.

- Exposure to materials
    - Grout crews should be trained in the use of personnel protective equipment required for use in mixing and grouting.
    - Grout crews should be trained in the procedures to follow in the event of accidental exposure to chemicals, etc.

- Irritation of skin from cement based materials
  - Gloves should be worn for the mixing and grouting operation.

4.2.5 Casing

The grout casing should be of sufficient size to permit free flow of the grout with minimal head losses. Pipes smaller than 45 mm (1.75 in.) internal diameter are generally not used because they are prone to blockage. The casing must fit snugly into the hole to prevent grout from flowing up the annulus around it. Casing with an outside diameter of 65 mm (2.5 in.) or less will typically have sufficient friction, or can be wedged, to retain it in the hole during grouting. Due to their larger end area, casing larger than 65 mm (2.5 inches) generally require some means of external restraint to prevent being forced out of the hole by grout pressure acting on the end of the casing. Anchorage of larger casing is sometimes accomplished by using the weight of a drilling rig or front end loader as a reaction.

Individual joints of casing used in upstage injection should be no longer than about five feet in order to facilitate removal during injection, except in the rare instances where withdrawal is accomplished with a drill rig or similar machine. It must be of sufficient strength to withstand the very high withdrawal forces required. Additionally, it must also withstand the forces of driving when so installed. Conventional casing manufactured for core drilling is thus generally not suitable for compaction grouting. Well experienced contractors often use proprietary casing that has been proven to withstand the forces involved, and generally supplied in lengths of about 1 m (≈ 3 feet).

Where casing is installed by driving, or self-drilling, a disposable tip is used. The tip may be a point or cap for driving, but may have teeth or a fishtail plate to aid in drilling. The tip may also have openings to permit fluid circulation where water is used as a lubricant for circulation in the drilling. The casing must be withdrawn slightly and the tip knocked out prior to grouting. For downstage progression, the holes are drilled. This is usually accomplished with rotary-wash drilling using either a small drill rig (Figure 4-6) or handheld boring motor (Figure 4-7).

Figure 4-6 A small drilling rig

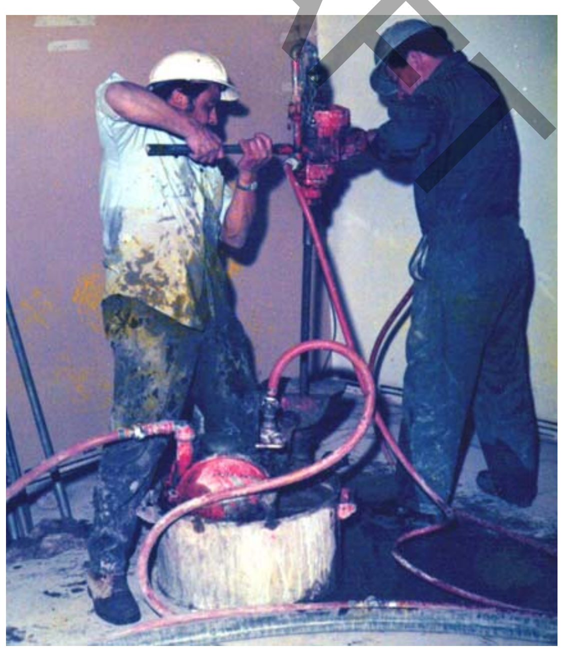


Figure 4-7 Drilling with hand held bore motor

4.2.6 Header

The header is a pipe that connects the grout supply hose to the casing and provides a place to mount a pressure gauge and/or transducer. The header for grouting is a pipe of the same diameter as the casing with a 90° large radius bend and a port for attaching a gauge saver and pressure gauge. The radius of the bend should be at least 3 times the pipe outer diameter to limit constrictions in the grout flow path. There should be no change in diameter between the pressure gauge and the casing, as the constriction would interrupt the flow and could cause errors in the indicated gauge pressure.

A typical compaction grout header is illustrated in Figure 4-8.

Figure 4-8 Typical compaction grouting header: note duplex jacks for casing extraction.

4.2.7 Fittings

Couplings and connections in the grout line should be constant inside diameter and should not protrude into the grout flow. They must be watertight under the full range of grout pressures to be used. Even minor leakage will allow water to be squeezed out of the passing grout which can result in plugging of the line.

4.2.8 Pressure gauges

Pressure gauges should have a dial with a minimum diameter of three inches so as to be plainly visible. They must be provided with a gauge saver or other means to prevent contamination with the grout.

4.3 Drilling

Grout holes can be established using a variety of techniques. Drilling might be by either hand-held pneumatic drill motors, or any type of compact or standard drill rig. Alternately, casings can be driven in place with pneumatic or hydraulic drivers, small pile hammers, etc. Regardless of the exact method employed, the casings must be of sufficient strength to withstand the placing and withdrawal forces and form a tight seal with the surrounding soil such that grout is not allowed to move upwards from the tip during injection.

Examples of casing being driven are shown in Figure 4-9. Placement by this method requires soil that if free of rocks, boulders, or debris, and such placement is thus generally limited to depths of less than about 15 m (≈ 50 feet). Driving exerts continuous dynamic forces which can cause fatigue breakage of the casing. This requires a generally heavier and more robust casing than is used in drilling.

Drilling is generally accomplished by rotary-wash procedures though rotary percussion equipment is sometimes used, especially in hard or rocky ground. In such cases, either water or air is used for circulation flush to remove the cuttings, although air circulation will tend to ravel the hole surfaces when used in relatively clean granular soils. Down-the-hole (DTH) hammers have been used for compaction grouting holes. These operate on either air or water, and in either case release very large amounts of exhaust product which provides ample circulation flush. Ground disturbance some distance from the hole has been experienced when using air operated DTH drills. While this can be of some concern, one must consider that the soil surrounding the hole will be subsequently grouted, likely healing any loosening which might have occurred.

Most compaction grouting is performed in and around existing structures. Compact drill rigs such as illustrated in Figure 4-6 are thus the most commonly used, although there is no limitation to size, and in extreme applications, large rigs have proven useful. Whereas the casing is most often pulled with a separate hydraulic withdrawal system as shown in Figure 4-8, some work has been accomplished with the drill rig remaining over the hole and used for casing withdrawal. Obviously, a large and powerful rig such as shown in Figure 4-10 is required for such applications. Conversely, where the holes are in isolated or difficult to access areas, hand held drills as illustrated in Figure 4-7 have been widely used. These are however generally limited to use in soils relatively free of large rocks or debris. In combination with special lightweight drill rod, these have been found effective to depths of about 30 m (≈ 100 feet).

(a)

(b)

Figure 4-9 Installing casing by driving with (a) a hand held hydraulic vibratory hammer and (b) a drop hammer

Figure 4-10 Large drill rig used to pull casing as well as drill hole.

5. SUBSURFACE INVESTIGATION FOR COMPACTION GROUTING

The purpose of the subsurface investigation for compaction grouting is to gain sufficient information to design a successful grouting program. The primary geotechnical parameters required include:

- Permeability
- Relative Density (or Soil State)
- Grain Size Distribution
- Compressibility/Consolidation
- Void Ratio
- Specific Gravity
- Unit Weight
- Shear Strength Parameters

Frequently index properties are used to estimate the above parameters, and to assess variability/uniformity of fine grained soils. For many routine compaction grouting projects index properties such as Atterberg limits, in conjunction with gradation analyses (sieve and hydrometer) and Standard Penetration Tests (SPT) are often adequate to estimate permeability, compressibility and shear strength. In situ tests such as the Cone Penetration Test (CPT) and Pressuremeter Test (PMT) are very useful in refining the engineer's understanding of strength, compressibility, density and void ratio, as well as the variability of the soils in both lateral and vertical extent.

A preferred test for density determination is the CPT (cone penetration test) in its modern variant the electronic piezocone with computer data logging; ASTM D3441-05 is a standard for this equipment. The CPT may be used within most commonly grouted soils, although it is ineffective in rocky soil, gravels, and strongly cemented soils. The test offers measurements at typically 3/4" (20mm) intervals with an accuracy and repeatability of better than 1%.

The CPT provides three channels of soil response data: the tip resistance (q_c), the sleeve friction (f_s) and the induced pore water pressure during the sounding (u_c). The in situ relative density can be estimated from these measurements. In the estimation of in situ relative density, the soil type must be allowed for because of, simplistically, compressibility. Sandy silts are more compressible than gravelly sands, and correspondingly have much less penetration resistance for the same relative density – the difference can be a factor of 3.

Special problem soils such as collapsing soils may require specialized tests to evaluate their behavior. This may include shrink/swell or consolidation tests. Additionally, for sensitive soils and situations requiring additional care, testing to determine the soil response to shearing is recommended.

Heterogeneity and variability of the subsoil directly impact the effectiveness of all grouting methods. The most significant focus of a geotechnical investigation is determining the extent and variability of the subsurface horizons. A sure road to

disappointment in a grouting program is to inadequately delineate the extent of a problem soil layer or to overestimate the extent of a horizon that is amenable to grouting. And because compaction grouting increases the weight of the treated soil mass appreciably, it is essential to confirm the depth to competent strata capable of supporting both the original loads and added weight of the grout.

5.1 Investigation planning

The ASCE "Geotechnical Baseline Reports of Underground Construction: Guidelines and Practices" (1997) provides useful guidance in the preparation and planning for geotechnical investigations, as does the Federal Highway Administration report, GEC5 (2002). One difficulty in planning an investigation for grouting is that the geotechnical investigation has often been completed before grouting is determined to be an option for the site. Two alternate approaches are described below. The first approach outlines some minimum requirements that can easily be incorporated into any geotechnical investigation. The second approach outlines more specific requirements that should be incorporated into a geotechnical investigation specifically for grouting design.

5.2 General investigations

The first type of exploration would apply to a case where general site knowledge is limited and the goal of the program is to develop an overall understanding of the site and its suitability for the intended use. Byle (2002) provides a good overview.

5.2.1 Data review

For all geotechnical investigations, some preliminary evaluation of site conditions is warranted. A review of past use(s) of the site, through a client interview or by reviewing historical maps or a Phase I Environmental Site Assessment (ESA) report can give valuable information relating to possible locations and extent of prior facilities and land uses that could produce conditions where grouting may be required. ESA's are often required for real estate transactions and usually contain detailed information on the past use of a property. These may include aerial photographs and fire insurance maps that give a good picture of prior site conditions. Geotechnical engineers should routinely ask for this information, since it may also give an indication of the presence of contaminants that might be encountered in borings or other field investigations.

Geological maps give information on the regional, local and site geology, depending upon their scale. United States Geological Survey (USGS) topographic maps can give an idea of areas of fill or regrading (depending on the date of the topography) and can be useful in evaluating the geomorphology of the area.. United States Department of the Interior Soils Conservation Service (SCS) Maps (http://soildatamart.nrcs.usda.gov) provide information on the surface soils and often include vintage aerial photographs that can be useful in evaluating changes at the site over time.

The client should always be asked for any previous studies and subsurface data available.

5.2.2 Sampling

All investigations should include representative sampling of all strata and should obtain and retain samples from each soil type encountered. This may be achieved using a driven sampler, of which the standard split spoon sampler is a popular example.

Additionally every investigation should have provision for obtaining undisturbed samples (e.g. using a Shelby thin-walled tube sampler or a piston sampler) in case they are required. Undisturbed samples should be taken in any strata where they are feasible. The cost of samples is nominal and it is easier to convince a client to pay for additional laboratory tests than to fund a remobilization to get samples that could have been obtained the first time out. Even if no testing is planned, samples should be taken and retained so that they can be tested later, if necessary. Representative samples should be taken from test pits as well as borings. Photographs or videotape of test pits should also be taken, since they provide specialty contractors with a much better view of the subsurface conditions than do logs alone.

5.2.3 Investigation limits

Establish limits and criteria for the investigation. This could include:

a. If not using continuous sampling, samples should be obtained at any change in strata. This is evidenced by any change in the rate or resistance to drilling, or a change in the cuttings returned.
b. Never terminate a boring in fill or soft soil. Borings must continue to a soil that is capable of supporting not only the existing or proposed structure and the body loads of the soil itself, but also the weight of the grout to be injected.
c. Verify refusal. Do not log auger or spoon refusal as bedrock unless coring, or other means, verifies this.
d. Where significant differences in subsurface conditions are found between adjacent borings, probes, pits, etc., consider additional exploration to define the limits and location of the transitions. For larger investigations, this can sometimes be accomplished simply by relocating the test borings during the investigation.
e. Make sure that the field engineer/inspector knows what the expected conditions are and to check with the engineer in charge if anything different is encountered.
f. Always obtain water level readings. Obtain 24-hour or longer stabilized readings wherever possible.
g. Determine a reference elevation for all borings. Grouting may be completed during construction, at which time the site may have been regraded. Elevations are essential to locate problem zones during grouting.
h. Determine accurate reference locations for the exploration points. Often

accurate survey coordinates are not obtained. In the absence of this accuracy, repeatable dimensions should be obtained and recorded on the location plan. These dimensions must be measurements from structures that will be present after the start of construction so that the boring logs can be related to a location on the site.

5.2.4 Laboratory testing

If grouting is being considered, soil type should be determined (e.g. ASTM D2487). This is usually achieved by performing moisture content, gradation analysis and Atterberg limits for all soil types encountered. Void ratio and unit weight should be obtained from undisturbed samples. Strength, compressibility and permeability testing are useful and should be provided where the soil response (accounting for the effect of pore pressure changes induced by dilation/contraction) could adversely affect adjacent structures or the effectiveness of the compaction grouting. Where organic soils are encountered, test for organic content.

Further descriptions of the applicability of laboratory tests is provided in Table 5-1.

5.2.5 Analysis and report

Where grouting is anticipated it is important to provide all information possible in the report. Include complete soil descriptions that appropriately characterize each stratum. Simplified descriptions such as "brown silty sand" are not sufficient. Describe fill materials in detail including all constituents identified in the field investigation. In the report identify the known limits of the area to be grouted, and the known or estimated properties of the soil which may include:

- Relative Density/Consistency
- Void Ratio
- Permeability
- Degree of Saturation
- Plasticity
- Gradation including D_{10}, D_{85}, and coefficient of uniformity
- Non-soil materials present
- Soil structure/geologic origin (e.g. varved/lacustrine, glacial till, rubble-fill, etc.)

For each parameter state whether it was measured or estimated, and the source of the information (e.g. test type). Where estimated or correlated, the methods for obtaining the information should be identified in the report.

When discussing the composition of a fill layer, consider not only the information needed to predict grout injection behavior, but also factors that may impact the drilling or pipe installation methods. Items such as wood or metal will have a great impact on the drilling.

5.3 Investigations for grouting design

Where there has been a preliminary investigation, or where it is known that compaction grouting will be required, the investigation should be more focused on the needs of the grouting program. This will extend beyond the basics needs of design discussed above. Factors to consider will also include the quality control (QC) methods which will be used. Often this stage of investigation can be an opportunity to collect baseline data for future verification testing. Byle (2002) provides a good overview.

5.3.1 Defining the purpose of grouting

Defining the purpose of the grouting may seem like an obvious step, but neglecting this is often the cause of a failed design. Compaction grouting can serve many functions and different information is needed to assess the feasibility of achieving different purposes. It is important to define what is hoped to be gained by grouting, and plan the investigation to gather the information necessary to achieve the desired goal. Some of the reasons for grouting may include:

- Improving soil strength or bearing capacity
- Preventing or arresting settlement
- Mitigation of the liquefaction potential of the soil
- Mitigating ground subsidence due to underground construction

5.3.2 Defining the mechanism of grouting

Identification of the specific mechanism, or mechanisms, by which grouting will achieve the defined purpose is essential to planning a complete investigation. This requires a knowledge of grouting technology to assess feasible approaches based on the preliminary geotechnical information. Most grouting methods, including compaction grouting, will increase soil strength if they are successful, although they achieve this by different mechanisms. A goal of the geotechnical investigation should be to determine sufficient soil parameters to define the feasibility of the grouting method, and provide sufficient information for design of the grouting program.

To properly plan the investigation, one must look more closely to assess the specific mechanisms that will be at work during and after the grouting. These may include generation of residual stresses, consolidation, elastic deformation, plastic deformation, displacement and migration of pore fluid, chemical reactions within the grout, and chemical reactions between the grout and the soil. Defining how these mechanisms work for each project requires the gathering of site information. The types of information that may be required, and the design purpose of the information, are summarized in Table 5-1.

Table 5-1 Site Information for Design

Information	Design Purpose
Geometry and characteristics of subsurface layers (in three dimensions)	Define limits and quantities of grouting.
Comprehensive logs of test borings	Characterize soil to be grouted and highlight areas of potential difficulties during both drilling and grouting.
Geometry of subsurface structures (e.g. tunnels, retaining walls, utilities, etc.)	Characterize interference and obstructions to grouting. Define limit to allowable subsurface movements.
Elevation of, or depth to, competent bearing material	Establishes depth of required treatment.
Vertical and horizontal moduli of subgrade reaction	Establish zones of influence and determine pressure limitations. Prevent unwanted "hard zones".
Consolidation parameters	Overconsoildation Ratio (OCR) and coefficient of consolidation may be used to estimate strength, permeability and pore pressure influences on grout
Pore Pressures	Existing excess pore pressures may be present in underconsolidated sediments that will affect grouting. Negative pore pressures may permit compaction grouting in cohesive soils.
Permeability	Assess pore pressure dissipation to select optimal pumping rates.
Unique characteristics of non-soil materials	Grout interaction (physical and chemical). Strength of grouted product.
Organic content	Potential for future movements due to continuing organic decomposition. Affects curing and grout strength.
Soil chemistry	Grout chemical interactions. Impacts of contaminants if released to surface.
Sensitivity of surrounding structures to movement, loadings, damage by grouting activity	Establish influence zones, cutoff criteria and limits on the grouting. Define monitoring requirements.
Liquefaction potential	For seismic remediation, define initial and target relative density for design and quality control.

Information	Design Purpose
Critical failure mechanisms that could be precipitated by grouting	Risk assessment. Define grouting sequence, volumes and injection rates.
Moisture-Density condition	Evaluate current saturation and expected volume change to assess potential for generation of excess pore pressures during grouting
Soil Fabric/ Secondary Structure	Soil fabric and cementation effects may define pressure response of the soil to displacement.
Sinkholes and solution features	Establish limits of grouting and quantity estimates.

It is impossible to list all of the parameters that would be needed for all projects on Table 5-1 because of the limitless diversity of conditions that grouting can address. Each project will have unique constraints that have to be established and investigated.

5.3.3 Determine the extent of grouting

The investigation should specifically identify the limits within which grouting is needed. It is important to remember that in soils, even grouted soils, the stresses dissipate outward in all directions. The investigation should explore beyond the effects of the grouting. Where the purpose of grouting is to strengthen the soils, the investigation should extend to the limits of the influence of the stresses that exceed the ungrouted soil capacity.

Often grouting is performed to mitigate an area of loose, soft, or otherwise unacceptable soil. It is important that the investigation is both sufficiently broad, and sufficiently detailed, to define the limits of the unacceptable area. The grouting designer and contractor must know what the conditions will be at the periphery of the grouted area. These perimeter conditions will define the amount of effort (and cost) required to contain the grout and meet the project objectives within the target area. Conditions at the perimeter of the grout injection will also influence the magnitude of densification, ground heaving or high lateral pressures that develop beyond this perimeter.

