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Grout Engineering for Directional Drilled Bores

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1. ABSTRACT

Grouting of horizontally directional drilled (HDD) bores is becoming a more frequent requirement but failures continue. Grouting is an engineered product, which may be applied to HDD issues. This paper provides an overview of grouting capabilities, design approach for planning a successful installation, and several types of installation procedures.

Grouting failures have included structural and thermal issues along with failing to meet the often unrealistic expectations of the owner/regulator. HDD construction is frequently used in multiple business sectors for reasons specific to that business entity, which usually lacks the knowledge of the HDD process, but wants grout for rational reason. Owner's and regulators faced with HDD crossings are more frequently requiring grout to stabilize the ground above the drill path, to protect certain features from settlement like infrastructure, or to block preferential ground water pathways that could destabilize levee or water conveyance systems. Power transmission owners require grouting to adjust soil properties and promote cooling of underground power cables.

Subsurface modification by grouting, even around underground structures like pipelines, has been around for many years and is a proven technology. It does have a scientific and engineering basis that permits reasonable designs based on an engineered approach with realistic expectations and higher probability of project success from the perspective of all stakeholders.

2. INTRODUCTION

The word 'grout' encompasses a wide range of products and properties. Subsurface grout application may be a filler of cavities, a ground stabilizer, a water block, a thermal insulator or transmitter, or simply a means to consolidate and improving the soil properties (compaction grouting). Grout properties are varied to accomplish these multiple tasks and project objectives. Thus, different projects require different properties of grout and application to meet both project purpose and project construction criteria. The result is that grout requires project specific formulization. There are simply too many objectives and delivery systems; it is unrealistic to expect that one 'typical' grout could work for all situations. This is a basic premise necessary for a successful project.

This paper focuses on an engineered approach to grout that can be used for filling the annular space in an HDD bore and also provides some guidelines for changing properties to accomplish this task by working with various components of a grout mix. This paper assumes that the reader has a basic understanding of the HDD process[1].

[1] Sidebar 1 - compaction grout has been used successfully to form a seal around an HDD installed water pipe entering a cofferdam at a depth of 60 feet in saturated soil which replaced the need to dewater the area during the cofferdam penetration.

2. PLANNING

Planning a grout installation includes: defining what is necessary for the project design success, defining at least one way to construct the grout installation, identifying potential failure mechanisms, and designing methods for managing or avoiding the failure mechanisms. Planning may also include defining a means and method that can be used to complete the grout installation. A contractor may or may not follow the engineered approach but good engineering requires at least one way to construct. Table 1 provides typical construction practices that may be considered when planning an annular grout fill.

Table 1. Typical Construction Practices

Construction Type	Construction Sequence	Construction Options
Cased Horizontal Directional Drill (HDD) with single or multiple product pipe(s)	Construct HDD and install casing. Plan for minimum area fill ratio of product to casing area of 50% and for grout to be placed from one end of the casing.	Central Mix may not be available in small orders. Grout mixes with high fines can contaminate a batch plant requiring cleaning before the plant can resume normal operations.
	Install product with/without spacers and tremie pipes then fill the product pipe(s) and product to casing annulus with clean water.	
	Construct bulkheads and containment pits at both ends of the casing with a minimum of 2 grout tubes to the low point and a vent tube at each end with a valve located at the top of the casing.	Mobile Mixer can produce a designed high flowability and low abrasion mix with level feed to a constant displacement pump. Mixer requires calibration and training.
	Pump water and thin grout into the grout tube at one end followed by design grout. Continue until design grout returns are noted from vents at far end. Close the vent and continue to grout until grout emits from the second vent.	Design mix to keep pump discharge pressure below burst pressure of tremie pipes and downhole discharge pressure below burst pressure of casing and buckling collapse pressure of product pipe.
Uncased Horizontal Directional Drill (HDD) with single or multiple product pipes	Construct HDD in rock or soil that will maintain a hole. Collapsing, caving, or unstable hole will not accept theoretical grout volume and may not be reliably grouted. Plan to grout from both ends.	Can fill product pipes with water and pressurize if necessary to prevent buckling.
	Install product assembly consisting of the product pipe with/without spacers and grout tubes (tremies) that extend from each end of the HDD and terminating with the longest tremies within 5 feet of the deepest point along the HDD drill path. Include additional tremies placed at periodic intervals not exceeding around 200 feet toward each end.	Use additives like pump aid and water reducers if necessary with special aggregate blend for reduction of discharge pressures in the casing.
	Fill product pipe(s) with clean water and pressurize if necessary to prevent buckling.	Design grout is recognized by measuring the unit weight of the grout at the vent and determining that the weight is within about 2 pcf of the grout at the pump. Be
	Construct containment pits at each end of the HDD for water and grout containment.	

Construction Type	Construction Sequence	Construction Options
	Pump water and thin grout into one of the longest tremies until theoretical volume reaches the second longest tremie then start pumping also through the other longest tremie from the other end of the tunnel. Pump theoretical volumes to fill each volume to the next grout tube plus a design amount then switch to the next grout tube. Continue until grout emerges from the vents at each end.	prepared to remove water as the grout displaces the water during the grouting.

3. GROUT ENGINEERING APPROACH

Engineering as a process, is a means to assess and mitigate risk of encountering a hazard associated with some element of the grouting process or the product during or after grout installation by the use of science and judgment. An engineered approach to grouting should be a collaborative effort between a specialty grout designer, the installation contractor, and the project designer. Risk mitigation for high risk projects may include laboratory testing of test mixes to verify the designed properties of the mix. If there are questions during construction regarding handling of the mix, a full scale field test may be used to verify the process.

Contingency planning is an often overlooked critical component of a grouting plan. Annular grouting is considered a high risk operation when compared to many types of construction grouting like slab jacking and hence relatively expensive. The grouting contractor is exposed to risks which could have considerable impact on the cost of the project. For instance, in the event that the installed grout fails to meet the performance criteria or designed properties, it is not often possible to remove the grout and this can result in an entire HDD bore failure. A completely new bore may be required at added cost and time. Therefore, contingencies should be included in a grout design to fix a design or construction problem or component failure during active grout placement[2].

4. CONSTRUCTABILITY GUIDELINES

Construction properties necessary for grouting are dependent on the construction method selected for the installation and designed grout properties. A main factor that affects the designed properties of the grout is the type of binder used. The type of binder used may also impact contractor qualifications and ability to do the work as different binders have significant differences in how they are constructed.

Cost variations between construction methods are significant. For example, grout provided by a central mix operation and placed in a manner similar to concrete for foundations when a seal at the end of an HDD construction is the only design requirement may be relatively inexpensive. Custom field blending and pumping into remote confined spaces along an uncased HDD bore of considerable length will be relatively expensive.

Grouts have been successfully formulated to pump without segregation and at relatively low pressures for several thousands of feet. Failures have included collapsed product pipes, melted product pipes, grout filled product pipes, broken product pipes, and incomplete grouting of the product pipe which could compromise the long term system performance. Installation cost should include some design cost to mitigate risks that could occur during installation. Design cost tends to range between 6% and 15% of the grouting construction cost depending on the degree of risk. Failure to properly plan and design the grouting operation can result in the following:

- Grout placement pressure that collapses or burst product pipes;
- Use of non-structural materials as casing and product pipes (instead of structurally rated materials) resulting in broken connections and collapsed pipes;

[2] HDPE tremie pipes have been successfully mechanically breached and restored to service for cement based grouting at distances of over 700 feet after grout flash set at the discharge of the tremie rendered the tremie inoperable.

- Use of Portland cement based grouts which generate heat during curing and could significantly reduce the strength of plastics resulting in collapse or melting of plastic ducts and pipes;
- Use of glued couplings (instead of mechanical couplings) that easily fail under high grout loads letting fluid grouts penetrate into pipe or duct space.