5.3.4 Select exploration methods

Select methods of exploration and testing that will provide information on subsurface conditions specifically related to the mechanism and extent of grouting. Select methods of investigation that will obtain in situ data, including soil samples, necessary to establish the following:

- Limits of the zone to be grouted
- Spatial variability of the materials within the zone of grouting
- Boundary conditions for the grouting
- Soil permeability
- Soil classification

- Soil state (or relative density)
- Appropriate soil chemistry
- Details of all pertinent constituents of the soil (including large particles)
- Compatibility between the mechanism for compaction grouting and the soil
- Special geologic or other conditions affecting the grouting
- Appropriateness of proposed drilling methods

Background data on soil characteristics related to the desired outcome of the compaction grouting should also be obtained in the investigation. It is prudent to use some of the proposed verification methods during the exploration to establish a baseline for comparison with the post-grouting verification testing. For example, if CPT testing was proposed to evaluate the soil improvement by compaction grouting, it is imperative to have baseline data available for comparison. This aids in establishing realistic performance limits, and in the setting of reasonable target values for performance specifications. Of particular concern for the QC program will be to identify the normal site variability given by the verification tool. (For example, if the SPT will be the QC tool, what is the existing variation in N_{60} value, and will the acceptance criteria be to increase this average or median value by a certain margin, or to meet a target value.)

Geophysical tools should be considered in conjunction with conventional intrusive methods where more continuous profiles of subsurface conditions are desired and where the site conditions can be accurately detected and depicted with the geophysical methods.

5.3.5 Logging of field investigation

Comprehensive logs of all test borings should be provided. These are not only required for design purposes, but are also of crucial importance in estimating the cost and time required to complete the work. All drilling anomalies and obstructions encountered should be described in detail. Where rocks or cobbles are encountered, size and hardness should be stated and methods used to penetrate or displace them described. The presence of organic matter or other content foreign to the site should be included.

In the case of filled ground, depth of contact with the underlying natural material should be provided. Experience has shown in the case of apparent fill failures, the culprit soils are often in the bottom portions of the fill or the underlying natural materials. Special care should be given to this zone, and the presence of organic materials, nested boulders or other anomalies noted. Where rotary wash drilling methods are being used, any loss of drill fluid circulation should be reported. As stated previously, all borings must extend to competent geomaterials capable of supporting the overlying soil, any overlying structures, *and the weight of the injected grout.*

Where geophysical methods are used, record the parameters of the tests and arrangement of equipment used. Retain raw data for further analysis and interpretation that may be needed. Confirm all geophysical methods with borings or test pits. Report confirmation points with geophysical data.

5.3.6 Field inspectors

Field inspectors for a grouting investigation, just as for any other geotechnical investigation, must be informed about the purpose of the investigation and the parameters of interest. An agreed and consistent methodology for reporting soil properties should be used to ensure consistency, such as ASTM D5434-03 (Standard Guide for Field Logging of Subsurface Explorations of Soil and Rock) and ASTM D2487-06 (the Unified Soil Classification System).

Inspectors should be cognizant of the purpose and mechanism of the drilling and grouting so that they can recognize adverse or limiting conditions when they are encountered, and modify the investigation as required. Inspectors for grouting investigations must be diligent to note everything related to the subsurface exploration, in addition to logging samples.

5.3.7 Flexibility to accommodate the unexpected

Ground conditions are not always as anticipated. The exploration program must be flexible to accommodate the unexpected. Also, creativity may be necessary to ascertain the characteristics of materials that will not stay in samplers, are too large to sample, or just do not lend themselves to conventional investigation techniques. This may entail techniques such as: over-driving spoon samplers, using Dennison or Piston samplers, taking block samples from test pits, doing field scale direct shear tests, preloading, geophysics, injecting solution grout to solidify the ground and then sampling using a Shelby tube to retain loose sand, using dyes, using an air-track drill, using a Becker Hammer, etc. The goal of the investigation is to identify the site conditions well enough to develop a grouting program, not to follow a standard investigation plan.

There are times when it is absolutely necessary to think outside of the box!

5.3.8 Record and report everything

It may seem a routine occurrence, but things like the loss of drill fluid circulation or getting no cuttings during auger drilling, can make a substantial difference in the interpretation of a boring log. If the driller is wearing out bits rapidly, if the rate of hole advance drops or increases, this should be noted on the logs. The conditions affecting the drilling of test borings will affect the drilling of grout holes. Drilling can make up more than 50% of the total cost of a grouting project. If there is a rock outcrop across the street or down the hill; if your borings hit groundwater at 1 meter, but the site is 20 feet above a dry creek bed; if a site worker tells the inspector that there was a 2-meter diameter sewer abandoned within the site; if you notice that the north side of an adjacent building has settled; if gas came out of the hole ... REPORT IT! The grouting designer and contractor need to have as clear, or clearer, an understanding of subsurface conditions as the engineer who writes the geotechnical report.

5.4 References

American Society of Civil Engineers (1997). *Geotechnical Baseline Reports of Underground Construction: Guidelines and Practices*. ISBN: 0-7844-0249-3.

American Society of Testing and Materials Standard (2000). *D2487-06 Standard Classification of Soils for Engineering Purposes (Unified Soil Classification System)*.

American Society of Testing and Materials Standard (2003). *D5434-03 Standard Guide for Field Logging of Subsurface Explorations of Soil and Rock*.

Byle, M.J. (2000). Geotechnical Investigations for Grouting in Soil. In *Performance Confirmation of Constructed Geotechnical Facilities, GSP No. 94*, pp. 427-440. Presented at Geo-Institute Specialty Conference on Performance Confirmation of Constructed Geotechnical Facilities held at the University of Massachusetts, Amherst, MA, April 2000.

Federal Highway Administration (2002) FHWA-IF-02-034 *Geotechnical Engineering Circular No. 5 - Evaluation of Soil and Rock Properties*.

6. DESIGN OF COMPACTION GROUTING

6.1 Introduction

The ability to inject grout of predictable quantity and quality into the subsurface will be affected by the physical factors of the subsoil into which it is injected, including:

- Homogeneity of the soil (affects the shape of the grout mass injected)
- The presence of secondary structure providing preferential paths for grout
- Cohesive and frictional strength of the soil
- Compressibility of the soil
- Propensity of the soil to build up and dissipate pore pressures (soil permeability)
- Presence and proximity of subterranean structures or openings
- Isotropy/anisotropy of soil properties (minor effect for compaction grouting)
- Existing stress field in the soil
- Free surfaces

Based on this information it is possible to estimate the grouting pressure, grout injection rate, and injected volumes required to achieve the desired densification. The accuracy of this engineering estimate will be related to how accurately the material properties of the in situ soil are known and the appropriateness of the analyses. The precise grouting parameters will not be known however, until at least some of the grouting has been performed and even then they can vary in different areas of a particular site.

This section discusses the design of compaction grouting to achieve a controlled injection of grout resulting in the desired densification. Many different processes need to be taken into account for a full understanding including (and this is not an exhaustive list):

- The pressure – volume behavior of the in situ soil that is being grouted
- The effect of injection rate on the soil's behavior
- Pressure losses in the grout delivery line
- The arrangement of the grout holes
- The injection sequence

Broadly, when contemplating ground modification of any sort, and including compaction grouting, two questions arise; what can be achieved? And how can this best be done? Section 6.2, considers how the shape of the compaction grout bulb is typically idealized for engineering analysis. This is important because the type of soil movement, and specifically whether the soil volume changes are mainly shear or mean stress induced, has a large influence on the predicted grouting effectiveness. Section 6.3 considers the attributes that make a soil suitable for compaction grouting.

The different processes occurring during grouting are summarized in Sections 6.4, 6.5 and 6.6. Injection sequencing and spacing is discussed in Sections 6.7 and 6.8. A simple method for estimating grout quantities is presented in Section 6.9, with the effect of confinement due to secondary grout holes and adjacent structures given in Section 6.10. The importance of understanding what is meant by grout refusal, and the importance of

keeping records are discussed in Sections 6.11 and 6.12 respectively. Additional information on verification is provided in Section 8.

6.2 Geometric idealization of the grout mass

During compaction grouting the applied stress at the grout:soil interface exceeds the yield stress of the soil and permanent displacements occur. As grout is injected, the soil substrate is displaced and plastically deformed in a limited zone around the injected grout. Beyond this zone of plastic deformation the soil reacts elastically. The relative size of the elastic and plastic zones depends on the amount of grout injected and the characteristics of the soil.

Figure 6-1 Compaction grouting test column extraction using internal reinforcing bar

It is uncontroversial to assume, for uniform soil properties, that the expansion of the grout bulb will be radial from the injection location. This reduces a complex 3-D situation to something very simple with one distance variable: radius. It is usually assumed that for field grouting applications, the applicable radial expansion is cylindrical. This follows for two reasons. First, typical staged grout column construction results in restraint above and/or below the expanding grout bulb. The pre-existing grout bulb acts to prevent vertical grout expansion. Second, for sands and silty-sands (commonly grouted soils) the lateral in situ stress is typically lower than the vertical stress (i.e. $K_0<1.0$). Therefore the direction of least resistance for grout flow is laterally.

The cylindrical shape of the grout expansion has also been observed in practice. Figure 6-1 and Figure 6-2 show excavated compaction grout columns.

So far the idealizations discussed are only applicable to single grout mass expansions. Most grouting projects involve multiple grout holes and the soil between these grout holes is affected by multiple grout expansions. Multiple grout holes make the assumption of symmetric displacements around the grouted hole invalid. Therefore, grouting analyses ought to be conducted using a 3-D representation of the grout holes, accounting for the sequence in which the grout holes are to be grouted.

Figure 6-2 Excavation exposes top of Grout column

To date this level of analysis is not routinely carried out in general practice, but should be considered on sensitive jobs.

6.3 Suitability of in situ soil for compaction grouting

The major component of soil improvement from compaction grouting is the induced increase in density of the in situ soil. For a soil to be suitable for compaction grouting:

- the soil must densify during grout injection, and
- the grout must displace, not permeate or hydraulically fracture, the in situ soil as discussed in Chapter 3.

The first requirement is that soils must densify during grout injection. During grouting the in situ soil is subjected to an increase in the mean stress causing a corresponding compression of the soil. At the same time the in situ soil is also being sheared, causing a change in volume due to dilation/contraction. The shear component of volume change is generally much larger than that caused by the increasing mean stress – when sheared sand is commonly 3 to 5 times more compressible than the isotropic normal compression response (see Jefferies & Been 2000). Therefore for compaction grouting to be effective the soil must become denser when sheared.

One of the most widely used measures of density in the geotechnical industry, and hence of the propensity for a soil to dilate or contract during shear, is the relative density, D_r. Relative density is defined as

$$D_r = \left(\frac{e_{max} - e}{e_{max} - e_{min}} \right)$$

where

e = void ratio of the in situ soil
e_{max} = maximum void ratio of the in situ soil
e_{min} = minimum void ratio of the in situ soil

The relation between the value of relative density and the soil description originally given by Terzaghi and Peck (1948) is reproduced as Table 6-1.

Table 6-1 Relationship between Relative Density and Soil Description

Relative Density (%)	**Descriptive Term**	**Approximate ψ**
0 – 15	Very loose	+0.1
15 – 35	Loose	0.0
35 – 65	Medium Dense	-0.05
65 – 85	Dense	-0.1
85 – 100	Very Dense	-0.3

Relative density may also be directly, although approximately, related to other field density measurements; for example CPT density interpretations. However, although widely used, relative density is not an accurate measure of the propensity of a soil to densify when sheared. The results of even a modest laboratory test program can be used to show that relative density may be misleading. It is well known that dilatancy can be suppressed by increasing the mean stress. In addition, when dealing with sands with a few per cent silt, one mixture at 40 percent relative density can dilate while another mixture at 60 per cent relative density can be contractive (Been & Jefferies, 1985). One alternative which avoids these errors is the state parameter approach. The "state parameter", ψ, is independent of pressure, mineralogy, etc (see Been & Jefferies 1985, 1986 for more details). Hence state parameter, although less common, is used in this section as the main measure of the state of the soil. However the descriptions in Table 6-1 may be used to loosely link ψ and D_r.

The state parameter, ψ, is defined as:

$$\psi = e - e_{crit}$$

where

e_{crit} = void ratio of the soil at the critical state at the same mean effective stress

The critical state for a soil is reached at very large shear strains, where the void ratio of the soil remains constant with increasing shear. At the critical state ψ is equal to zero. At lower strain levels initially dense soils ($e < e_c$ or $\psi < 0$) dilate when sheared, while looser soils ($e > e_c$ or $\psi > 0$) compress when sheared. Soils initially at $\psi = 0$ show no net change in volume due to shearing. Hence the state parameter may be used to predict the potential for densification during shearing.

At the end of a compaction grout injection stage, strains close to the grout bulb will be extremely large and the soil will likely have reached the critical state. Therefore, the looser the soil, the greater the potential densification to be achieved by compaction grouting. Sands with densities in the range *dense* to *very dense* will likely dilate during compaction grouting and the procedure should not be used in such soils.

The second requirement, that the grout displace the soil and not permeate into the pores often excludes soils with large grain sizes, such as gravel. Hence gravels are rarely compaction grouted, although with very slow injection rates densification may be possible. Further, the soil must at least partially drain during grouting.

The requirement for at least partial drainage usually excludes normally consolidated high plasticity clay soils from being densified using compaction grouting, because for any common and economically justifiable grout injection rate, clays exhibit an undrained response. Calculations indicate that even though the mean stress is increased around the grout bulb, subsequent consolidation as the excess pore pressures dissipate leads to only small density changes during grouting (Kovacevic et al, 2000). For compaction grouting to be effective is such soils, intermittent injections using very low pumping rates are required. The pore pressure must be continuously monitored during injection and any pressure increases recovered prior to further injection. On the other hand, modest drainage with mixed soils of low plasticity leads to very effective grouting despite the presence of substantial excess pore water pressures at reasonable injection rates (Jefferies & Shuttle, 2002).

In summary, compaction grouting can be effective for sandy gravels through to low plasticity clayey soils when these soils are loose to medium dense (i.e. when the soil undergoes a net contraction when sheared from in situ to large strain failure conditions). The procedure has been successfully used in high plasticity clays, however both intermittent pumping and very slow injection rates are required which becomes very expensive and limits such work to very special requirements.

6.4 Pressure-volume behavior of in situ soil

Change in soil density caused by shearing the soil and increasing the mean pressure is the mechanism of compaction grouting. Soils being considered for grouting usually fall within the range of behaviors shown on Figure 6-3, this figure being for the conditions measured in drained triaxial compression.

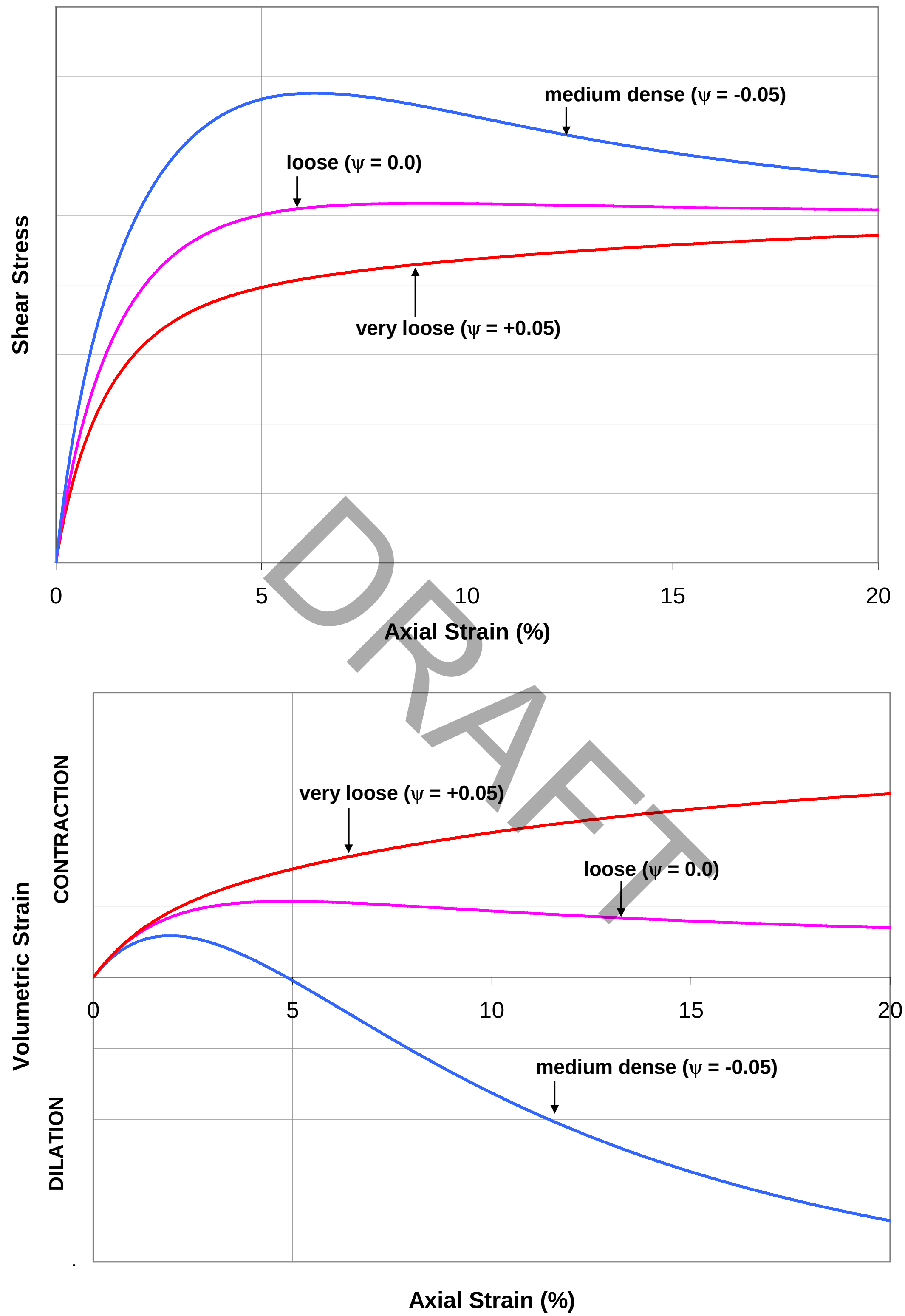


Figure 6-3 Typical soil responses in triaxial compression

The behaviors shown on Figure 6-3 are characterized by the state parameter. Figure 6-3 shows linked plots of shear stress (normalized by initial mean stress) plotted against axial strain, and the volumetric strain against axial strain.

Very loose soils ($\psi > 0.05$) are contractive and amenable to significant densification during grouting. Loose soils ($\psi \approx 0$) are also somewhat contractive because of the change in the critical void ratio as the mean stress increases. Loose to medium dense (lightly dilatant $\psi \approx -0.05$) soils show initial contractive strains followed by the onset of dilation. Whether dilation overcomes this initial compression depends on the mean stress increase and the soil's compressibility. The soil's material properties, strength for example, will affect the relationship between stresses and strains that develops, but the basic pattern remains that shown on Figure 6-3 and this is essentially a function of the state parameter (or relative density).

The behavior the soil exhibits in situ depends on its relative density or state in exactly the same way as it does in the triaxial test – hence assessing the in situ relative density is the first step to any analysis. Commonly this will involve penetration tests. The SPT (standard penetration test) is widely used and is simple to do. It is also highly variable and imprecise – hence not a good test on which to base engineering design. These problems are exaggerated if the SPT data are not corrected for the energy of the equipment used (Skempton, 1986).

As discussed in Secion 5, a preferred test is the CPT (cone penetration test) in its modern variant the electronic piezocone with computer data logging. There are sophisticated ways of determining in situ state and relative density from CPT data given knowledge of some other soil properties (e.g. slope of the CSL line). Been et al. (1987) provided the first methodology for this while Shuttle & Jefferies (1998) evaluated this framework and presented a systematic method for interpretation of state and density from the CPT. The difficulty is that for most field situations the required test data to use these sophisticated methods won't be available, but they can be justified on sensitive or important projects.

There is a long history of inferring soil type from the CPT (e.g. Schmertmann, 1978, Douglas & Olsen, 1981, Robertson & Campanella, 1983). Plewes et al. (1992) extended the soil type classification scheme to include quantitative estimates of the state parameter. Figure 6-4 shows a proposed relationship between cone resistance and state or relative density. This chart uses a familiar CPT soil type interpretation chart as its base and lays relative density contours on it, providing a simple interpretation of CPT data. The limitation of this approach is that the correlations were originally developed from testing on clean sands, and the chart can be misleading if used with materials such as calcarious soils, or sands containing high proportions of easily crushed grains (feldspars for example), and in these situations it will be necessary to obtain the supporting data for a better method.

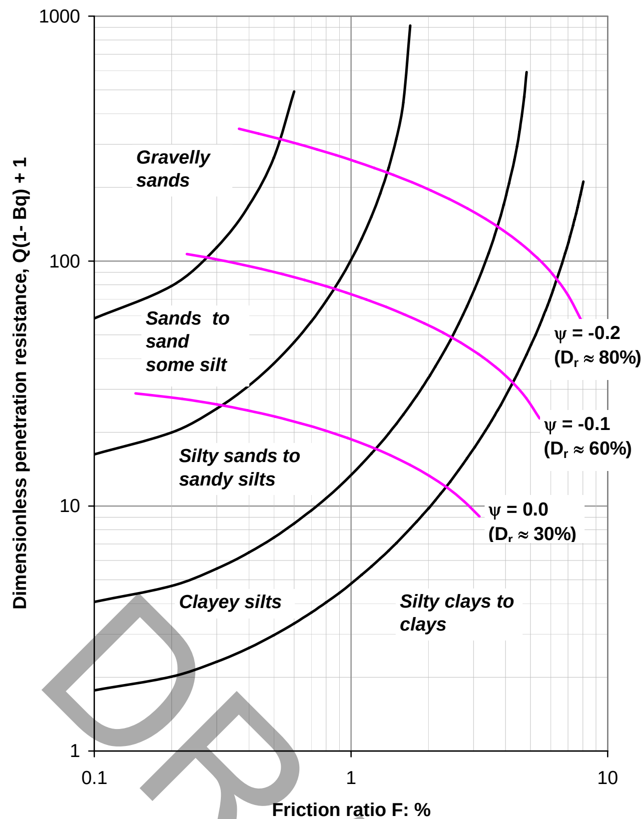


Figure 6-4 Cone resistance versus friction ratio

In the end, grouting is expensive and if confidence in the achieved densification is required there is no substitute for testing the target horizon to determine the shear modulus profile, the compressibility of the soils involved, and to estimate the relative density, or preferably the parameters of its critical state. Especially on sensitive sites, reasonable analyses require measured data, not guessed properties.

6.5 Pressure-volume behavior of grout

The grout design is critical to a successful compaction grouting project as discussed in Chapter 3. Despite the practical importance of the grout mixture, no analysis to date has looked at the grout behavior itself. Grouting is assumed to be an essentially inert way of applying pressure to the soil, at least for analysis of grouting effectiveness.

It is important not to lose sight of the limitations this assumption places on any analysis. The lack of understanding of grout behavior limits our understanding as to why hydrofracturing occurs in some instances and not others, which in turn limits our ability to develop and improve the grouts used. We are dependent on accumulated experience alone from which it is dangerous to deviate. On the other hand, it is clear that grouts are themselves soil mixtures and that water may move out of them (i.e. bleed) as the grout exits the injection pipe. This means that:

- The volume of the grout reduces after grout fluid permeates the in situ soil; therefore the grout bulb size is overestimated if the pumped grout volume is used.
- The boundary condition at the grout/soil interface is usually assumed in analysis to be impermeable. This is inaccurate if bleeding occurs, and this permeable grout soil interface leads to a pressure loss due to seepage of pore fluid beyond the grout bulb. The pressure loss is a function of the internal permeability of the grout, the size of the grout mass injected, and the permeability of the soil. The mechanics and nature of this grout-soil interaction has not been addressed in the literature and no accepted means of estimating it exist. Therefore in practice, the grout pore fluid pressure losses are usually ignored.

A better understanding of in situ grout behavior is crucial to improving the industry's understanding of compaction grouting.

6.6 Pressure losses in the casing

Controlled grouting requires that injection pressures and flow rates be measured (and recorded/displayed) during grouting. Practically, this means a pressure gauge and preferably transducers located at the surface. Analyses on the other hand start with the expansion of the grout bulb at the base of the injection pipe. There is then a disconnection between what we can practically measure and what we are analyzing, the disconnect arising from what happens to the grout as it moves down the grout pipe.

Not all of the pressure applied by the grout pump is reflected as stress on the soil. Pressure is required to push the grout through the grout lines, as can be observed by the pressure difference measured between an in-line pressure transducer and a transducer at the injection header (Figure 6-5). In this case, the in-line pressure was measured at a grout flowlogger, a device used to record grout pressure and flow during production. The logger was positioned 22.9 m upstream of the injection header, and 15.25 m downstream of the grout pump. The losses will depend on the length and configuration of the injection system (e.g. hose or pipe, size, number and radius of bends and elbows, and the diameter and wall type, etc.), the rate of injection, grout rheology, injection pressure, and other factors. Three main sources of pressure losses are injection losses, line losses and pressure loss due to seepage of pore fluid beyond the grout bulb. Injection losses and line losses are primarily related to equipment and grout properties. An additional pressure loss due to seepage of pore fluid beyond the grout bulb was discussed in Section 6.5. As no accepted means of estimating this loss exist, in practice it is usually ignored.

The usual approach for measuring the injection and line losses is to measure the pressure loss in the pipe by laying a length of pipe out on surface and pumping grout through it. This then gives an offset pressure used to relate the grout bulb pressure to that measured at the surface (after also allowing for a calculated pressure head from self weight of the grout). Where very deep grout holes are required, the surface approach to calculating line losses contains some errors because the pressure in the grout near the surface differs from that at depth, resulting in different saturation and void ratio.

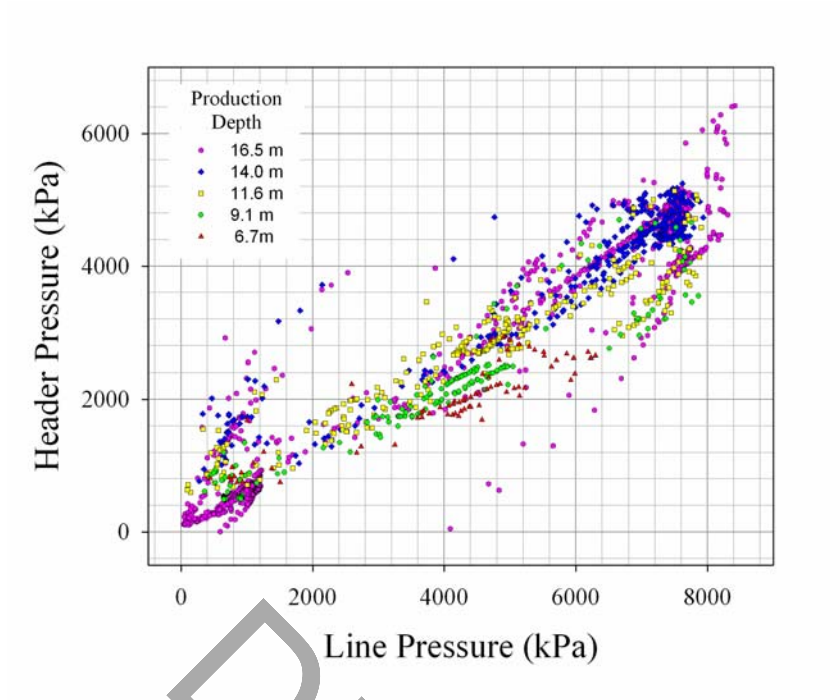


Figure 6-5 Pressure drop relation between the flowlogger and grout injection header (Geraci, 2007)

Despite this lack of detailed information, for many soils the pressure loss appears to be small compared to the injection pressure and hence the conventional approach of a simple pressure offset between hole collar, and injection point is reasonable.

6.7 Injection sequence

Analyses on soil behavior during grout injection have concentrated on the ground response to grout in a single hole. However, these same analyses also show a great dependence on boundary conditions and particularly the distance to stiff ground. This means that grout hole spacing, and whether it is a primary or secondary hole, is of prime importance. The secondary holes already have densified ground around them (due to primary grouting) and this denser ground provides a reaction which enhances the effectiveness of the grouting. Although by no means fully explored yet, analyses to date suggest that a disproportionate amount of grouting effectiveness arises from the "secondary" holes. Grout hole sequencing is therefore an important control. The optimum arrangement of grout hole sequencing is not known, but experience shows that isolation of the area to be improved and the typical primary/secondary injection sequence is very effective.

To analyze multiple holes at the same time requires a 3-D software package. Hence these analyses are very rare. To account for the stiffness of the pre-existing grout holes in a typical 2-D axisymmetric analysis, cylindrical cavity expansion of a single grout hole is

analyzed with a stiffer soil added at the radius of the primary grout holes to mimic the increased resistance.

On sloping ground, prior to general grouting, one or more containment rows of holes should be injected on or at the base of the slope to act as a buttress. Similarly, grout zones may be used to stabilize areas of displacement weakness.

6.8 Injection spacing

The required spacing of injections is determined based on the zone of influence, degree of control required and purpose of the grouting. The spacing of grout injections has been reported to range from 2.4 m (8 ft) to 3.6 m (12 ft) (Warner 1982), 2.5 m (8 ft) (Bandimere, 1997), 1.8 m (6 ft) (Stilley, 1982). However, it is important to note that too high a grout injection rate can detrimentally influence the amount of grout injected at an individual grout hole, thereby increasing the number of grout holes required (i.e. closer hole spacing). At higher injection rates the in situ soil may behave in an undrained manner. An undrained in situ soil response results in poorer densification, and the limit pressure is reached at lower injection volumes. Hence as the soil becomes more undrained less densification occurs at each grout hole.

In general the selected spacing should be determined from site-specific conditions. The sensitivity of the site to movement and the soil in situ dilation/contraction behavior will determine the largest injection that can be safely made. The diameter of the injected mass is dependent on the starting density, required improvement and the rate of injection. Grout hole spacing is typically on the order of 3 to 6 times the predicted mass diameter.

6.9 Estimating grout quantities

Estimating the quantity of grout required is a daunting prospect for most grouting projects. By far the largest complaint of owners is that the design consultant underestimated the grout quantities. The grout quantity can be reliably controlled and predicted only if sufficient in situ soil information is available, if the grout consistency and injection methods are properly specified to limit mobility of the grout, and the engineer takes an active role in quality assurance, control of the injection process and verification of quantities during grouting. When the grouting is properly controlled, the quantities of grout required can be estimated with reasonable accuracy using very simple methods if sufficient information about the existing soil conditions is known. Unfortunately, while good grouting practice improves grout volume estimates, many compaction grouting projects involve soils of variable type and/or density and sufficient information on existing soil conditions can be difficult to obtain.

6.9.1 Densification

To achieve densification during compaction grouting it is first necessary to ensure that during shear the volume change of the in situ soil in the zone of influence will be predominantly contractive. Although not appropriately treated by compaction grouting, dense soils will dilate during grouting, resulting in a looser soil (see Section 6.3 for more details).

If compaction grouting is appropriate, a simple approach to roughly estimating the quantity of grout needed for densification is to compute the volume reduction required to achieve a target density. Consider the example in Figure 6-6. In this example it is desired to obtain a minimum dry density of 1600 kg/m^3 for the full thickness of the fill in Layer 2 under the building footprint and 3 m beyond the building limits. Increasing the dry density from 1400 kg/m^3 to 1600 kg/m^3 would require a 14.3 % increase in density. This increase in density corresponds to a 12.5 % reduction in volume of the soil mass (from assuming that the mass remains constant and knowing mass = volume * density, if the initial and final volumes are Vol_i and Vol_f respectively. Then $Vol_i * 1400 = Vol_f * 1600$, giving $Vol_f = 1400/1600\ Vol_i$ or $Vol_f = 0.875\ Vol_i$ – a reduction of 12.5%). This volume reduction is achieved by displacing (and therefore densifying) the soil with grout. To compute the volume of grout required, multiply the volume of soil to be improved (16 m x 16 m x 3 m deep = 768 m^3) by 12.5 % (the reduction in volume). This gives the total volume of grout needed to be 96 m^3. Typically this would be injected in vertical holes spaced 2 m to 4 m apart. Assuming a 2.5 m hole spacing, this would require approximately 41 grout holes injected at the average rate of 0.78 m^3 of grout per linear meter of injection hole.

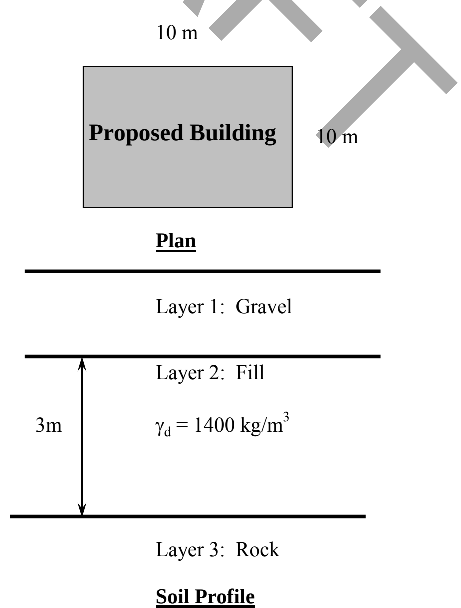


Figure 6-6 Example compaction grouting problem

6.10 Limitations on grout injection

Many factors affect the amount of grout that can be safely and controllably injected. These include:
- confinement
- movement sensitivity of nearby structures
- pumping rate
- special placement requirements

6.10.1 Soil confinement

Grout, even very stiff grout, will conform to the stress and stiffness conditions in the soil. Homogeneity and isotropy conditions will affect the shape of the injected grout mass and thus the control of injection. Non-homogeneous and anisotropic subsurface conditions will, by and large, yield non-homogeneous and anisotropic grout masses.

Where there is little confining stress, very slow pumping rates must be used. Should the rate be excessive, the surface of the ground may heave and/or fracturing occurs. The ideal cylindrical shape resulting from properly staged injection at appropriate pumping rates is shown in Figure 6-7.

Some typical shapes are illustrated in Figure 6-8. Other unusual shapes may result from various combinations of grout properties, stress states, stratigraphy and subsurface obstructions (Figure 6-9).

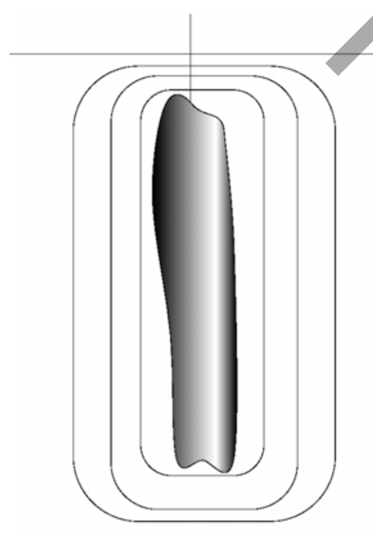


Figure 6-7 Idealized radial distribution of grout in a homogeneous soil

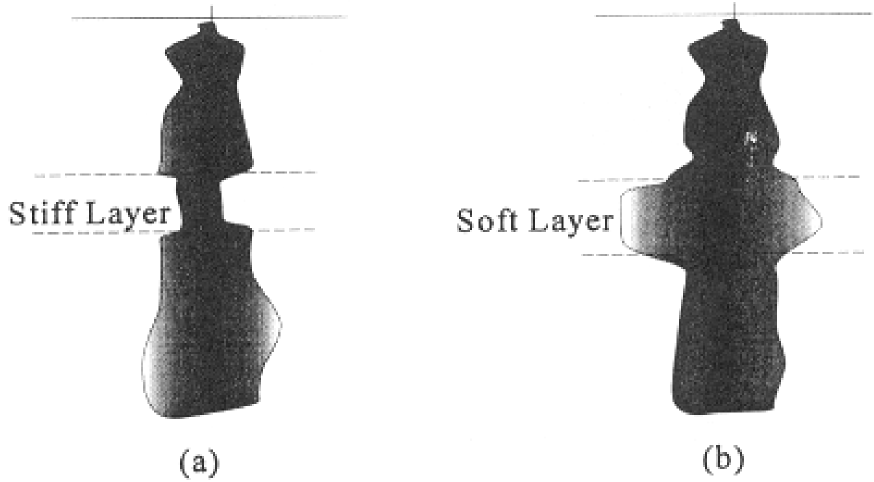
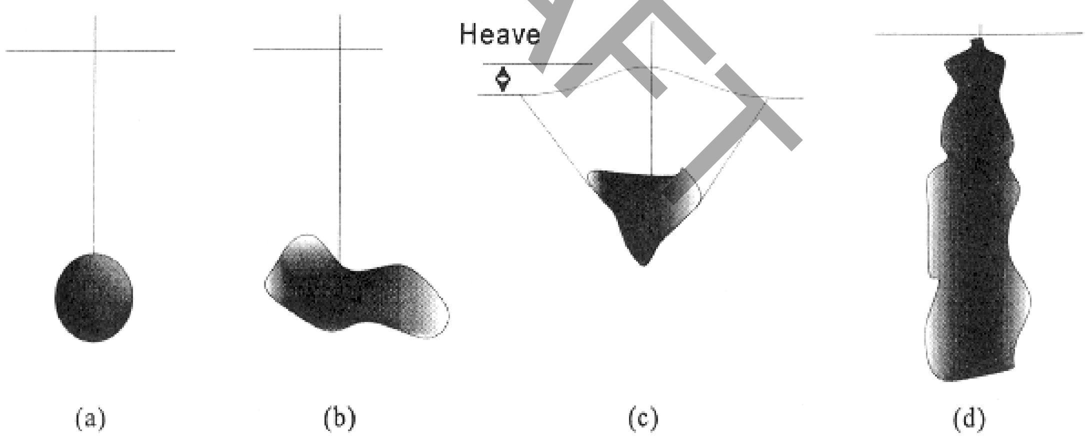


Figure 6-8 Influence of soil layering on column shape (a) stiff layer causes reduced cross section, (b) soft later produces enlargement (Byle, 2000)



(a) Ideal sphere at depth in homogeneous granular soil.
(b) Irregular shape in non-homogenous stratum or filling a void.
(c) Quasi- conical shape due to lack of overburden confinement.
(d) Columnar shape by controlled staged injection.

Figure 6-9 Injected grout shapes (Byle, 2000)

6.10.2 Influence on structures

Grouting may influence structures by applying loads and inducing movements. Although not considered compaction grouting, it is frequently desired to raise a settled structure as well as arrest movement. In other circumstances the aim is to densify the soil without impacting overlying or adjacent structures.

Movements induced in the soil by compaction grouting are controllable, and the magnitude of any such movements will be dependent upon the grout injection rate. Slower injection rates will result in a greater quantity of grout being injected prior to the initiation of movements. When movement does occur, however, it will in general be proportional to the volume of material displaced, i.e. the volume of grout injected or "take" after the movement started.

The volume of soil displaced will be slightly less than the volume of grout due to the escape of pore fluid from the grout and volume changes associated with compression of the grout during injection and curing. However, in application, the grout and displacement volume are generally assumed to be equal. The magnitude of the error associated with this assumption is believed to be small, however that has not been verified.