Lack of understanding of the need for annular grouting design for both project and construction criteria often is the cause of these failures. Most grouting contractors are not experienced with HDD annular fill grouts. Additionally, a grouting contractor is also allowed to rely on specifications describing annular grouting as engineered and constructible using the grouting contractor standard means and methods. This approach may get the grout in the annulus but may not adequately address the limitations of the installed product and the interaction between the installed product and the grouting operation. The contractor must be informed of limitations on grouting means and methods imposed by project design and project material selection to be able to successfully price and install a high performance annular grout.

Typical project specification elements that will impact construction include specified aggregate blends, grain size distribution, aggregate grain roundness, additive performance, water/cement ratios (0.35 < w/c < 0.6), tremie pipe sizes and structural capacity, product pipe structural capacity, amount of cement in the mix, type of cement in the mix, maximum aggregate size as compared to the tremie pipe and annular space size, mix working time, and the pump and mixing method just to name a few. As an example, a working aggregate grain size distribution needs to be well graded to permit relatively low pressure during pumping such as illustrated in Figure 1. Specification of Cement Sand or Mason Sand may easily lead to construction failure.

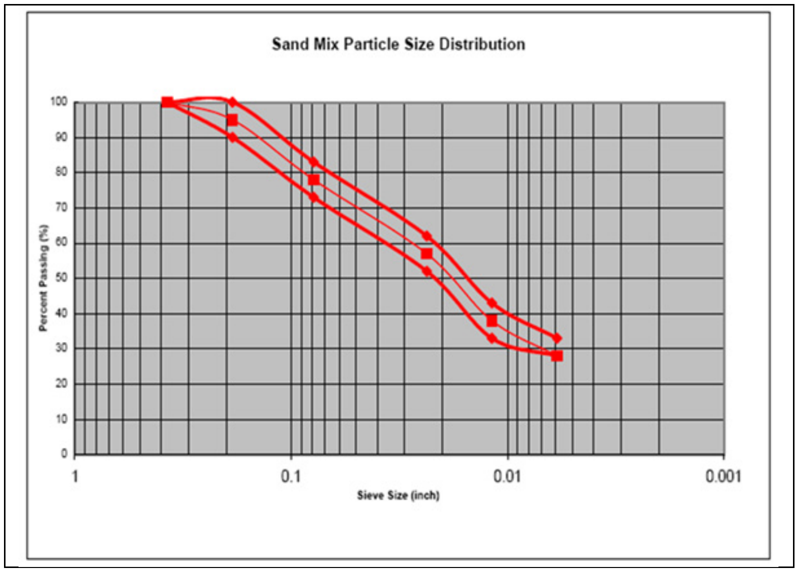

Figure 1. Typical grain size distribution specifications for HDD annular fill grouting

Table 2 provides guidance on which material properties and procedures will influence grout performance. Material selection may then be completed based on installation requirements, material availability, and construction cost. Material cost depends on the specific properties required and the availability of these materials. Construction cost depends on installation time and the selected construction means and methods plus a risk factor associated with placing the grout at the desired location[3].

3. GROUT MIX DESIGN GUIDELINES

Mix design is like making a cake; various ingredients are selected and blended with specific tools to achieve specific design criteria. Properties vary to meet design criteria include: strength, permeability, thermal conductivity, weight, and flowability. Construction is the process of handling the ingredients with specific tools to obtain the designed product. Properties of the ingredients and the curing of the mix that may be varied by design include: set time; friction resistance to flow; temperature; aggregate mineralogy, shape, and grain size distribution; and additives.

Table 2. Design Elements That Can Be Engineered For Grout Placement

[3] Grout risk factors are high and costs are high. HDD contractors are not grouters and few will even attempt to grout. Small specialty firms are normally hired to design and install grout. Grouting cost may be in the range of $60 to $200 per foot of bore length compared to bore and installed product cost that may range between $600 and $4,000 per foot of bore length. Failure can bankrupt a small specialty firm.

Construction Criteria	**COMMENTS**	
Batching	Central Mix: Stay with materials already available at plant, site close to plant, retard mix for travel and installation delays	Site Mix in Mobile Mixer or Grout mixer: Wide variety of mixes available providing that mixer is calibrated and experienced crew is used. Can pre-blend and have fresh mix in amounts that can meet installation demands with no delays.
Pump Type	Progressive cavity	Piston or diaphragm pump
Grout Type	Slurry - ASTM Flow Cone 25 to 50 seconds	Aggregate mixes - ASTM Flow Cone (35 to 60 seconds)
Pump Distance	>5,000 feet	<2,000'
Tremie Size	As large as possible with minimum 6 times maximum aggregate size.	
Tremie material	Select material based on burst capacity vs anticipated friction induced internal pressure and erosion of material from abrasive grout flow. Flush coupled: steel, HDPE, PVC, and fiberglass.	
Tremie Installation	Pre-fabricated with product bundle and pulled into hole or may be pushed in along a bore entry or exit tangent. Design material stiffness for installation loads in tension or compression.	
Tremie Length	Controlled by design of aggregate angularity, aggregate grain size distribution, viscosity of mix, and flow velocity. Design based on tremie internal pressure capacity against burst strength, grout erosion capability, and length of tremie. Know the ultimate burst limit. Know your internal pressure during grouting.	
Working Time	Central Mix Design; Select set time to permit travel time from plant site and wait time. Allow water addition at site. Monitor temperature for acceptance.	Mobile Mixer can adjust set time from almost immediate set to delay by days if needed.
Annulus Pressure	Controlled by design of aggregate angularity, aggregate grain size distribution, viscosity of mix, and flow velocity. Design to remain less than the unconfined buckling pressure of internal pipes or ducts and/or burst strength of confining pipe or casing. Can pressurize internal pipes to increase annular pressure limits.	
Temperature	Portland Cement rule is 10 degrees increase in temperature above mix water temperature for every 100 pounds of cement per cubic yard. Slag cements have lower heat of hydration as does Type J.	
Heat Conductivity	Low conductivity is an insulator and can help retain cold or heat or insulate from external cold or heat	High conductivity such as used in thermal grouts for the power industry require specific aggregate mineralogy, gradation, and density
Water Permeability	Cellular blends can have high water permeability	Most blends have low permeability
Mix Stability	Mix needs to be able to be pumped and flow in an annulus without segregation. This is done by design by selection of well graded aggregate blends to optimize particle surface area, amount of mix water, and additives.	

Grout mixes are a blend of various components selected to achieve a specific project objective. More common components include: Portland cement, slag cement, pozzolan materials, water, bentonite, Fly Ash C or F, natural or manufactured sand, silica sand, and various cement additives. Several of these components are selected by the grout designer to be blended to achieve specific project design and construction properties. Table 3 provides some of the properties of various binders that may be used for different reasons.

Project design criteria determine which grout properties are necessary to meet the requirements of the project. Construction design criteria are determined by the installation equipment and method used to install the grout including: pump; tremie size, material, and length; product thermal and pressure limitations; set time requirements to permit adequate working time; and mix stability during the construction process.

Table 3. Grout binder options and properties

BINDER	PROPERITES							
	Availability	**Relative Cost**	**Strength**	**Local Experience**	**Additive Technology**	**Set Time**	**Central Mix Batching**	**Adverse Reactions**
Portland Type I/II	Very	Low	50-12,000 psi	Common	Advanced	Up to 24 hrs	Possible	Bentonite Chlorites
Portland API Class G	Moderate	Moderate	50-6,000 psi	Limited	Advanced	Up to 48 hrs	Possible	Bentonite Chlorites
Portland Microfine	Low	High Moderate	50-6,000 psi	Limited	Advanced	Up to 24 hrs	Difficult	Bentonite Chlorites
Slag Cements	Low	Moderate	50-6,000 psi	Low	Advanced	Up to 4 wks	No	
Pozzolans Flyash	Moderate	Moderate	5-50 psi	Common	Moderate	Slow	Possible	
Bentonite	Moderate	$700/ton	3-20 psi	Low	Advanced	Slow	No	Portland cement