Movements in soil may occur in all three dimensions. It is important to consider the three dimensional nature of movements since they can affect buried utilities, retaining walls, septic tanks, vaults and other buried structures in addition to structures bearing on the grouted area.

Uplift is usually localized and centered about the point of injection.

Surface heave is a frequent refusal criterion and typically limited to between 2.5 mm (0.1 inch) or 1.2 mm (0.05 inch) per stage. It is important to consider the cumulative surface response resulting from grouting at multiple stages, including the potential influence from neighboring injection points. When carefully controlled, this effect can be used to recover settlement of supported structures and restore grades. However, it is important to limit surface uplift to an elastic or "recoverable" range when uplift is not desired, or could otherwise damage overlying or adjacent structures. Recent use of instrumented monitoring techniques has proven to be of value as an indicator of grouting-induced surface motion while still working in the recoverable range.

Another technique historically used to limit the cumulative effect of surface uplift involves the use of top-down grouting, also referred to as 'stage-down' or 'descending stage' grouting. This process is most effective in soft, near-surface soils, since the grout-induced heave tends to settle back between stages. Top-down grouting is a more costly process because of the need to re-drill the grout injection holes after each stage, but may be the most effective way to restore a settled structure to grade where the faulty soil is at a shallow depth. Combinations of bottom-up and top-down grouting may be used in certain cases; however top-down grouting is rarely used at depths greater than 15 to 20 ft (4.6 m to 6.1 m). Once stage-down grouting is completed, stage-up grouting may be used

to address soils in the deeper treatment profile. The initial top-down grout mass provides confinement and a firm surface to lift against as the bottom up grouting is completed.

6.11 Measuring refusal

Refusal criteria, together with grout injection behavior, can be used to evaluate the soil conditions and improvement produced. In order to obtain uniform and predictable results in compaction grouting it is important to set appropriate refusal criteria. Where these criteria are not well established, refusal is determined by the grouter, and may be established based on whether it is profitable or convenient to continue injection which might not achieve the desired result. Refusal for each stage of grouting should be defined as the point where additional grout injection does not advance the purpose of the work. Good grouting should have more than one criterion to define refusal. Common refusal criteria might include one or more of the following:

- A pressure limit at a given injection rate
- A grout volume limit per stage (can be a function of injection pressure)
- Undesired movement
- Maximum allowable lift

6.12 Grouting records

By maintaining good records of both the drilling of grout holes and grout injections, it is possible to use the grouting data to verify soil improvement. Ideally these records should be electronic. The grouting may be looked upon as a large scale pressuremeter test that measures the soil stiffness based on the volume injected and the pressures generated at a given injection rate. Split spaced grouting, where holes are injected in an alternating pattern of primary, secondary and occasionally tertiary holes, should produce records of increasing rates of pressure gain at a given injection rate and reduced injection volumes for the later phases of grouting.

The grouting records should be evaluated in the field continually throughout the work to assess the effectiveness of the grouting, and to adjust the grouting program to address subsurface conditions identified by the work.

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7. ANALYSIS OF COMPACTION GROUTING

7.1 Introduction

This chapter presents methods of analysis, with their limitations, and is intended as a resource for those involved in compaction grouting. The analyses are arranged from simplest to most complex, with the limitations of the analysis being highlighted where appropriate. As with all engineering, the analyses have assumptions and limitations and the applicability of any approach is problem dependent: the user must determine whether a particular analysis idealization is applicable to the problem at hand.

Finally, Sections 7.3, 7.4 and 7.5 look at field and experimental methods of understanding the behavior of the soil during compaction grouting.

7.2 Methods of analysis

7.2.1 Geometric idealization

Most analyses idealize grouting as expansion of a cylindrical column of grout in the ground. This reduces a complex 3-D situation to something very simple with one space variable: radius. It also allows access to considerable literature, as this idealization has been used in many situations over at least the last 50 years (and not just soil – the original studies were motivated by battleship gun barrel design). Radial symmetry is crucial to obtain "closed-form" solutions even with simple soil models, and is very convenient for numerical approaches as well.

As discussed in Section 6.2 for a single grout hole the cylindrical simplification seems justified. Excavation of grout bulbs following grouting (see Figure 6-1 and Figure 6-2), and observation of inclinometer responses during grouting, has shown behavior consistent with a cylindrical grout expansion. A limited set of 2-D finite element analyses were also carried out for BCHydro in connection with the Bennett Dam remediation (BCHydro, 1998) to examine the effect of anisotropic stress in the horizontal plane on grout behavior. Surprisingly little anisotropy of the grout bulb developed and work then continued with the assumption of radial symmetry.

Radial symmetry can also be invoked without the restriction of purely horizontal movement of the grout (i.e. cylindrical expansion). Two well-known alternatives have been used to represent grout expansion. The first also involves radial movement relative to the (presumed vertical) grout hole, but the boundary condition above and below the radially expanding grout bulb is constant normal (presumed vertical) stress: this allows free movement of the ground in the axial direction of the hole. This alternative is referred to as the plane stress idealization and was used by Kovacevic et al. (2000).

The second alternative is for the ground to move away from the grout bulb equally in all directions. This alternative is referred to as the spherical cavity idealization. However no field study that supports this grout idealization has been found.

7.2.2 Alternative soil models

Analysis of grouting forces us to consider compatibility since it is the volume of grout injected that does the work in compacting the soil – the familiar soil mechanics approach of simply considering limiting stress states with no consideration of displacements (e.g. slope stability analysis) will not work. Analysis needs a representation of the stress-strain behavior of the ground (commonly called a constitutive model). Although a wide range of constitutive models have been published, more than 60, most are unsuitable for compaction grouting.

The simplest model for soil is to assume that it is elastic. Although used in practice there are two fundamental problems associated with a purely elastic idealization. First, although soil is elastic at small strains, its behavior during grouting is dominated by plasticity. To some extent using hyperbolic laws for the elastic modulus (reducing the modulus with increasing shear stress) can mimic plasticity. However, hyperbolic laws do not give the freedom needed to get the correct volumetric strain. Second, and by far the most important point, elastic stress distributions are symmetrical around an expanding grout bulb. There is an equal and opposite decrease in the circumferential stress to the increase in the radial stress, leaving the mean stress unchanged, see Figure 7-1. Because part of the effectiveness of compaction grouting depends on means stress increase, representing soil as simply an elastic material misses an important mechanism. And, the radial stress distribution will be grossly wrong once enough grout has been injected to start the soil yielding, a process that takes as little as 0.1 ft^3/ft of grout. For these reasons, this approach should not be followed. At least one further level of sophistication is required.

One approach is to use a simple extension of the familiar Mohr Coulomb strength criterion and incorporate elasticity for stress states of less than fully mobilized strength with dilation once the failure (yield) criterion is reached. This model is called a non-associated Mohr Coulomb model (NAMC), the phrase non-associated being used because the friction and dilation angles are different. Soil compression during grouting is modeled using negative dilation angles. Obviously such a model cannot handle the densification effect with denser than critical ground, but there are semi-analytical solutions for the NAMC model and it can be a useful first approximation. There are four soil parameters in the NAMC model: shear modulus, Poisson's ratio, dilation angle, and large strain friction angle. Often the dilation and large strain (or critical state) friction angles can be played off each other to get an approximation of the desired stress-stain behavior, but the big limitation remains the assumption that the dilation angle is a constant. Figure 7-2 shows an example of the behavior of the NAMC model for a loose soil with contractive behavior – clearly there is no sense that the model approaches the critical state (with associated zero plastic volume change with additional shear strains) at large strains as needed.

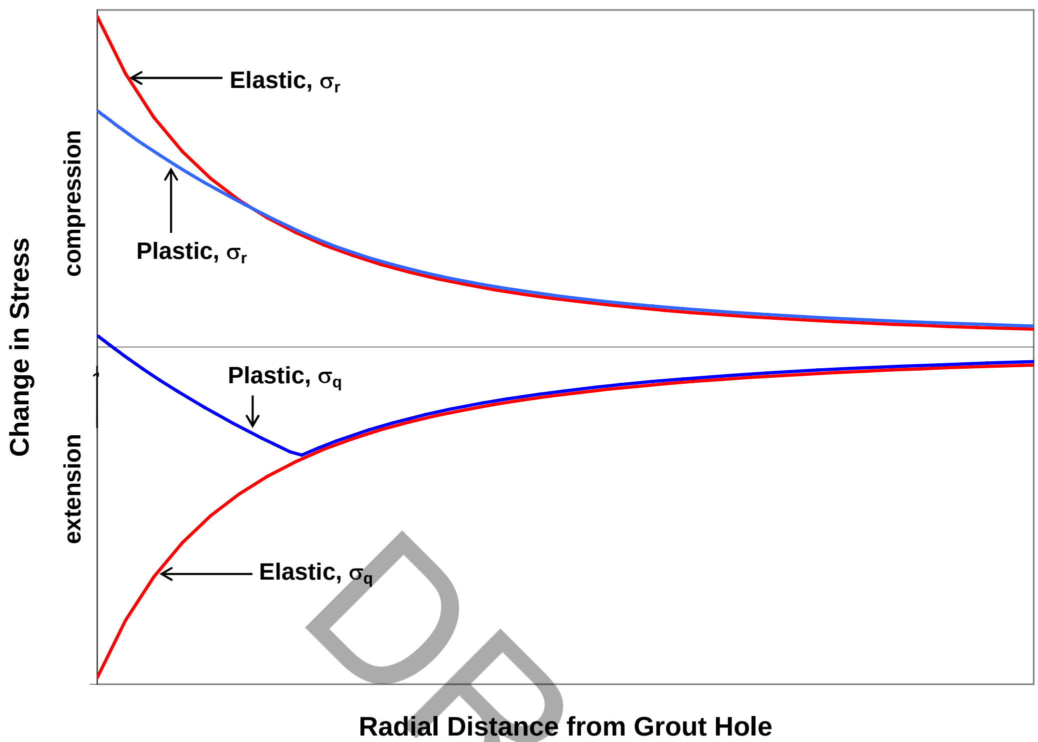

Figure 7-1 Radial stress versus distance from grout hole (elastic and plastic response)

Because compaction grouting changes the density of the ground, proper analysis requires models that predict how varying density changes the soil strength, compressibility, etc. This requirement has typically led to the adoption of critical state models as the effect of density on soil behavior is the essence of this class of constitutive model, although any soil model generating realistic stress and volume changes is appropriate. Kovacevic et al. (2000) used Modified CamClay as the basis for their simulations, while NorSand was adopted by Shuttle & Jefferies (2000).

Modified CamClay – the well known model put forward by Roscoe & Burland (1968) - is a reasonable approximation for very loose granular soils, but overstates strength increase caused by density change. The attraction of Modified CamClay is its simplicity and availability in many commercial finite element codes.

An example of a more complex and realistic critical state model is NorSand (Jefferies, 1993). NorSand has two more parameters than CamClay and can be viewed as a generalization of critical state ideas (CamClay can be recovered as a particular case of NorSand by appropriate choice of parameters). The behavior of the NorSand model is compared to NAMC model on Figure 7-2 using an equivalently loose parameter set.

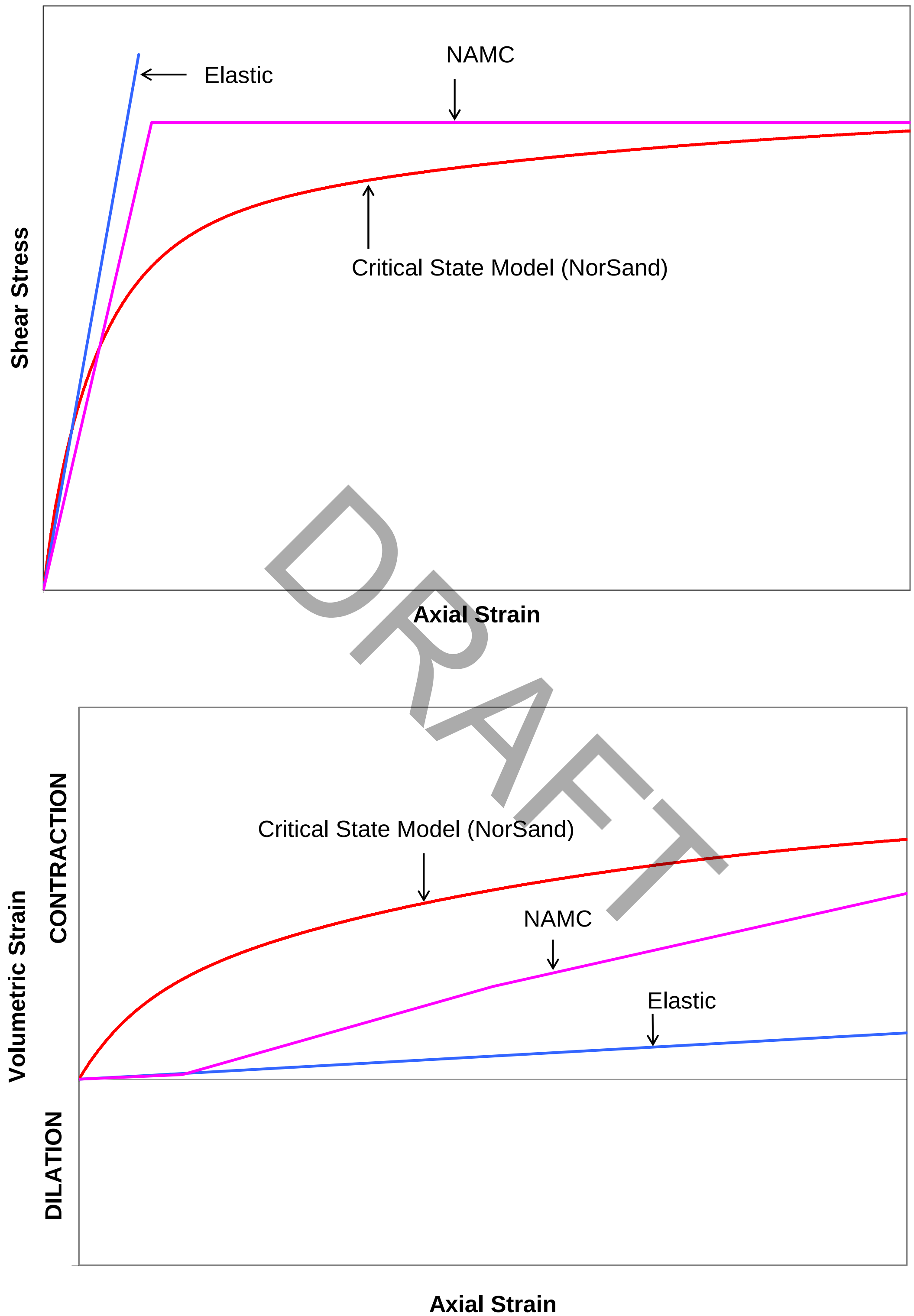

Figure 7-2 Behavior of alternative soil models for triaxial compression of loose sand

Although not used for analyses of grouting to date, variants of the bounding surface models are being developed that have the required attributes. These models tend to be more complex and require more input parameters, but do capture a finer level of detail in soil behavior.

7.2.3 Importance of large strain

During compaction grouting the soil is typically sheared to many hundreds of percent strain. At these large strain levels there is a large difference between the small strain and large strain measures, with the assumption that higher order terms in the strain definition as negligible being quite wrong. Small strain analyses are unable to replicate the limit pressure observed in the field, and are unsuitable for estimating limit pressures during grouting for this reason alone. However, small strain solutions also miscalculate the volume changes from displacement of the soil during grouting. This volume change is fundamental to the grouting process and cannot be neglected.

Large strain analyses are documented widely in the literature and the procedures are well known. Some commercial finite element codes incorporate large strain capabilities (e.g. FLAC, ABAQUS, PLAXIS) and the finite element implementation of large strain is standard (see Zienkiewicz and Taylor, 1991).

For completeness the Green large strain formulation is given below. Basically the difference between small and large strain is that in the large strain formulation the coordinates are updated to account for the movement of the soil.

The total Green strain ε_T is considered to be comprised of the standard Cauchy small strain, ε_S, and a large displacement component, ε_L, such that;

$$\varepsilon = \varepsilon_S + \varepsilon_L$$

which for the cylindrical geometry used in compaction grouting analyses may be written as:

$$\varepsilon_r = -\frac{\partial u}{\partial r} + \frac{1}{2}\left(-\frac{\partial u}{\partial r}\right)^2$$

$$\varepsilon_\theta = -\frac{u}{r} + \frac{1}{2}\left(-\frac{u}{r}\right)^2$$

where ε_r and ε_θ are the radial and total circumference strains respectively, and *u* is the radial displacement at radius *r*.

7.2.4 Simple approach

Analytic solutions are available for cylindrical and spherical expansion of simple soil models allowing the engineer to carry out fast scoping calculations. These solutions allow estimation of stress distributions and their relationship to cavity displacements, as well as to calculate the limit pressures expected during grouting. All of these analytic solutions may be simply implemented in a spreadsheet (and may be downloaded from the Grouting Committee Web Site).

In using analytical solutions, the basic step is to decouple the estimate of achieved compaction from the calculations of stresses and limit pressures. Obviously a user can iterate between the two types of analysis to get a feel for the proposed grouting.

Decoupling proceeds as follows. Achieved compaction from injection of a volume ΔV of grout into a grouted interval L long gives an average change of void ratio in the soil, Δe:

$$\Delta e = \frac{(1+e_0)}{A_0}\left(\frac{\Delta V}{L}\right)$$

where A_0 is the affected area of grouting. This simple equation assumes, however, that the area of the affected ground is known and that the densification will be uniform across the area. For an array of grout holes this is simply the total area of grouting divided by the number of holes. If grouting is near surface and has caused surface heave, then it is necessary to reduce the ΔV in proportion to the heave. The term $\Delta V/LA_0$ is sometimes referred to as the "net grout take ratio".

Where things get more problematic is in the early stages of a grouting project when we are dealing with one, or even a few holes, as at that time we cannot rely on symmetry to constrain the affected area. This is where it helps to look at the stress distribution and start estimating A_0 from the sensible radius of influence of the stresses – but keep in mind that underestimating A_0 overstates the compaction. Additionally, remember that this smaller radius of influence effectively increases A_0 for the adjacent grout holes. Therefore, lower densification should be anticipated close the boundary of the grouted area.

Stress distributions are obtained from the closed form solutions of the cavity expansion problem along with limit pressures. The first cavity expansion analyses by Bishop et al. (1945) and Hill (1950) addressed incompressible materials with associated flow rules, corresponding to the familiar and simple idealization of the undrained behavior of clay. The derivation of expansion for a cylindrical or spherical cavity in a linear elastic perfectly plastic Tresca material is standard (e.g. Gibson & Anderson, 1961, Carter et. al, 1986, Houlsby & Withers, 1988). However, this idealization, while simple, is inappropriate for compaction grouting as no volume change occurs.

Cavity expansion theory for non-associated Mohr-Coulomb (NAMC) flow has been considered by a number of workers including Carter et al. (1986) and Yu & Houlsby (1991). The central assumption of these studies has been that both the friction and dilation angles remain constant during shear. The Carter et al. solution has the required large strain features and is straightforward to implement with numerical integration in a spreadsheet. The downloadable file *carter.xls* on the Grouting Committee web site provides an implementation of this solution.

7.2.5 Numerical cavity expansion

Although the assumption of constant friction and dilation angles of the NAMC model leads to straightforward expressions with semi-analytical solutions and is hence extremely useful, it has the fundamental flaw that soil does not behave in such a manner in general. Reliable solutions require a soil stress-strain model that captures the evolution of dilatancy with accumulated strain and stress, as it is this behavior that distinguishes one sand from another and is magnified by the confinement of the cavity expansion. Numerical models are required for these realistic representations of soil behavior as analytical solutions do not exist.