One of the overlooked factors influencing mix bleed and segregation stability is surface area of component aggregates. More surface area permits easier flow resulting in lower pump pressures and annular pressure during construction, but requires added water. However, too much surface water will eventually reduce mix density and can lead to shrinkage. Figure 2 indicates the increase in surface area of a 1 cubic inch block when it is broken into smaller and smaller blocks. The figure indicates that the surface area grows exponentially as the particle diameter decreases and hence must be considered in the grout mix design.

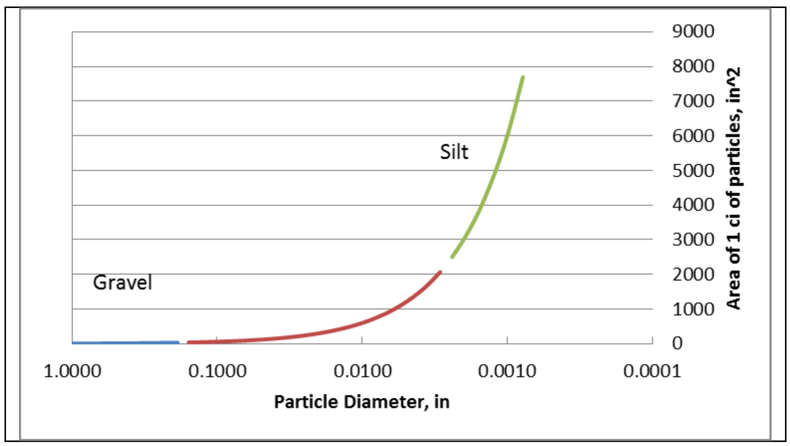

Figure 2. Relation of surface area for a constant volume comprised on different sized particles.

4. SPECIAL CONDITION – THERMAL GROUTING

Thermal grouting is frequently required in the power transmission builds. This grout requires all the planning of other grouts but also requires extensive added testing and planning because of the thermal requirements. As such, thermal grouting warrants a special discussion and attention when used as an annular fill grout.

Geothermal projects transfer heat between the ground reservoir and a user by the use of thermal fluids in pipes. Heat may be either absorbed or dissipated from the ground reservoir depending on the purpose of the geothermal system. Underground power transmission cables generate heat as a function of the amount of energy transferred through them. This heat must be dissipated from the cable by transferring to the ground at a rate that will prevent the cable from overheating which can result in a reduction of current flow (lost revenue) and eventually, cable failure or explosion. Geothermal grouts offer reliable and cost effective methods for this heat transfer for underground installations.

Ground freezing for construction, commercial freezer units, water cooling systems, and cryogenic systems, among others all have reduced efficiency because of heat absorbed from the ground reservoir. In all cases, the heat transfer is between the ground reservoir and the user and the force driving the system is the temperature difference between the reservoir and the user. The value of the thermal grout is typically assessed based on the financial returns from the enhanced efficiency of the system to conduct or resist heat flow.

Various factors influence the thermal properties of grouts. The grout property with the largest influence on the thermal performance is density followed by grout component material conductivity. Increased density is a product of the grain size distribution of the aggregate. If the voids are adequately filled with a denser material, then consequently the density increases. Laboratory testing has revealed that having a well graded aggregate down to the #400 sieve size provides the best chance of having a high density for a particular aggregate combination. Carrying the well grading concept to finer sizes can actually reduce density.

Mineral content of the aggregate is a second factor that can significantly influence thermal properties. Different minerals have different conductivities. The best natural conductors are aggregates with high silica percentage. High performance thermal grouts typically have aggregates that contain upwards of 99% silica. Some additives such as graphite can also be added to enhance conductivity. However, these additives are difficult to blend and are expensive. Use of these types of additives should be left to experienced designers with that product. Table 4 provides some typical values for common materials encountered with thermal grouting.