The simplification of grout expansion to a cylindrical approximation is also convenient for numerical modeling. Numerical modeling codes including realistic soil models and large strains can be complex. Reducing the problem to a single dimension result in savings in the time needed to set up the model and to the simulation time. However, the high degree of soil confinement in cavity expansion situations makes analyses sensitive to the soil parameters. Confinement also has the side effect of causing slow numerical convergence in some of the more widely available modeling software.

To date, the implementation of realistic soil models to the numerical analyses of cavity expansion is not common in the literature and therefore unlikely to be contemplated for any but the most sensitive projects. Two groups have looked at compaction grouting with detailed numerical simulations. Kovacevic et al. (2000) used Modified CamClay as the basis for their simulations, while NorSand was adopted by Shuttle & Jefferies (2000). A limitation of both approaches is the radial symmetry. As noted earlier, this assumption leads to reasonable simulations for primary grouting but is patently poor for secondary and any higher order holes, and adjacent to hard boundaries. Although the effect of these higher order holes can be "dummied" in a radial scheme by introducing stiffer/denser soil at some radius, this actually simulates a hole surrounded by a ring of stiff and dense ground. Actual ground conditions vary in density and stiffness with circumferential position. It is presently unclear how to adjust the radial analysis to properly capture the conditions during secondary, and higher order, grouting.

For completeness, Figure 7-3 shows the distribution of void ratio calculated by Shuttle & Jefferies (2000) for three initial states: very loose (ψ=+0.05), loose (ψ=+0.0), and medium dense (ψ=-0.10). These states correspond to the sand behaviors shown on Figure 6-3. The figure illustrates the expected behavior. The loosest soil shows the largest reduction in void ratio but the densification is limited to close to the grout bulb.

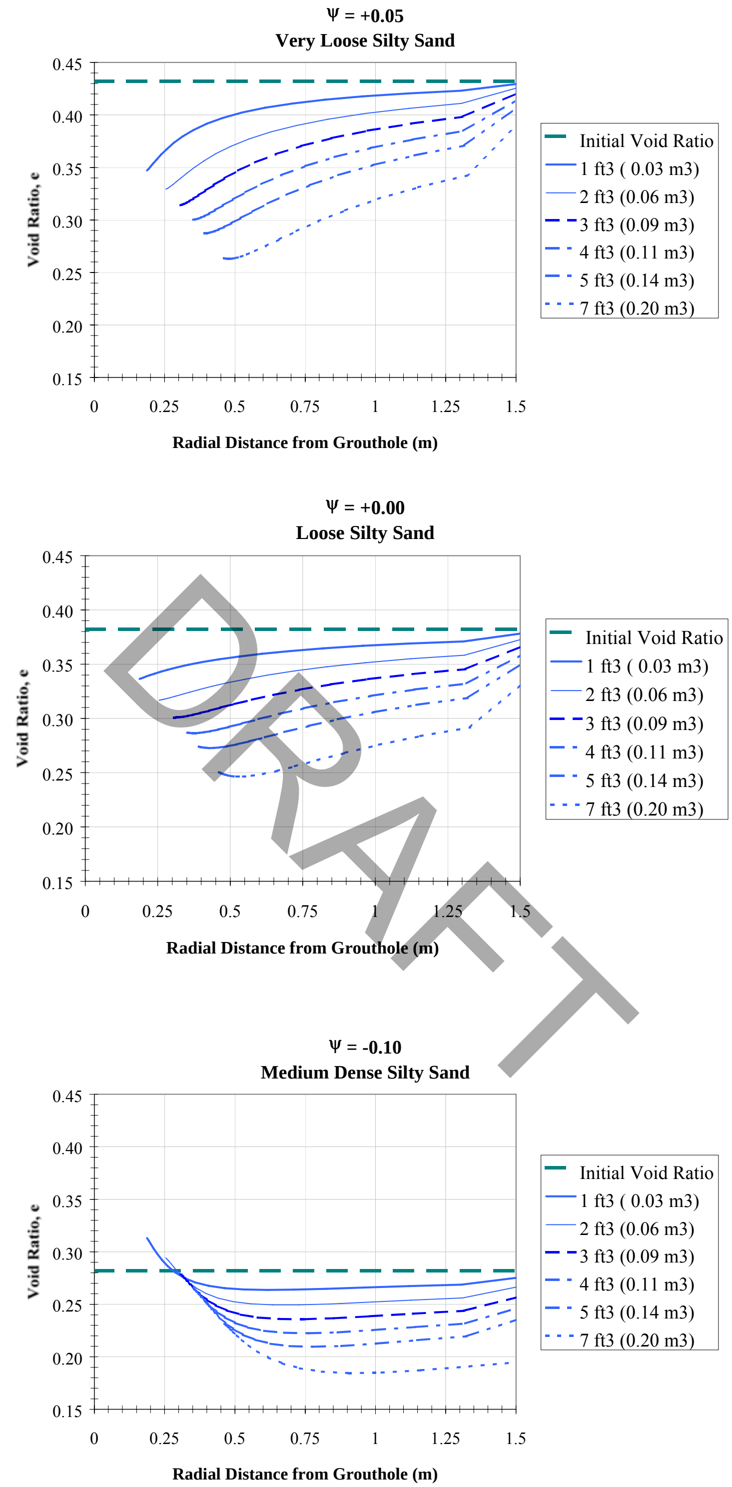

Figure 7-3 Distribution of void ratio for differing initial states: very loose (ψ=+0.05), loose (ψ=+0.0), and medium dense (ψ=-0.10).

The denser soil shows a slight increase in void ratio adjacent to the grout bulb at small injection volumes, but with increasing injection the soil densifies and the densification (although smaller in magnitude) is apparent deeper into the soil mass.

7.2.6 Commercial finite element codes

The numerical analyses discussed in the preceding section used research finite element codes. However, while this certainly leads to fast codes for the problem at hand, analysis is possible using standard commercial codes. Several commercial codes offer the required large strain feature together with some model for sand behavior. Some codes also offer the possibility of user defined soil models.

Three codes that may be of interest are:

ABAQUS – large strain, ModCamClay provided, user routines available
FLAC – large strain, ModCamClay provided, user routines available
PLAXIS – large strain, soft-soil CamClay type model, user routines available

These codes are supported by software organizations, and training courses for their use are available. All these codes have been quite widely used for other aspects of geotechnical engineering. However, like with all numerical analyses, the usefulness of the results is related to the adequacy of the inputs and appropriateness of the software options used. All results should be scrutinized for reasonableness remembering that due to the high confinement of the soil during compaction grouting any errors in analysis are likely magnified.

7.2.7 Consolidation of the in situ soil during and after grouting

The soil is usually desired to be drained during injection, and this limits the grout injection rate for finer soils. Allowable injection rates can be evaluated using a consolidation analysis of the grout injection. Such an analysis will allow calculation of whether the soil response during grouting will be drained, partially drained or fully undrained for the chosen grout injection rate.

A full analysis of the drainage of soil during compaction grouting requires a realistic soil model, coupling between the soil stress strain behavior and pore pressure response, and 3-D geometry. However, for scoping analyses a simple soil model, simplified geometry and an uncoupled solution may be used. The difference in hydraulic conductivity deduced between the approximate approach and the full analysis is typically of the order of a factor of two.

The equation for radial consolidation in an infinite medium is given by Soderberg (1962):

$$\frac{\delta u}{\delta t} = c_h \left(\frac{\delta^2 u}{\delta r^2} + \frac{1}{r} \frac{\delta u}{\delta r} \right)$$

where u is the excess pore pressure [kPa]
r is the radial distance [m]
t is the time [yr]
c_h is the horizontal coefficient of consolidation [m^2/yr]

This equation may be solved using the technique of finite differences if it is, incorrectly but conveniently, assumed that the soil-grout interface is impermeable. The other information required for a solution is the pore pressure distribution at the end of grouting. In reality the excess pore pressure distribution will be dependent upon the soil's change in soil density and its permeability. However, the interest here is only in estimating the dissipation time relative to the time of grout injection. Hence, a simple approximation is adequate. A possible approximation is that the pore pressure at the end of grout injection is equal to the grout pressure at the bulb, and the pressure reduces in proportion to the inverse of the radial distance from the injection casing (i.e. $u \propto 1/r$).

For soils that are partially drained during grouting the density of the soil will change during the consolidation process. To analyze this effect more complex analyses that include a realistic soil model, large strains and coupling of the stress-strain and pore pressure response (i.e. Biot, 1941) is required. No analytic solutions exist and numerical solution is required.

The effect of grouting under fully drained and fully undrained conditions is illustrated in Figure 7-4 (Kovacevic et. al., 2000). The contractive volumetric strain under drained loading is much greater than that achieved by undrained loading followed by consolidation. Partial drainage would achieve an intermediate amount of densification during compaction grouting.

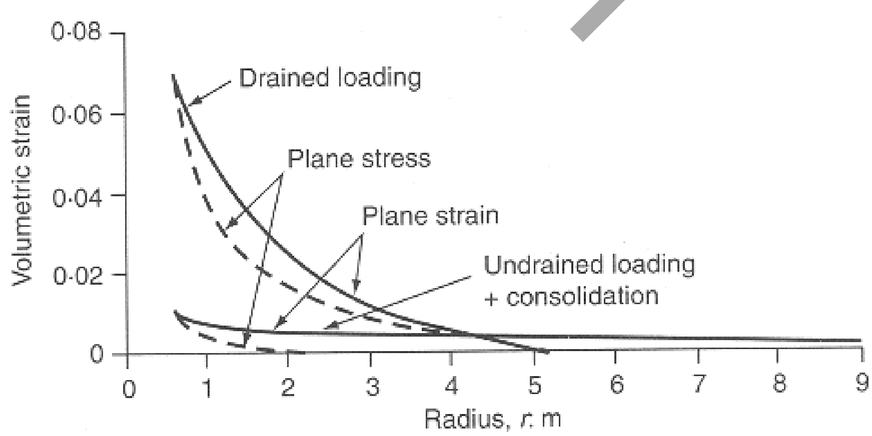

Figure 7-4 Finite element analysis assuming plane stress and plane strain. Volumetric strains following drained expansion and following undrained expansion and consolidation. Expansion from r = 0.1 m to r = 0.6 m (Kovacevic et. al, 2000)

7.3 Importance of monitoring grout injection

Analysis and experiment are not the only means which have progressed the understanding of grouting. Much can be learned by use of modern instrumentation and data acquisition systems during routine work.

Two key grout parameters are the injection pressure and grout flow rate. Ideally, these would be measured at the grout bulb. Practically, measurements at the hole collar usually have to suffice with corrections for the effect of the head loss/gain in the injection pipe below the collar. These types of measurements are now routine in fractured rock cement grouting, and the ability to monitor and display these grout parameters in real time has allowed developments such as the *GIN* method (Lombardi and Deere, 1993). But, more important, this type of grout data provides a direct measure of the ground response to the grouting, and analysis of the grouting records allows much better control of the work.

7.4 Centrifuge modeling

Although many full scale test trials have been undertaken to explore the compaction grout process, depth of confinement has been limited to less than 20 ft due to practical excavation depth to extricate the grouted masses. One possibility to explore the mechanics of compaction grouting within sensible experimental constraints is the geotechnical centrifuge, and this approach has been followed by Nichols & Goodings (2000a, b).

The geotechnical centrifuge enables small models (typically of about 500mm in size) to be constructed in a laboratory and yet still tested at prototype stress levels. This allows for depth effects to be seen, and the mechanics of grouting to be understood by stopping experiments at different stages and exhuming the grout bulb. However, the expense and effort of centrifuge testing will never make it a routine design tool and the contributions will be focused to providing insights on a research basis.

Centrifuge studies of compaction grouting to date might be described as preliminary, as attention has concentrated on development of bulb geometry and the range of parameters explored is less than comprehensive. Important aspects such as grouting pressures and achieved densification are only beginning to be evaluated.

The limitations of centrifuge work include the problems of grain size – production compaction grouts are not used in the tests. The existing full-scale experience suggests a very strong influence of grain size distribution of the grout on its effectiveness, and there is the possibility that grout to ground elastic stiffness may be an important parameter controlling the stability of the grout bulb. Considerable caution is warranted in the simple scaling up of centrifuge results. However, notwithstanding these difficulties, centrifuge testing does allow ready exploration of some issues and the work to date has shown that grouting can be successfully done within the centrifuge.

7.5 Field trials

Full scale injection, followed by excavation and visual observation, as well as testing of several hundred full scale injections, has occurred since the mid 1950s. These have included test injections that were totally extracted as well as evaluations of injected masses from more than 50 actual projects. Although not directly related to design, these field trials have greatly enhanced our understanding of how compaction grout behaves under real field conditions.

More details on field trials may be found in the literature including Brown and Warner (1973), Warner and Brown (1974), Warner (1992), Warner et al. (1992), and the ASCE Special Publications on Grouting (1992, 1997, 2000).

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8. VERIFICATION OF GROUTING EFFECTIVENESS

8.1 Overview of verification program development

The success or failure of a grouting job is related to human as well as technical factors. It is most important that prior to the start of grouting, 1) the problem has been defined in detail to the satisfaction of everyone involved, 2) agreement has been reached upon the criteria which define success or failure, and 3) data which may be necessary for "before" and "after" comparisons are gathered before grouting starts (ASCE Committee on Grouting, 1995).

Before starting the grouting job the existing conditions should be defined, as well as the desired effect of the grouting in sufficient detail such that conditions representing a satisfactory solution to the problem can also be specified. The owner, design engineer, and the grouting contractor should agree on the specific purpose of grouting, the conditions which define success or failure, and the tests, observations and/or data which can be used to verify the grouting results. Grout formulations, injection rates, pumping pressures and grout takes for each stage of each hole should be continuously monitored, recorded and evaluated, and appropriate changes based on the retrieved date made during the course of the work.

The single most important task to verify controlled injection of the intended quantity of grout in the required location is vigilant observation of the injection rate and pressure behavior during grouting. This must be combined with immediate adjustment of the pumping parameters where loss of control of the injection is indicated. A substantial advantage of compaction grouting is the ability to place grout in the intended location. When grout of proper rheology is injected in an appropriate manner, the grout will form an expanding, generally consistent, mass. Should hydraulic fracturing occur, it will be clearly indicated by a sudden drop in pressure which is a signal to reduce the injection rate and check the grout rheology.

The soil into which the grout is injected (referred to below as the "formation") is opaque to human vision, so the flow of grout into or through the formation cannot be monitored by direct observation. The final location of grout will be controlled to some degree by the practices and procedures used. While the grout mixture, stage sizes, rates of injection and other parameters should be set in the design, they should be adjusted during construction, as called for by the actual injection behavior, for proper control of the work. Since the soil may not be uniform and variations are not always predictable, there always remains some risk that the grout may find its way to some unintended location. However, this should be discernable by careful observation of the grout rheology, pumping rate, and pressure behavior during injection. The success or failure of a grouting operation can usually be determined as the work proceeds; through careful monitoring combined with prompt corrective action where indicated.

When the purpose of grouting is to add strength (or stability) to a formation, there is generally no way to judge success by simply observing the ground surface visually.

During the injection and when the grouting operation is completed, comprehensive records of grout take, grout hole location, injection depths, rates, and pressure behavior along with other construction data are valuable tools, and in many cases may be sufficient indicators of the proper placement of grout. The increase in soil strength or some indirectly related soil parameter is often measured to confirm the degree of improvement in the soil strength.

It is often assumed that if the grout sets in the desired location, the job is successful. Under this assumption, success of the grouting operation can be measured by field procedures which verify the grout location. Methods that measure the change in electrical conductivity or acoustical response have been researched with positive results. However, these methods require specialized equipment and expert personnel. On particularly important work, and depending on the site conditions and application, these methods may be justified.

Unknown or unanticipated underground conditions may adversely affect grouting performance. Detailed geotechnical investigation is the best method to avoid unnecessary surprises. However, it is unreasonable to assume that any level of investigation will identify every possible situation. This is why a thorough monitoring program during injection is so essential. Careful monitoring and evaluation of grouting parameters during the course of the work can enable previously unknown conditions to be identified and treated appropriately.

A good overview on how to plan an effective verification program is given by the ASCE Committee on Grouting (1995).

8.2 Planning an effective program

8.2.1 Goals of verification

In planning an effective program it is important the properties to be measured are clearly defined. Verification of compaction grouting typically involves indirect methods that are correlated to density. The cost of any method of verification should be balanced against the benefit to be gained.

Poorly defined verification goals can lead to confusion. If verification is provided as an afterthought without a clear goal, disputes can arise concerning whether the grouting has been successful. For compaction grouting the following key questions should be answered:

- What degree of densification is required?
- How will the verification test results be evaluated?
- What will be the acceptance criteria?
- What are the consequences of failure?
- What is the cost for the verification?

Other questions may arise, such as the timeliness of the results and how the verification fits into the construction sequence.

Well defined verification goals will arise from the answers to all of these questions. A good verification program will be cost effective, provide an appropriate level of assurance, provide results in a reasonable time frame, and should use the simplest most reliable technology possible.

8.2.2 Verification by design

The time to begin the verification program is in the planning stages of the project. Verification methods should be selected consistent with project goals and incorporate the verification into the design and constructability evaluation. Specifications should be established for the grouting, monitoring and verification testing to provide the required level of quality assurance. It is important to consider interruptions to the grouting that may occur and to allow for before and after testing if needed to measure improvement.

The verification equipment and procedures should be made integral to the grouting program and other construction activities on the site. Where before and after testing involves instrumentation, consider the need to protect instrumentation left in place. Include redundant equipment in high hazard areas. Consider the construction site environment and its effect on the proposed equipment and tests where necessary. If a test section is desired, include it in the specification and include verification testing for the test section.

8.2.3 Test or pre-construction grouting

On large or sensitive projects, pre-construction grouting is an efficient way of optimizing the grouting procedures and can be cost-effective. On most projects a full pre-construction program is not warranted. However, every project benefits from reviewing the information gathered during the first few grout holes to see if grout hole spacing, grout pressures and grouting rates could be adjusted to improve the end result.

Where used, test grouting should include the same verification measures intended for the production grouting. Excavated test pits may be used to calibrate and verify the results of indirect tests. The project schedule should include sufficient time for the completion and evaluation of the test grouting prior to production grouting. It is of much less value to get the verification report indicating unacceptable areas after the grouting contractor has demobilized from the site than to get real time data.

8.2.4 Monitoring during construction

Monitoring during grouting is essential to verify proper performance. As a minimum, the grout consistency, injection rate, injection pressure and injected volume in each stage should be monitored and recorded. This data should be reviewed to evaluate the ground and grouting performance. Injection pressures will be lower, and injected volumes

higher, in softer or less dense areas. Secondary injections should show lower volumes and higher pressures because of the improvement induced by primary injections. A uniform pressure buildup at a given pumping rate will indicate generally uniform soil conditions and controlled densification. Gradual pressure changes are indicative of non-uniform soil, whereas a sudden pressure drop will signal hydraulic fracture of the formation and loss of control of the injection. Should the grout enter an underground conduit or structure, a rapid pressure drop will typically be followed by a steady increase in pressure. Additional split spaced holes may be used to verify the success of secondary grouting.

The drilling or driving of grout injection pipes should also be used as a tool to evaluate the grouting. Drilling or driving will encounter greater resistance in improved soils or when encountering grout. Drill cuttings will give evidence of the presence of previously placed grout.