Table 4. Typical Material Thermal Properties (Ref. 7)

Description	Thermal Resistivity Dry (°C-cm/W)
Soil Grains	
Quartz	12
Granite	30
Limestone	40
Sandstone	50
Shale (sound)	60
Shale (highly friable)	200
Mica	170
Others	
Ice	45
Water	165
Organics	500
Oil (petroleum)	800
Air	4500

Degree of saturation will have a very large impact on both the surrounding ground and the conductivity of the grout. It is very important to assess the final moisture content of the grout for the long term application and have test results for conductivity at that moisture content. Applications installed in the ground will typically assume the moisture content of the surrounding ground unless there is a sufficient temperature differential to actually dry out the grout and surrounding soil. This situation has been observed in thermal materials surrounding underground power transmission lines and has led to cable failures.

5. CONSTRUCTION

Quality can be planned into the project using information provided above. Construction quality control should match the planning effort of a project: what has been planned needs to be measured in the field. Poor quality control and poor understanding and cooperation between the owner and the contractor can lead to failed projects.

Prior to starting a complex grouting project, it is good practice to run a field test with all the planned equipment and maximum pump lengths. The pump efficiency can be measured by counting pump strokes needed to fill known size container and comparing to the theoretical stroke per output as pumps do not discharge 100% of the piston volume. The pump output pressure can be measured by holding the discharge of the tremie at about waist height and adjusting the pump rate until the grout lands about 3 feet from the discharge point – this is about one psi discharge pressure. The stroke rate at this time should be within the normal operating range of the pump. The grout properties can be measured at the pump and at the discharge point for slump or for time of efflux and for unit weight for compliance with the design. A grain size assessment should then be run on a sample of the aggregate to verify the blend. Once the blend is confirmed, a sufficient quantity of the accepted blend should be stockpiled to complete the project. A field grouting work sheet should be developed to record field grouting actions. This sheet may become very beneficial when something happens in the ground where it cannot be seen.

EXAMPLE GROUT PLANNING WORK SHEET

Project	**Date**	**Engineer**

PUMP

Model		see attached data sheet				
Max. production	35 cy/hr					
Volume per stroke	0.869 cf/stroke	0.0322 cy/stroke	Stroke =	39.00 in	Diameter =	7.00 in
Efficiency factor	0.85					

VOLUME CALCULATIONS

				Fixed Tremies in casing		
CASING		**PRODUCT**	**14" PVC**	**HDPE DR11**	**2"**	
ID	23.250 in	ID	14.770 in	ID	1.917 in	
OD	24.000 in	OD	17.400 in	OD	2.375 in	
Wall	0.375 in	DR	14.0	DR	11.000 in	
Casing Length	2,016.00 feet	Length	2,016.00 feet	QUANTITY	2	each
				Length 1	1996 feet	998 feet
				Length 2	1516 feet	758 feet
				Length 3	1016 feet	508 feet
				Length 4	516 feet	258 feet
				Area ID =	2.89 in^2	
				Area OD =	4.43 in^2	
Area ID		Area OD		Area OD-ID =	1.54 in^2	
	424.56 in^2		237.79 in^2	Area each =	0.011 ft^2	
	2.948 ft^2		1.651 ft^2			
Casing ID Volume =	5,943.8 cf	Carrier OD Volume =	3,329.0 cf	Tremie volume =	54.1 cf	

Total Grout Volume =	**2,561 cubic feet**	**2,948 strokes**	**1.462 strokes/LF casing**
	94.84 cy		**0.023076226 strokes/LF tremie**
Contingency =	10%		
Purchase Volume =	104.32 cy		

GROUT MIX

Material	**#/cy**		**Total Wt Purchase**
Mason Sand			0 tons
Cement (Type II)			0 tons
Fly Ash (Type F)			0 tons
Water			0 cubic feet
Strength		psi	
Density		pcf	
Efflux		sec	
This mix Water/Cement			

Tremie lengths and stroke counts

Casing length 2,016.00 feet

Grout from center toward ends. Grout tube 1 end located 10.00 feet from center of casing.

Installed length = Length in casing plus stickout of 20.00 feet from end of casing for each tube

Tremie end spacing = 250 feet

	Installed Length	Strokes to fill tremie	Length in casing	Grout length	Per Tremie Strokes: Strokes	Per Tremie Strokes: Adjusted Strokes	Total Strokes
Tremie 1	1,018 feet	23	998 feet	250 feet	366	430	860
Tremie 2	778 feet	18	758 feet	250 feet	366	430	860
Tremie 3	528 feet	12	508 feet	250 feet	366	430	860
Tremie 4	278 feet	6	258 feet	258 feet	377	444	888
Total Tremie/Side =	2,602 feet		2,522 feet				
Number of Sides =	2			Efficiency Factror =	1.00	0.85	
Total Tremie Length =	**5,204 feet**			Total Strokes per side =	1,474	1,734	3,468

MAXIMUM GROUT PRESSURE

Maximum elevation change entry to Casing Invert =	33 feet		
Grout Density =	125.0 pcf		
Carrier Pipe Water Density =	62.4 pcf		
Carrier Pipe Pressureization =	100.00 psi		
Internal Pressure in Carrier Pipe at invert =	128.65 psi		
Temperature =	**73 deg. F**	**120 deg. F**	**140 deg. F**
Unconstrained Buckling pressure of Carrier Pipe (FS=1) =	303.00 psi	240.00 psi	212.00 psi
Maximum Total External Pressure to buckle Carrier Pipe =	**431.65 psi**	**368.65 psi**	**340.65 psi**
External Static Grout Pressure applied on Carrier pipe at invert =	28.65 psi		
Grout drag factor =	0.20 psi.LF Casing		
Drag factor length =	250 LF		
Dynamic Pressure =	50.00 psi		
Total Applied Grouting Pressure =	**78.65 psi**		
Action pressure for Carrier Pipe Gage =	71.35 psi		
Maximum Carrier Pipe Pressure Gage Reading =	312.00 psi		

ESTIMATED GROUT TIME

Est. stroke rate =	6 strokes/min
# of pumps =	2
Total Strokes =	3,468 strokes
Total Minutes =	289 min
Hours =	4.82 hrs

2/27/2011

Figure 3. Example of Grout Installation Worksheet

During installation, a recording of the amount of grout placed along with time that the pump(s) started and stopped should be taken as well as frequently measuring and recording the grout unit weight. The unit weight is the best indicator that may be quickly acquired for assessing the quality of the mix. When grout emerges from the vents, the density should be measured and pumping continued until the density is acceptably close to the design density. Additionally, if the caning has been filled with water, the water discharge rate or volume must be monitored as it should be about the same as the grout injection rate. If the product pipe has been pressurized to prevent collapse, the pressure gauges must be monitored for change. The pressure gauges can provide an early indication that the grout pressure in the annulus has exceeded the internal pressure of the product pipe and something needs to be done quickly to prevent collapse of the product pipe. It is also good to obtain samples of the grout periodically during the installation for thermal testing. However, the testing takes several days thus it is not appropriate for quality control during the installation process.

Grout for trenchless projects is not the regular street level grout or concrete. It requires careful planning within a group of stakeholders, engineering design, and quality construction for completing a successful installation. Poor planning and construction can lead to collapsed or burst product pipes that cannot be used which will require a completely new installation. In conclusion:

- Define design and construction criteria.
- Involve an experienced grouting team.
- Design both product and grout materials
- Aggregates have a significant influence on construction and design properties.
- Use full scale testing for critical installations to verify grout properties prior to pumping.
- Verify design and construction parameters during construction.

A failed grouting program can cost as much as the replacement cost of a new build, this is not considered good practice.

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