More advanced compaction grouting has adopted electronic monitoring and computer based data acquisition. The equipment is essentially the same as used for cement grouting: a flowmeter, electronic pressure transducers, and a PC based data acquisition system. Electromagnetic flow meters that are often used with suspension grouts however, require the grout to be saturated for accurate measurement, so ultrasonic flow meters are required. The data acquisition usually involves an external analogue to digital converter proving a signal through the RS232 port to a PC running a widow-hosted data acquisition program).

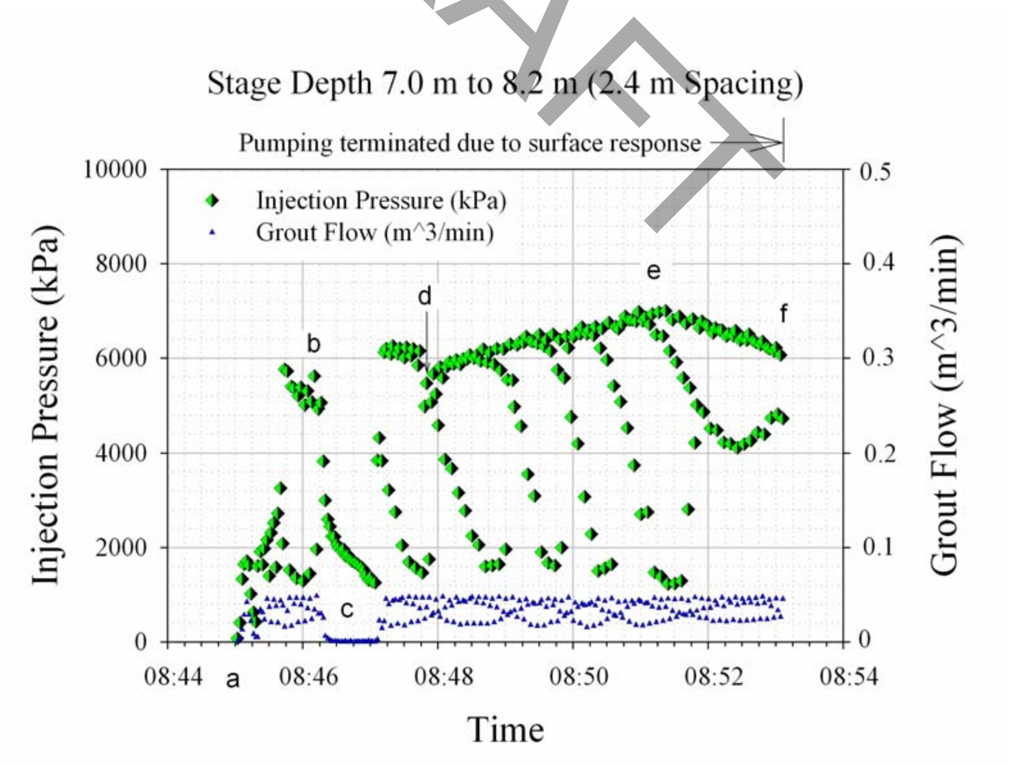

Figure 8-1 Time history of measured pressure and flow during compaction grouting (Geraci, 2007)

The compaction grouting data can be analyzed to understand the progress of compaction, control the introduction of additional holes, changes to grout flow rates, injection pressures, etc. Garner et al. (2000) and Warner et al. (2003) describe the use of near real time analysis in this way for the remediation of Bennett dam. Additionally, monitored injection pressures and grout flow rate could provide early warning of surface heave (see reduction in pressure with constant grout flow rate between 'e' and 'f' in Figure 8-1).

8.3 Verification methods

A wide variety of testing methods can be used to either directly or indirectly measure the performance of grouting. These include primarily mechanical and geophysical methods. The focus of these methods is to determine the improvement in the subsurface density after grouting. Some of these methods are non-intrusive and/or non-destructive and can be used without disturbing or damaging the grouted area. The non-destructive methods generally are indirect and require interpretation of the desired information from some other measured property.

The remainder of the chapter includes a selection of currently available methods for determining the performance of grouting.

8.4 Detecting movement

Selection of a method for detecting movement is related to the type of movement to be measured. Movement types consist of differential shear, extension/contraction, elevational and angular distortion. The selection of measurement method is based on an evaluation of accessibility, required accuracy and response time, and cost. Dunnicliff (1993) presents a comprehensive discussion of the various movement monitoring devices and the basis for their use. Since there are such a wide variety of instruments, only a brief discussion of instruments common to grouting applications is included herein. The reader is directed to the literature for further information on movement monitoring (e.g. Patel, et al., 1982; Warner, 1982; Neff et al., 1982).

8.4.1 Crack monitors

It is often desired to control or mitigate damage to structures, or prevent movement between adjacent structures, by grouting. Monitoring movement on flat structural surfaces is generally far less expensive than subsurface monitoring. Where the location of the movement is controlled by structural joints, cracks or other zones of weakness, measurement can be made by simple means, such as placing a pencil tick on either side of the defect, of which the distance between can be periodically measured. Even better is attaching a card or stick on one side, that extends across the joint. Any movement can be observed by offset of a pencil mark on the device, which indicates the original opening. Alternately, rulers can be placed across the joint in a similar manner, usually with one side of the defect at a major distance graduation. The beginning measurement of the free side is recorded and any movement can be observed by the change in measurement.

Although it will not give an exact value of the movement, simply placing a piece of duct tape across a crack or joint can give a signal that movement has occurred. Should the defect open, one side of the tape will be torn free. Should the defect close, a belly in the tape will be formed. Figure 8-2 illustrates these simple crack monitors.

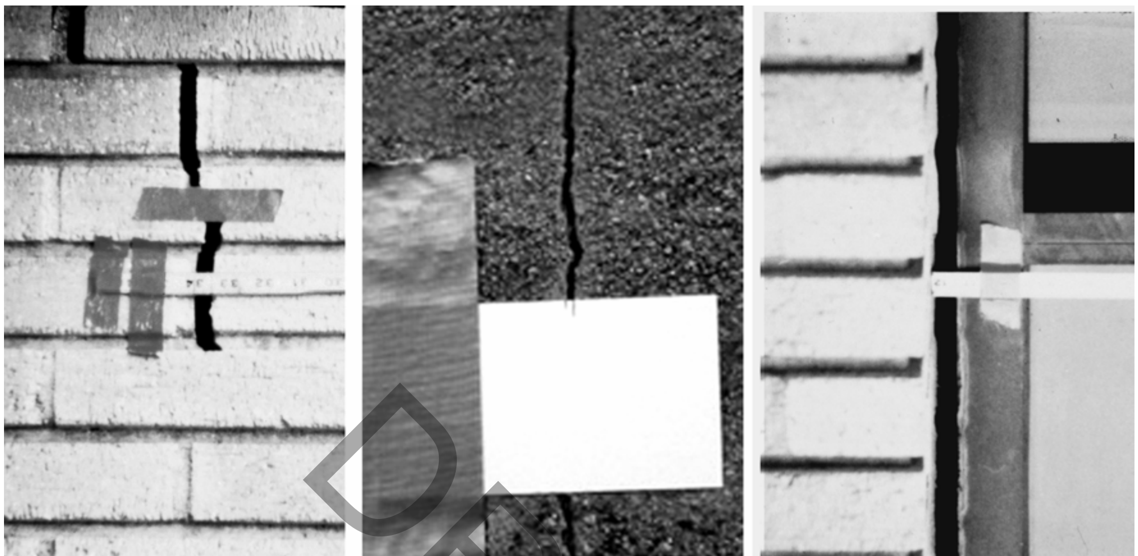

Figure 8-2 Simple crack width monitoring devices.

Although not common in grouting, where precise measurement is required mechanical crack gages including pins and tape, pins and calipers, or grid crack monitors can be used. All of these are generally inexpensive. The choice of method is made on the basis of required accuracy and span. Where measurement is required across a gap of more than a few millimeters, pins and either tape or an extensometer are appropriate. The pins should be placed in pairs diagonally to the crack or joint to measure shear. The installation of the pins may damage architectural surfaces and this should be considered when selecting the mounting method. For most grouting operations, measurements are needed only for a short time period. Thus use of pencil or paint marks is every bit as effective, plus these can be removed without marring the surface. Electronic extensometers or convergence gages can be used for special applications where continuous monitoring is required via a recorder or telemetry for remote monitoring.

8.4.2 Tiltmeters

Tiltmeters measure angular movement or rotation of surfaces. A simple tilt measurement is to measure horizontal deviation over the length of a plumb line or spirit level. More sophisticated devices such as the portable inclinometer and electronic tiltmeters using accelerometers or vibrating wire technology are also available. Both accelerometers and vibrating wire instruments can be set up to be permanently mounted and read remotely.

Tiltmeters are used primarily for detection and control of structure movements induced during grouting, but may also be used to assess structure movements after grouting.

8.4.3 String lines, plumb bobs, and spirit levels

A simple string line drawn tightly across the area of interest is unquestionably simple, yet is a very effective method to detect differential movement. The line must be firmly anchored on both ends, which must be beyond the zone of influence of the grouting. This is not much of a problem as nylon line, such as used for masonry, can be easily stretched for 30 ft or more without any sagging. The line is preferentially positioned about 25 mm (1 inch) off of the surface and changes in the gap measured with a "gauge block" equal in height to the original gap as illustrated in Figure 8-3.

Figure 8-3 Gauge block to check for surface movement under string line

Common plumb bobs and carpenters levels are useful for monitoring structures. Vertical tilt can be observed from a changing position at the bottom of a plumb line suspended from the top of a structure. The line is best held out from the surface a few inches at the top and a bracket fixed to the surface at the base. A mark indicating the starting position should be placed on the bracket as illustrated in Figure 8-4. A carpenters' level can be placed on virtually any near horizontal surface or across a joint as shown in Figure 8-5. A wedge is conveniently placed under the low end so the instrument is absolutely level with the bubble perfectly centered. Any change in level can thus be easily observed. The value of any movement can be ascertained by measuring the distance required to re-level the instrument by lifting the low end.

Figure 8-4 Plumb line suspended from top of structure. Note mark on bracket

Figure 8-5 Carpenters level wedged to a level position across pavement joint

8.4.4 Fluid levels

For active short term monitoring of structural or ground surface level changes, a fluid level can be used. Fluid levels consist of a reservoir and one or more measurement tubes. The system operates on the principal that a fluid will seek the same level as the reservoir in the tube. With a scale attached, they can be used to measure relative elevation between the tube location and the reservoir. These are commonly used in compaction grouting and slab jacking to monitor lift and contour floors as well as monitor for ground heave. Figure 8-6 illustrates examples of such use. On the left, a terminal tube has simply been fixed to the wall of a structure with masking tape, with an adjacent ruler to measure any changes in water level. The water is colored red enhancing its visibility. This is easily accomplished with food colors. In the center, a worker observes the water level in a the tube attached to a post supported by a stand on the ground surface, and on the right, a worker is placing a mark on the tube indicating the starting water level against which any changes will be based.

Fluid levels are generally quite accurate but can be affected by air bubbles in the lines, so it is best to keep them filled at all times. That is the purpose of the golf tee in Figure 8-6, shown hanging from a string attached to the top of the tube shown on the left. It is used as a plug to retain the water when the system is not in use. Care should be taken when using fluid levels for long term applications, since evaporation, fluid degradation, freezing and other factors can affect their accuracy.

Figure 8-6 Examples of manometer tube terminals.

8.4.5 Rotating laser levels

Rotating Laser Levels (Figure 8-7) consist of a rotating laser beam that impinges upon one or more target prisms. The prisms are placed on stands or attached to structures and set to the level of the rotating beam. An audible sound will emanate from any target that moves out of the laser plane. This method is typically used during construction to establish planer surfaces of structures, slabs or the ground surface. Although laser instruments will indicate a change of position, they will not provide a direct measure of the magnitude of such movement, so where used should be backed up with other devices such as a surveyors level instrument. The degree accuracy of these instruments varies greatly and those commonly used in construction are usually not of sufficient accuracy for compaction grouting where the detection of even minute heave is required.

8.5 Evaluating density changes

Compaction grouting, as defined in this Guide, will increase the density of the soil. Density changes can be measured by comparing the in situ density before and after grouting. The density testing method and density standard should be consistent with the expected range of improvement of the grouting. Compaction grouting increases the density of the soil surrounding the mass of grout injected. The soil density between grout bulbs will not be uniform.

Figure 8-7 Rotating Laser Level for Heave Monitoring

Direct Methods of density determination include the Sand Cone test, Rubber-Balloon test, Drive Cylinder test and for coarse soils the Sleeve Method test. Other direct methods such as weighing cut block samples and the like may also be feasible depending upon the nature and cohesive strength of the grouted soil. All of these methods, except possibly the Drive Cylinder test, can only be performed on the ground surface or in a test pit so they are seldom used in connection with compaction grouting. The most difficult aspect of density testing below the ground surface is obtaining an undisturbed volume of soil. Direct methods for density testing at depth are only appropriate for soils that possess sufficient cohesion to hold together during sampling.

Indirect methods for evaluating soil density include the standard penetration test (SPT), cone penetration test (CPT), dilatometer (DMT), pressuremeter test (PMT), nuclear density test, and seismic methods. Seismic methods have been shown to be effective in measuring changes in soil density where inclusions make up a relatively small proportion of the soil volume, but should be correlated with physical tests (Byle, et al., 1991).

Both CPT and SPT (Salley, et al., 1987, Tokoro, et al., 1982, Welsh, 1986) have been used to evaluate densification by compaction grouting. Density is commonly related to penetration resistance for natural soils. Welsh (1986) indicates that typically a three- to five-fold improvement in the SPT 'N' value can be obtained up to N = 25 and CPT penetration resistance increases from 8 to 15 MPa are reported.

Downhole nuclear density testing has been used but is not commonly available, nor is it required for most applications. However, when properly calibrated the nuclear density test generally gives reliable measurements of soil density. Partos et al., (1982) found the downhole nuclear density

probe to provide repeatable testing at the same locations during the grouting that could not be achieved with the SPT.

The conventional nuclear testing gage can be used to measure density of the upper 200 to 450 mm (8 to 18 in.) of the soil. Down-hole versions of the nuclear densimeter probes can be used at any depth in a borehole to measure density below grade within 100 to 200 mm (4 to 8 in.) of the borehole. However, because of the requirement for borings and the high total cost, nuclear testing is reserved for special applications and not frequently used with compaction grouting.

8.5.1 Penetration resistance

The consistency of a soil is commonly evaluated by pushing or pounding a probe into the soil and measuring the force needed to advance the probe. There are two basic approaches: static and dynamic. The static methods advance a probe by applying a static force to the probe to advance it. The dynamic methods apply an impact of known energy and count the number of impacts needed to advance the probe.

8.5.1.1 Cone Penetrometer Test

The most common static method is the cone penetrometer test (CPT). The CPT is often termed "quasi-static" since the force is measured while the probe (cone) is being advanced at 10 to 20 mm/s (0.4 to 0.8 in/s). There are many variations of the CPT but most differ in the method of measuring the applied force and differentiating between the side friction and end bearing of the probe. Historically, the two main types of CPT devices were the mechanical cones and the electronic cones. Although the mechanical cone is still in use, nowadays the electrical cone is more common. Both cones typically have conical points with a 60° point angle and a projected area of 10 cm^2 (1.55 in^2). Modern CPT friction cones have a friction sleeve which is the same diameter as the conical tip. The force needed to slide this sleeve through the hole created by the tip is measured. The mechanical cones use push rods to first push a tip section and then the friction sleeve into the ground. Electric cones use strain gages and/or load cells to measure the force in lieu of the hydraulic pressure acting on the rods. The electric cone can typically measure friction and tip resistance simultaneously. Most of the modern cones now also include inclinometers and piezometers for additional data on alignment and pore pressures. Many cones also include options such as geophones for seismic testing (e.g. to obtain the elastic shear modulus of the ground), electrodes for resistivity testing, or infrared equipment for identifying organic compounds and other contaminants (Bratton, et al., 1995).

CPT data consist of force measurements for tip resistance versus depth. Friction cones provide additional friction resistance data. The results of the cone resistance, friction resistance and the ratio between friction and cone resistance are plotted side by side at the same scale versus depth. These data can be interpreted to derive soil parameters. By comparing the test results before and after grouting, the improvement can be calculated.

The CPT has advantages of being relatively quick, low cost and providing near continuous data over the full depth of the probe. Disadvantages are the CPT cannot penetrate very hard or dense

materials such as rubble, large gravel and hardened grouts and the CPT evaluates only a relatively small plan area.

8.5.1.2 Dynamic Penetration Test Methods

Dynamic methods are among the oldest and simplest methods in use. Dynamic penetration tests using cones or other types of probes enjoy wide use, but the Standard Penetration Test (SPT) is probably the single most widely used method of evaluating soil. The SPT test (ASTM D 1586-99) uses a 63.5 kg (140 lb) hammer falling through 0.76 m (30 in) to drive a 35 mm I.D. split barrel sampler. The number of hammer blows is recorded to advance/drive the sampler 0.15 to 0.3 m (6 to 12 in). The resistance values are indicative of the soil stiffness or relative density and are locally correlated with a variety of soil properties. The method is typically used in boreholes. A disturbed sample of the soil is obtained and can be visually examined or submitted to laboratory testing. To obtain reliable and repeatable soil properties it is strongly recommended that the SPT results be corrected for stress level and the energy of the equipment (ASTM D4633-05).

Many other dynamic penetration tests are available including smaller hand held penetrometers, some of which provide samples. Correlations for these other penetrometers are not so widely available and may need to be developed for each application. For some large projects it may be feasible to consider developing correlations for use of lighter penetrometers where only shallow testing is needed.

Penetrometers evaluate only the material in the immediate vicinity of the point of the probe or sampler, and therefore the boring method can influence the results of penetration tests. Methods such as jetting, or wash borings, can disturb the soils to a significant depth below the sampling point which may cause spurious penetration values.

Probe tests give acceptable results in fine grained soils. They cannot be used in soil formations containing rock particles large enough to deflect or halt the probe. Also, probe test results become increasingly difficult to interpret with increasing depth: the lateral resistance of the soil increases and becomes the major factor in probe resistance.

8.5.2 Excavation/coring

Excavation of pits or shafts to directly observe the location and shape of the grout masses is a useful tool for research and establishing that proper injection parameters have been used. Because of its expense and the fact that inappropriate injection can be determined from observation of the injection rate and pressure behavior during grouting (as discussed in Section 8.1) they are very seldom used for production grouting.

8.6 Geophysical methods

Geophysical test methods measure physical properties of the ground. Commonly, these properties include the shear wave velocity, electrical resistance or conductivity, gravitational

properties, radar reflectivity, etc. The most common geophysical methods are seismic, electrical, electromagnetic, acoustic emissions and micro-gravimetric methods.

At the present time geophysical methods are not widely used on compaction grouting projects. Boreholes are generally required for subsurface condition evaluation, and evaluation of geophysical results usually requires expert interpretation. Typically the particular geophysical method must also be calibrated to other more direct tests. It is thus expensive and the results subject to question. Hence its use is limited to very important projects, and generally only in combination with other methods.

8.7 Summary and conclusions

There is no substitute for good engineering and a qualified contractor. Even so, conditions present under the ground surface may not be as expected. Verification testing is an essential part of achieving the desired performance of grouting. Since we cannot see through the ground, we must use various techniques to derive the information we desire using non-visual means. No single method can guarantee a successful grouting project. A combination of thorough exploration prior to design, sound engineering, continuous quality monitoring and evaluation of the grout injection rate and pressure behavior (including maintenance of good records during construction) is needed to provide an effective product.

The most common verification testing for strength is the simplest. The Standard Penetration Test (SPT) is used extensively despite its limitations. Cone Penetration Tests (CPT) are also used frequently and are gaining popular acceptance. And of course, continuous monitoring and evaluation of the injection parameters during grouting is essential. One of the most effective tools for evaluating success is often the review of grouting parameters recorded during secondary and subsequent split spaced holes. Noting increases in the pressure achieved or reduction in the volume injected to reach a refusal criteria is a positive indication of success. As a project progresses, these types of indicators can often be correlated with post grouting verification SPT and CPT testing.

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9. APPLICATIONS

Compaction grouting is a type of limited mobility grouting in which densification of soils is the major objective. This section summarizes a range of engineering situations in which compaction grouting has commonly been used. Compaction grouting is equally effective in dry or saturated conditions, and has even been applied under water. In addition to densification of loose soils, the concept can also be applied to collapsible soils.

Typically, compaction grouting is applied in connection with one of two objectives; to fix soil that has failed under a structure, or to improve soil ahead of construction. However, the applications can also be categorized by the project to which compaction grouting is applied. By this "application" definition, the use of compaction grouting for settlement correction and liquefaction mitigation comprise about 90% of current total usage.

In this chapter the applications have been broadly organized into those applications for which preventing additional settlement is usually the main objective, and those for which soil improvement ahead of construction is of primary importance.

The list of possible applications given is not exhaustive, and the reader is encouraged to review the case history literature for other successful compaction grouting applications.

9.1 Settlement correction

By far, the widest use of compaction grouting is for improving soil in place to mitigate settlement damage. The procedure is particularly suited for such work as the grout pump can be located distant and only small equipment is needed at the injection site, which allows application in even the most restricted spaces, Figure 9.1.

Figure 9.1 Compaction grouting can be performed in even the most restricted spaces.

Controlled lifting is typically accomplished by connecting a single pump to a successive series of injection points, and sequencing for maximum desired effect. Although rarer, multiple injections can also be made using several pumps to provide more uniform jacking if desired.

By continuing to inject grout after observing initial surface movement, controlled grout lift can be used to jack structures to level or improved elevation gradients. Such jacking requires careful monitoring and highly skilled performance and can be beyond the abilities of normal crews. An ancillary benefit of such lifting can be the reduction of structural stresses, accumulated during initial deformation.

9.1.1 Soil improvement under existing structures

Compaction or densification can be applied for remediation of soils beneath an existing structure to improve its load-carrying capacity. A requirement for higher bearing loads is often associated with renovations, or additions, to structures. A renovation, although not necessarily increasing the bearing loads, may require higher bearing capacities to comply with today's more stringent building codes. Additions to existing buildings often increase the loads carried by the already loaded soil, and if the ground is not densified to increase its stiffness, settlement of the existing structure may result.

9.1.2 Deep foundations

The benefits of densification associated with compaction grouting are not limited to shallow foundation systems. Injection of grout at the base of a pile may enhance the end bearing of the element by densification of the soil beneath the pile as well as by increasing the bearing area. Furthermore, densification of the soils surrounding piles along their length can increase the lateral stresses and the side friction capacity. This same process can, and has, been applied to large diameter drilled shafts to enhance their capacity.

9.1.3 Improving collapsible soils

In this application the breakdown of the soil structure results in a significant reduction in strength until the density is improved. Therefore compaction grouting should only be considered in collapsible soils where the reduction in strength can have no detrimental effect on any adjacent structures, nor adversely affect the stability of the site.

Damaging surface settlements in areas of collapsible soils can often result from inadvertent or accidental introduction of water to the subsurface through pipe leaks or localized surface absorption, especially in traditionally arid climates. Compaction grouting has been successfully applied in such cases as a settlement mitigation measure, although practical grouting treatment may be limited to the "wetted" subsurface plume where weakly-cemented soil structure has already been compromised by moisture intrusion. An important consideration in these situations may involve assessing the risk for continued or additional subsurface water intrusion, and recommendations for mitigation measures as warranted.

9.1.4 Settlement mitigation references

Examples of settlement correction for buildings documented in the literature include Akiyama et al., 1996; Byle, 1991; Engineering News Record, 1977; Kling et al, 2003; Lamb and Hourihan, 1995; Stilley, 1982 and Wong et al. 1996. Foundations for other structures are discussed in Ali & Geraci, 2003; Reed et al, 1998; and Wehling & Rennie, 2003. Deep foundation repair is described in detail in Warner & Brown, 1974 and Warner, 1978. The repair of tunnels is documented in Boghart et al., 2003.

9.2 Pre-construction soil densification applications

9.2.1 Liquefaction mitigation

The recent wave of seismic code revisions and lifeline reliability improvements has resulted in a need for methods to reduce liquefaction potential both under existing structures and for new construction. The densification associated with compaction grouting has proven to be an ideal tool to meet these needs in many situations, especially where near or beneath existing structures or other sensitive infrastructure elements.

9.2.2 Soil improvement under proposed structures

Where site conditions for new construction dictate, ground treatment with compaction grouting beneath the entire structure or in the area of specific foundation elements can be performed to improve soil conditions and allow smaller foundation elements. In many cases, compaction grouting treatment can represent a significant measure of economy by eliminating the need for deep foundations or structurally supported floor systems. Examples of this application include densification of loose materials beneath foundations to limit settlement, improving loose soils to resist liquefaction potential, and densification of materials to improve strength properties.

9.2.3 Soft ground tunneling

Tunneling has also found uses for compaction grouting. By increasing the density of the soil, and hence its stiffness, tunnel advancement may be facilitated while associated surface settlement troughs are reduced. Soil lost and/or disturbed by the tunneling operation can be replaced or densified as the heading advances, precluding damaging settlement.

9.2.4 Foundations involving lateral loading

Compaction grouting can improve the lateral resistance of piles and other foundations by increasing the density of the resisting soil. This increase in density improves the soil's shearing resistance. The increase in density (or unit weight) of the soil will also increase the mass of the passive wedge, increasing the lateral load resistance. Increased soil stiffness associated with soil densification will also reduce the deflection of laterally loaded piles. Compaction grouting may also be used to improve soil around earth anchors to increase their capacity when used a tiebacks for retaining walls.

Vertical compaction grout columns restrained top and bottom, and containing a piece of structural reinforcement, have been used to compact the soil while resisting small lateral loads. Termed compaction grout piles, these lightly reinforced piles are most efficient if loaded axially in compression to maximize the compressive area of the pile and avoid tensile cracking, for example if constructed as battered piles. To ensure adequate grout cover around the reinforcement these piles are usually of at least 0.46 m (1.5 foot) diameter.

Compaction grouting should be used with care around existing structures where grout injection may induce increased lateral loadings.

9.2.5 Pre-construction soil densification references

Examples of liquefaction mitigation using compaction grouting are given in Donovan et al., 1984; Mitchell & Wentz, 1991 and Warner 1981. Two examples of soil improvement for soft ground tunneling using compaction grouting are given in Baker et al., 1983 and Borden et al., 1992. Soil improvement for soil modification prior to structure construction is discussed for a die forging operation in Partos et al., 1982.

9.3 Sinkhole remediation

The low mobility of compaction grout makes it an ideal material for remediation of sinkholes. The control of grout movement during injection allows compaction grouting to be used on sensitive structures such as embankment dams (e.g. Garner et al., 1992). Loose soil in sinkholes can be densified and in Karst formations the movement of the grout as a contiguous mass makes it efficient for filling voids.

Examples of sinkhole remediation using compaction grouting are given in Garner et al. 1992.

9.4 Further information

Compaction grouting has potential application where loose soils exist and an increase in soil density, with an associated increase in soil strength and stiffness, is desirable. Many successful case histories have been documented in the literature, covering an extremely wide range of engineering applications. A selection of these case histories can be found in the proceedings of ASCE sponsored specialty conferences on grouting and ground improvement, most published as Geotechnical Special Publications (GSP). These include “Grouting in Geotechnical Engineering” (Wallace Hayward Baker, 1982) and GSP no. 57 (Byle and Borden, 1995), number 66 (Vipulanandan, 1997), GSP no. 80 (Johnsen and Berry, 1998), GSP no. 104 (Krizek and Sharp, 2000), and GSP no. 120 (Johnsen, Bruce, and Byle, 2003).

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APPENDIX A

GUIDE SPECIFICATIONS FOR COMPACTION GROUTING

USING THE BOTTOM-UP SYSTEM

Guide Specifications for Compaction Grouting
Using the Bottom-Up System

1.0 Scope of Work

Compaction grouting shall be performed as generally depicted on the plans, outlined in these specifications and as directed by the engineer. Changes may be called for in both the exact layout and number of grout holes as conditions encountered during the work are evaluated. The purpose of the work is to densify compressible soil within the specified work area.

Define scope of project. If grout jacking of settled improvements is to be included so state and provide final elevations and required tolerances.
The work can be done on a prescription or performance basis. Prescriptive specifications should provide the pumping rate and the maximum pumping pressure required. Performance requirements usually require the soil to be improved to a given density usually based upon either final SPT, or CPT resistance values.

2.0 Access and Site Conditions

The contractor shall visit the site and independently verify any access or work related restrictions. The type and condition of the soil to be improved is delineated in the geotechnical report of____________________ ____________________dated___________.

Provide any restrictions of working time or area of work. Compaction grouting can be performed with little interference to a facilities normal operation, but if required should be clearly defined. Refer to plans if applicable. All available geotechnical data should be provided to prospective contractors with the plans and specifications. Because compaction grouting adds considerable weight to the treated soil it is imperative to extend the grouting to a competent soil or formational material. The anticipated depths should be stated and provisions for additional depth to reach such a competent layer should be provided.

3.0 Treatment Area and Depth

The soils shall be grouted at the locations and to the depths outlined in the plans and specifications. The grout hole locations and depths are based on the best available geotechnical and structural exploration data, however, all grouting locations have not been explored in detail. The precise limits of the area to be grouted and the exact

Generally a plan showing the anticipated grout hole locations will be provided. Prospective contractors should also be furnished all available geotechnical information. Any information relative to the existence of buried rocks, boulders, abandoned foundations or other substructure should be included.

location and required depth of the individual grout holes are not positively known but will be revealed as the work progresses. The engineer at his discretion may move the location of the proposed holes, change the proposed depths to be grouted, add new holes or eliminate some of the proposed holes shown on the plans.

4.0 Subsurface Pipes and Utilities

The location of existing underground utilities is indicated on the plans. The contractor shall protect these lines and repair at no cost to the owner any that are damaged if located within one foot of the location designated on the plans. Contractor will not be responsible for damage to utilities that are not shown on the plans, or that are located more than one foot distant from the location indicated on the plans.

Contractors should not be held responsible for substructure for which the location is unknown. Although specifications sometimes assign all risk for such damage to the contractor, such will come at a high price and is seldom in the best interests of the owner. The use of a pipe locating specialist service should be considered where extensive substructure exists.

Contractor shall access existing sewer or drain lines both upstream and downstream of the area to be grouted. Clear water shall be run into the upstream access and observed downstream such that any leakage of grout into the line will be observed. Grout injection shall immediately stop upon the appearance of leakage into the line and it shall be thoroughly flushed out and cleared of any grout.

The flow in wastewater pipes can usually be observed by accessing downstream manholes, cleanouts, or excavated inspection holes. Grout color will show in the fluid waste upon grout entering the line and prior to complete blockage allowing flushing from the pipe.

5.0 Materials

5.1 Grout Mixture

The grout mixture shall consist of cement, water and aggregate. The slump shall not exceed 1.5 inches when measured using the ASTM C 143 slump test cone.

Although using ASTM C 143 as a guide, do not specify slump determination <u>as per</u> the C 143 test as it requires rodding of the grout as the mold is filled. Such rodding will result in holes in the somewhat cohesive compaction grout mix.

A minimum of ___________% cement by weight of the aggregate shall be used.

Most compaction grout includes from 6% to 12% cement, however, cement is not required subject to provision of enough fines in the aggregate to provide the required pumpability.

The grout shall obtain a minimum unconfined compressive strength of ______psi when tested in accordance with the requirements of ASTM C 39.

The strength of the grout is of relatively little importance as the purpose of the injection is to compress and densify the adjacent soils. A common requirement for compressive strength is 100 psi. Specification of excessively high compressive strengths provides little benefit and can add appreciable cost. In many cases no strength requirements for the grout might be preferable.

Additives such as concrete pumping aids, gums, gelling agents, high plasticity clay (e.g. bentonite), or similar materials shall not be used.

Regardless of slump, such additives can cause the grout to behave in the ground as a fluid, resulting in hydraulic fracturing and loss of control.

5.2 Cement

Cement shall be Type I or Type II as per the requirements of ASTM C 150. Other types of cement may be used subject to the engineer's approval.

It is important to keep in mind the purpose of the grout, which is to expand in a homogeneous mass so as to displace and compact the adjacent soils. High strength is seldom required so the properties of the cement if used are of relatively little importance.

The cement can be delivered to the job site in bags or by bulk delivery. Bulk delivered cement shall be stored in appropriate silos or other containers especially designed for cement storage. Cement storage facilities shall be subject to the engineer's approval.

5.3 Aggregates

The grout aggregate shall consist of naturally occurring, round grained materials conforming to the grain size distribution shown in the envelope on Plate 1.

Proper grout aggregate gradation is fundamental to satisfactory performance of compaction grouting. Use of crushed or angular aggregates does not adversely affect the properties of the hardened grout, but can result in pumpability problems. Such should not be prohibited

but grout pumpability should be the responsibility of the contractor, and will not be a problem with natural round grained materials.

The inclusion of clay size particles in the aggregate shall be limited to 5% by mass (see Plate 1). The portion of the aggregate passing a No. 40 sieve shall not possess a plasticity index (PI) greater than 15 when tested in accordance with ASTM 424.

The presence of high plasticity clay or excessive amounts of other clays in the grout may result in the loss of injection control and hydraulic fracturing of the soil. This is a common cause of compaction grouting failures that must be avoided.

5.4 Water

Water shall be free of excessive amounts of salts, or other impurities that adversely affect the set or hydration of the cement in the grout mixture as specified by ASTM C1602, Standard Specification for Mixing Water Used in the Production of Hydraulic Cement Concrete, 2004.

Again, it is good to keep in mind that strength of the grout is usually of relatively little importance.

6.0 Drilling and Grouting Equipment

6.1 Drilling Equipment

Drilling equipment shall be capable of advancing the grout holes to the required depth through the existing soil and rock materials as well as any natural or man-made obstructions. The term drilling herein used shall include driving methods for casing placement. Either rotary or rotary percussive drilling equipment can be used.

Some contractors prefer to drive a casing utilizing a disposable plug on the bottom end that is knocked out prior to grout injection.

Circulation flush shall be accomplished with water or air-water foam. The use of other drilling fluids or mud shall be subject to the engineer's approval.

Remnants of many drilling fluids and especially mud can result in hydraulic fracturing of the soil and loss of control of the grout injection when pressurized by the grout. Compressed air is not efficient in damp or wet conditions and can cause damage to the formation.

6.2 Grout Casing

The casing shall be a minimum of 1 ¾ inches, maximum of 3 inches internal diameter and possess sufficient strength to withstand the drilling/driving, grout injection, and withdrawal forces required for the work. It shall have flush joints on both the interior and exterior surfaces. The joints may be threaded or welded. The maximum casing joint length shall be five feet unless withdrawal is by the drill rig or similar apparatus and real time computer monitoring is being used. In such case an additional pressure transducer shall be provided at the header.

Larger casing will have no adverse effect on the work, but is obviously heavier and more difficult to handle. Grout may free-fall in casing greater than three inches inside diameter which can place undesirable static head pressure in the hole. Casing is normally withdrawn by portable withdrawal jacks and man handled. On very deep or specialized applications it might be handled by the drill rig or similar apparatus.

Any casing or holes lost due to broken or bent casing, insufficient casing strength, or the contractor's inability to pull the casing, shall be abandoned and new replacement holes shall be drilled and grouted at the contractor's expense.

Casings occasionally bend, break, or become stuck, especially in deep holes and/or rocky conditions. Contractors are more likely to use adequate equipment and casing systems if they must bear the cost of such problems.

6.3 Casing Withdrawal System

The casing withdrawal system shall be capable of withdrawing the casing in the required stages under both normal and extraordinary conditions. Any hole lost due to the contractor's inability to pull the casing will be replaced with a new hole at the contractor's expense.

6.4 Grout Batcher/Mixer

The grout mixing system shall be capable of precisely proportioning the mix constituents and blending them into a homogeneous grout of uniform consistency. It shall be capable of continuously proportioning and mixing the grout in sufficient quantity, without interruption due to inadequate

Continuous production of a grout of uniform consistency (slump) requires both quality equipment and a competent operator.

proportioning or mechanical limitations. Automatic volumetric proportioning and mixing systems complying with the requirements of ASTM C 885 and/or ACI 304 will be acceptable. Where used the automatic metering systems shall be calibrated in the presence of the engineer prior to the beginning of grout injection and at any additional times required by the engineer. Properly calibrated volumetric containers and scales required for proper calibration shall be provided by the contractor.

There are many manufacturers that supply equipment complying with these standards. Many grouting contractors use homemade or in some cases obsolete batching units that are not in compliance. The specifier is cautioned to review both the standard and the equipment proposed for use to assure compliance.

Batch type mixers may be used subject to provision of an accurate means of proportioning the individual grout constituents.

Some contractors prefer to use batch type mixers, often in combination with a preblended grout material furnished in bags.

6.5 Grout Pump

The pump shall be of the piston type and have a grout pumping piston no greater than four inches in diameter. It shall provide positive displacement of the grout and be capable of pumping at variable rates of 0.2 to 2 cubic feet per minute at continuous pressures of up to 1,000 psi.

Larger size cylinders result in inadequate velocity of the grout through the system and allow for excessive leakage at the seals due to their greater circumference. In some applications, greater pressure capability and/or a greater or lesser pumping rate will be required. Specify accordingly. Keep in mind that line friction will result in a pressure loss within the delivery line. Line loss will typically be less than 2 psi per foot of flexible hose and 1 psi per foot of rigid steel tube. It will be significantly higher for flexible hose when pumping pressure is above about 500 psi.

The pump shall be in first class operating condition and capable of complete filling of the grout cylinders on each stroke. It shall be equipped with a force-feed or other mechanism as required to assure such complete filling. Short stroking of the pump will not be allowed and any grout pumped during such malfunctions will be at the contractor's expense.

Small-line concrete pumps are most often used for compaction grouting. These pumps usually are equipped with very long material cylinders. While quite adequate for plastic concrete, complete filling with the relatively sticky grout mix is often difficult.

A remote off-on control for the pump shall be provided at the grout injection point. An accurate system to measure the quantity of grout pumped at any time interval shall be provided. The grout volume measuring system shall be calibrated by the contractor each day of pumping at the beginning of work and at any other time that short stroking or a change of the grout pumping rate is suspected.

6.6 Grout Delivery Line

The grout delivery line shall consist of high pressure flexible hose or a combination of hose and rigid pipeline and be watertight under pressure. It shall be a maximum of two inches in diameter. All components of the delivery line including coupling clamps shall be in good condition and capable of handling the pumping pressures to be used with a minimum safety factor of two. A pressure test of the delivery line to confirm its conformance herewith shall be performed as required by the engineer.

Water tightness of the delivery line is essential. Even a slow drip from a coupling can result in excessive water loss from the grout resulting in downstream plugs. Most compaction grouting employs 2 inch delivery line and 1 1/2 inch lines have been successfully used. Larger lines result in insufficient grout velocity which delays the arrival of fresh grout to the header and can contribute to line blockages. Flexible hose is subject to internal expansion at higher pressures wherein the grout extrusion increases in diameter resulting in very high line loss as the expanded extrusion encounters couplings or fittings which do not expand. Premium steel braid hose should be used when pumping pressures greater than about 500 psi.

6.7 Pressure Gauges

Pressure gauges shall be installed at the grout pump and at the grout header (top of hole casing). All gauges shall be accurate and in good working order. They shall be protected from grout intrusion by suitable gauge protectors. Gauges shall have a minimum dial diameter of three inches, and the maximum pressure range shall be not greater than 150% of the anticipated

A three inch dial is about the smallest that can be readily read from a reasonable distance.
Gauge readings are not accurate in the upper and lower 25% of the dial range.

maximum grout pressure. A sufficient number of spare pressure gauges shall be maintained on the job site and any gauge of questionable accuracy shall be promptly replaced.

The primary purpose of the pressure gauges is to monitor for safe pressures and observe pressure trends – extreme accuracy is not required.

7.0 Data Acquisition and Reporting

7.1 Logged information

The contractor shall maintain and provide the engineer a continuous log delineating the drilling and grout injection parameters for each hole. Minimum data provided on the log shall include:

1. Date(s) and time the hole was drilled.
2. The drilled depth.
3. Any obstructions encountered or unusual events occurring during drilling.
4. Depth drilled and/or elevation of both the top and bottom of the hole.
5. Date(s) and time grouting of the hole was started and ended.
6. Injection pressure at the pump and at the hole collar in three minute intervals from the time grouting starts.
7. The injected volume at each three minute interval.
8. Grout termination criteria.
9. Location and amount of any uplift or displacement of any structure or the ground surface during grouting, if any.
10. Notation of any other observations relating to the grouting.

Pressure and rate of injection are directly related. The pressure will increase with an increase of the injection rate and will lower as the injection rate is reduced. Both values are of equal importance, and one without the other of limited usefulness.

The name of the person preparing the logs and the current date shall occur on all pages of the log, and the pages shall be numbered chronologically from the

Knowing the time events occur allows calculation of the pumping rates which are fundamental to understanding the effectiveness of the work. Further,

start of work. The current time shall be noted at each log entry.

knowledge of the times of various events allows analysis of the project execution and production should this be required following completion of the work.

7.2 Real Time Computer Monitoring

Where used, the primary pressure transducer shall be located at the grout header immediately above the top of the casing. As a minimum, continuous plots of both pressure and injection rate shall be recorded in a time domain. Data shall be recorded in a format compatible with contemporary spreadsheet software such as Microsoft Excel, and shall be supplied to the engineer in digital, and when requested printed, form. A suitable printer shall be supplied.

Some contractors tout proprietary software that only they can open. This prevents the engineer from opening, enlarging, or otherwise manipulating the data for optimal analysis. Off the shelf computer monitoring equipment is available on the open market.

7.3 Daily Report

The contractor shall provide a daily report delineating the activities for each day that his people are on the job site. The log shall provide at minimum the following:

- Date
- Weather
- Hole numbers of holes drilled
- Hole numbers of holes grouted
- Materials received and time of delivery.
- Names of any visitors and time on job.
- Details of any accidents, injuries, or other unusual events including time.

Copies of receipts or delivery tickets for all materials delivered to the job site shall be provided to the engineer.

Knowing the quantities of material delivered to the job site allows a check of the payment quantities billed as well as confirmation of the quantity of grout actually injected. Product yield on the order of 22 to 23 cubic feet of grout per moist-delivered ton of silty sand aggregate

is common.

7.4 Movement Monitoring System

The contractor shall provide instrumentation to detect any movement of the ground surface or any structure within a radius of 30 feet from any hole being grouted. The monitoring devices shall be capable of detecting movements of 1/32 inch or more in any direction.

The instrumentation may include but is not limited to string lines, telltales, manometers, lasers, and optical devices. Backup surveyor's instruments shall be provided in such quantity as to allow evaluation of the movement of all structures without the necessity of moving the instrument location during injection. The original position of all structures shall be established prior to grout injection by the placement of suitable markings or targets thereon.

The contractor shall dedicate experienced and fully qualified personnel to monitor the instrumentation in order to prevent any damage to the site or structures. Any damage that does occur due to insufficient instrumentation or monitoring effort shall be repaired or replaced by the contractor at no cost to the owner.

Appropriate monitoring is often lacking and the frequent cause of damage during grouting.

8.0 Communication System

The contractor shall provide a communication system that allows immediate voice contact between the grout hole, pump operator, and monitoring personnel. Any damage that occurs as a result of lack of immediate communication shall be repaired or replaced by the contractor at no cost to the owner.

Lack of communication is another frequent cause of damage during grouting.

9.0 Order of Work

In general alternate primary holes will be grouted first followed by the intermediate secondary holes.

10.0 Drilling

10.1 Establishing Grout Holes

The grout holes can be produced either by drilling or driving a temporarily plugged casing. The method used shall be capable of penetrating rocks and other obstructions. Regardless of the method used, the casing shall be in tight intimate contact with the surrounding soil of the resulting hole so that it is firmly held in place and resistant to ejection from the grout pressure, and /or leakage of grout around the perimeter.

The exact method of effecting the holes is not significant on most work. On some projects however, specification of the exact drilling method is in order. As and example, hydro-collapsible and other dry soils require moisture in order for compaction to occur. The requirement of a drilling method using water for the circulation flush can provide the necessary moisture.

10.2 Hole Location

The exact location, depth, and spacing of the grout holes is subject to change as directed by the engineer during the performance of the grouting program.

10.3 Control of Drilling Circulation Flush

Water or other circulation media shall be captured and directed to an approved disposal location. Ponding of uncontrolled drilling flush or wastewater in the work area will not be permitted. Settling tanks or other devices to separate drill cuttings and other solids from the water shall be used when required.

Ponding of water and mud in the working area is a big problem with some contractors. Excessive water ponding on the surface can penetrate and weaken the upper soils so as to compromise their ability to restrain the grout forces. It also adversely affects the orderliness of the work and worker safety.

10.4 Water Injection

The injection of water into the drilled

Dry soils may require additional water for

holes in addition to any remnant water from the drill circulation may be required or prohibited by the engineer depending upon the exact soil conditions encountered.

adequate compaction. Contractors typically inject water to loosen stuck drill steel or casing and this must be reasonably controlled. The injection of excess water can weaken large volumes of soil at depth resulting in unacceptable surface settlement.

10.5 Drilling Log

The contractor shall prepare a log of each grout hole, which delineates the nature of the geomaterial penetrated. The log shall include the depths of hard or soft soil zones, any existing voids, reduction or loss of circulation flush, encountering of rocks, boulders, or any other significant conditions. Copies of the logs shall be provided to the engineer upon completion of drilling of each hole.

It is good practice to consider every hole an exploratory hole. Although the acquiring of detailed information is not practical during drilling of grout holes, a cursory description of the materials and conditions encountered can add valuable information to the known data.

11.0 Grout Injection

11.1 Depth Confirmation

The actual depth of the open grout hole shall be confirmed by measuring with a proper weighted measuring tape immediately prior to connection of the grout delivery line. The measured depth shall be noted. If it is less than the planned depth, the hole shall be redrilled to proper depth prior to grouting.

Occasionally driller's depth records are incorrect. Additionally caving or squeezing in of the holes can occur prior to grout injection.

11.2 Sequence

The sequence in which the holes are drilled and grouted is subject to the approval of, and may be modified by the engineer. Grout injection shall not be initiated into any hole within 12 feet of a hole previously grouted within the prior 12 hours. In general, holes located near a downslope or retaining wall shall be injected prior to those holes located at a more distant location.

The sequence in which the holes are injected has a profound influence upon the success of the work and the avoidance of further damage. Generally perimeter holes should be grouted prior to those on the interior. Zones that provide lesser lateral restraint such as those near downslopes or retaining walls should <u>always</u> be grouted first.

11.3 Grout Staging

Holes shall be injected in ascending stages starting at the bottom and working upwards. No stage shall be injected until the immediately underlying stage has been completed. Individual stage lengths shall be a minimum of 1 foot and a maximum of 4 feet in height.

Most contractors pull the casing in one foot increments which is valid for many jobs. Upward heave of overlying structures is a common refusal criterion. Whereas the heave resulting from one grout stage is insignificant, the cumulative heave of many stages can be considerable. Where this might be undesirable, specification of larger grout stages is recommended. The density improvement from the grouting is not diminished as a result of stage lengths up to about 4 feet. The stage length should consider the contractors casing system, however. Stages of 1, 1.5, or 3 feet are appropriate where 3 foot lengths of casing are being used, while one or 2.5 foot would be more reasonable where 5 foot joints are employed.

11.4 Access Requirements

Access to the mixing pumping and injection locations shall be provided to the engineer or his designated representatives at all times.

11.5 Injection Rate

The grout injection rate shall be as directed by the engineer. It is expected to be within a range of 0.5 and 2.0 cubic feet per minute and average 1.5 cubic feet per minute for the entire work. An adjustment will be made in the contract price if the average injection rate varies more than 25% up or down from the expected 1.5 cubic feet per minute.

Contractors usually want to pump at the fastest rate possible in order to minimize the cost of the work. However an excessively high pumping rate can promote early surface heave, negate effective densification, and lead to hydraulic fracturing. Fine grain soils require a slower pumping rate than do course grained deposits.

11.6 Grout Refusal Criteria

Grout injection into any stage of any grout hole shall be discontinued as directed by the engineer. Refusal

pressures must be measured at the approved rates of injection. General refusal criteria will be any one of the following:

- Pumping at a header pressure of 1,000 psi or more for a period of three minutes.

Some grout holes develop high pressure at the start of injection but take grout freely at significantly lower pressure after a few minutes of pumping. However, such high pressures accompanied by no appreciable grout flow may occur in "tight" formations or bedrock, and injection pressure will rapidly approach the limit of the delivery system, often well-beyond 1,000 psi. A blockage in the casing would behave in a similar manner, although the distinction can be made by slightly withdrawing the casing (with the pump stopped), and observing pressure response. A slight drop in pressure upon pulling the casing will corroborate a "tight" formation, and the casing may then be withdrawn slowly until grout begins to flow.

- Sustained pumping at a header pressure of 500 psi or greater.

Most soils are effectively compacted at sustained pressure within a range of 350 psi to 500 psi at a reasonable injection rate on the order of 1.5 cubic feet per minute. However, pressure limitation criteria should generally not be made until the work has started and injection behavior in the actual jobsite soils has been observed. Higher pressures should be considered for very important or deep holes.

- Unwanted displacement of an adjacent structure of greater than 1/8" occurs.

Movement tolerance is very structure and situation specific, and may also be constrained for contractual (legal) as well as technical reasons. It is crucial that the allowable movement tolerance be defined in advance of grouting – and this is the Owner's responsibility (usually determined by their structural engineer). As a general guide, for brittle structures

(those with little tensile strength), tolerable vertical movements may be as little as 1/32" and/or a differential movement as little as 1V in 1000H. Grouting work to this level of precision requires careful use of electronic monitoring systems, electrolevels in particular, likely supplemented by electronic precision leveling using an invar staff. Grouting near machinery (e.g. rolling mills) may require this level of precision or more. Conversely, steel framed buildings as found in light industrial use are more movement tolerant with an allowable differential movement of 1V in 200 H, or about 1/4" to 1/8" vertical deflection, and require less onerous movement control during grouting.

- Unwanted displacement of the ground surface of greater than 1/32" occurs during a grout stage.

Compaction grouting should cease as soon as heave is observed at surface (both to reduce the likelihood of damage to adjacent structures and because once heave occurs the effectiveness of the compaction reduces significantly). Due to the accumulation of heave during subsequent grouting stages, a very small tolerance on vertical movement should be specified. A value of 1/32" approximates to the magnitude of movement first detectable with the naked eye.

- A grout volume of ________cubic feet has been injected.

In reasonably uniform soil where the grout volume required to obtain the required density can be rationally determined, specification of an appropriate volume limitation for the injection is advisable. In those situations where the existing soil density is variable or where actual voids might exist (such as nested boulders) widely varying grout quantities will be injected and a volume refusal criteria is usually not in order. In such cases the use of pressure criteria is usually more prudent.

11.7 Improperly Grouted Holes

Any grout hole that is lost or damaged, does not reach the design depth, or is not continuously grouted as a result of equipment deficiencies or mechanical failure, inadequate control of the grout pipe (including allowing the grout pipe to be expelled from the hole due to insufficient restraint), inadequacy of the grout mix, improper drilling, mixing, or injection procedures shall be backfilled and replaced by another properly installed hole at no cost to the owner.

11.8 Groutjacking

The existing ____________ structure(s) shall be raised to the grades shown on the plans, further delineated in these specifications, or as directed by the engineer. All lifting efforts shall be performed uniformly around the structure and in small increments so as to limit further damage to the structure.

Jacking of settled surface improvements is often performed during the compaction grouting work. Not all contractors are suitably skilled at such lifting, however. Where lifting is to be accomplished, appropriate specification provisions are requisite, as is selection of a contractor of proven ability. It is often not necessary to return a structure to an absolute level position, but rather simply adjust the differential elevations such that they are not readily noticeable.

11.9 Hole Completion

Completed grout holes shall be filled to the ground surface with grout placed under a minimum pressure of 5 psi.

<u>12.0 Site Maintenance and Restoration</u>

12.1 Housekeeping

The contractor shall keep the site clean

and tidy at all times. Site improvements shall be protected from damage or becoming soiled through suitable temporary covering. Spilled grout shall be promptly picked up and moved to an appropriate waste storage area. Hoses, delivery lines, and other items that are not in immediate use shall be neatly stored in a manner that will not impede the ongoing work. All trash, used cement bags, etc. shall be collected and neatly stored for disposal. As soon as a reasonable quantity of such waste material has gathered, it shall be promptly removed from the site. Water and waste grout resulting from cleaning of the mixer and/or pump shall be promptly collected and disposed of. Water shall not be allowed to pond in the work area.

12.2 Site Cleanup

Upon completion of the work, all waste shall be removed from the site and the site shall be left in a "broom-clean" condition. Any remnants of drilling fluid or grout that have splattered on improvements shall be completely removed. Where suitable removal is not practicable, the affected areas shall be recoated or replaced to the satisfaction of the engineer.

Various levels of responsibility for site cleanup or restoration may be assigned to the grouting contractor, depending on its contractual role. At a minimum, the grouting contractor should remove excess material and waste, and leave the site in a "broom-clean" condition.

<u>13.0 Submittals</u>

Prior to the start of work the contractor shall submit to the engineer the following information. No work shall be commenced until the engineer's approval of the various submittals.

13.1 Grouting Plan

1. Description of all grouting equipment proposed for use

including but not limited to mixers, grout pumps, delivery lines and appurtenances. Information shall include the make, model, year manufactured, and general condition for each item. If items are to be rented, submit written verification that the unit will be available from the renter. Inspection of the listed equipment may be made prior to award of a contract.

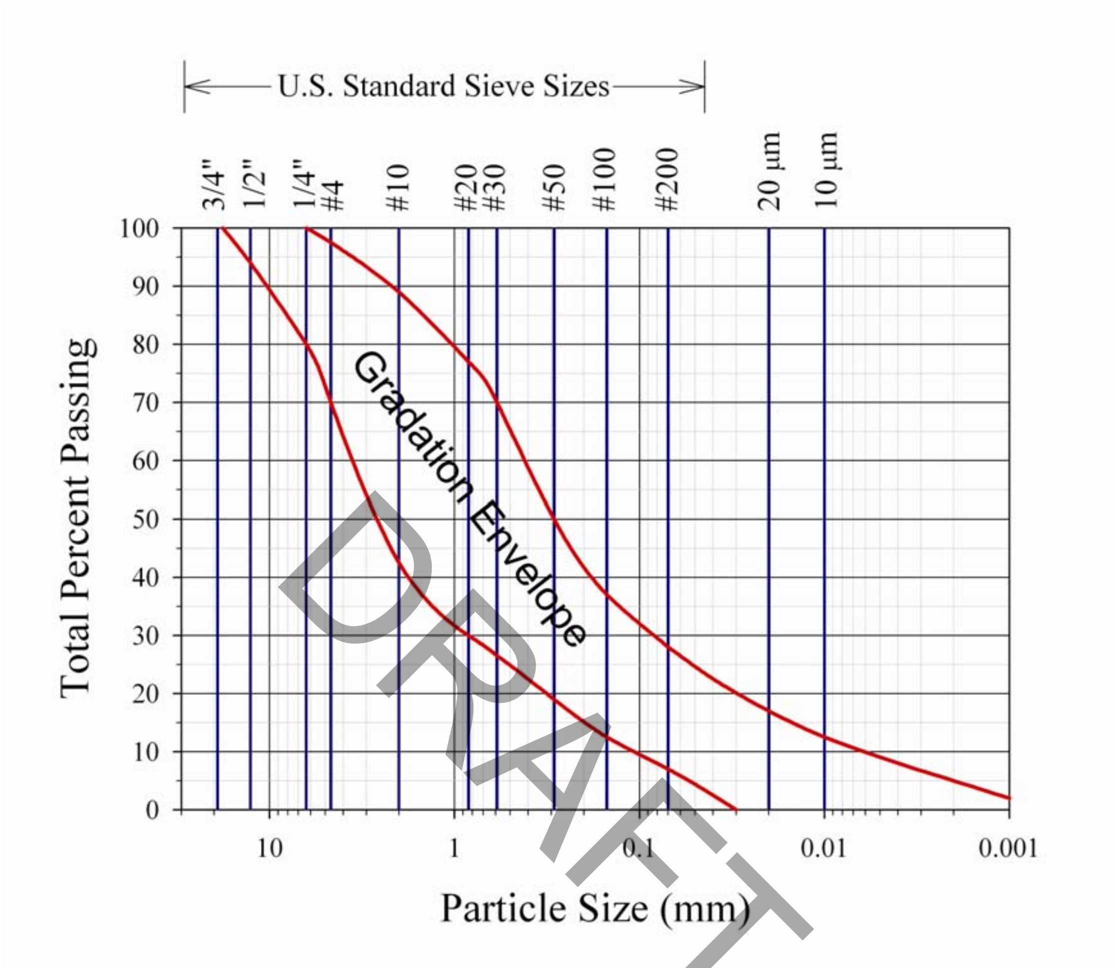
2. A description of all equipment and instruments to be used for surveys and monitoring of the ground surface and adjacent structures during the work.
3. Names and qualification statements for all personnel that will be used in the drilling, grouting, and monitoring operations. This will include all drillers, mixer and pump operators, grout header technicians, and all monitoring personnel. All listed personnel must have a minimum of three years continuous experience in similar grouting work.
4. A description of the drilling methods and equipment to be used.
5. A description of the casing and casing withdrawal system to be used including a review of prior experience in the use of such casing in similar soils and to similar depths as the contemplated project.
6. Grout material sources including grain size distribution and PI or hydrometer test results of the aggregate to be used, and the proposed mix design.
7. Methods and equipment for calibration of the proportioning of the grout constituents.
8. Methods and equipment for calibration of the grout quantity pumped and pumping rate.
9. Statement of proposed sequence of

operations.

10. Description of grout injection operations.
11. Method of structural lifting and description of proposed groutjacking operations.
12. Copies of proposed drilling and grouting record forms.

13.2 Monitoring Procedures

1. General plan and description of proposed monitoring operations.
2. Description and specifications of monitoring equipment and instruments.
3. Proposed methods to obtain and record monitoring data.
4. Copies of proposed monitoring data forms.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1/2"
1/4"
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#20
#30
#50
#100
#200
20 µm
10 µm
Total Percent Passing
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90
80
70
60
50
40
30
20
10
0
Gradation Envelope
10
1
0.1
0.01
0.001
Particle Size (mm)
DRAFT

PLATE 1