Successful Grout Curtain Installation - Means and Methods. Lake Needwood Dam, Rock Creek State Park, Derwood Maryland.

Abstract

Injection grouting, or pressure grouting, has been in practice in various forms since the 1800’s. Means and methods have continuously evolved over the past 2 decades and continue to evolve today. Currently, there are a variety of “accepted” systems in practice that have been successfully implemented for dam foundation grouting all over the world, but to date, no rigid “rules” have been established for the performance of this technology. This paper is intended to illustrate means and methods successfully used to install a grout curtain at Lake Needwood Dam in Derwood, Maryland. This information should be of value to owner/operators of similar problematic dam structures that may be evaluating grout curtain installation as a means of seepage control.

Lake Needwood Dam was built in 1964-1965, and has a 65-foot high earthen embankment constructed on a fractured rock foundation. The Dam is a flood control structure that captures floodwaters within the 12.8 square mile Upper Rock Creek watershed, and is designed to discharge floodwater through a 42-inch principal spillway at a controlled rate that remains consistently manageable for the channel and stream banks downstream from the dam. The MDE Dam Safety Division classifies Lake Needwood as a High Hazard Dam Structure.

In late June 2006, heavy rains resulting in over ten inches of rainfall caused a 23-foot rise in the water level in Lake Needwood, resulting in observed uncontrolled seepage from the downstream slope. According to initial evaluations, the dam had essentially developed a leak and was potentially on the verge of failure. Within a matter of hours, 2,400 people were evacuated from the downstream communities, including part of the City of Rockville, Maryland. Following inspection and a comprehensive investigation by MDE Engineers and county managers, it was determined that the earthen embankment was intact, and the observed seepage was a result of the increased head pressure forcing water through open joints and fractures within the underlying bedrock. Instrumentation showed that the water pressures within the foundation rock continued to increase, even after the storm had passed and the lake began to recede.

Geo-Con, a specialty Geotechnical Contractor, was contracted by MNCPPC to work with the URS Corporation to install a grout curtain intended to reduce seepage through the underlying fractured bedrock. The work began in April of 2007, and was successfully completed during October of the same year. This paper will detail means and methods used to install the grout curtain.

Topics will include:
- Drilling
- Water Testing
- Grout Mix Design
- Foundation Grouting
- Quality Control, Reporting, and Instrumentation
- Site Specific Problems and Solutions
- Completion and Verification

Background and Design

Following an extensive study and forensic evaluation of the dam, it was concluded that the majority of the seepage was from water flowing through the open joints and fractures in the bedrock. Curtain grouting of the bedrock, coupled with a new downstream drainage/filter blanket and berm were selected as the preferred means of remediating the dam. MNCPPC contracted the URS Corporation to design a grouting program to seal the fractures and reduce the permeability of the rock foundation beneath the central portion of the embankment. A two-line grout curtain was designed as shown in Figure 1 to reduce the rock foundation’s hydraulic conductivity to a residual Lugeon Value of 5 or less. URS developed requirements for:
The curtain alignment location required the construction of a work platform on the upstream face of the dam. Geo-Con subcontracted The Dirt Express Company to establish the required erosion and sediment controls and install a level stable work platform from which to install the curtain.

**Drilling**

Drilling order was performed in a Primary, Secondary, Tertiary, etc. fashion beginning with the downstream curtain line. Drilling began in the center of the alignment and progressed outward the abutments. Protecting the integrity of the existing earthen embankment necessitated the use of two separate drilling methods to accomplish the installation of the borings for the grout curtain.
Soil Drilling

The project specification specifically prohibited the use of drilling fluid or air to remove cuttings while drilling the soil overburden and installing the PVC casing, in compliance with Army Corps of Engineers Regulation ER-1110-1-1807. Geo-Con subcontracted ProSonic (Boart-Longyear) Drilling to install the PVC casing using sonic drilling methods. A Sonic or ResonantSonic drill uses high frequency mechanical oscillations, developed in the special drill head, to transmit resonant vibrations and rotary power through the specially designed drill tooling to the drill bit allowing it to achieve drilling penetration without the need for drilling fluids or air. Frequencies in the range of 50 Hz to more than 180 Hz can be generated. The driller adjusts the frequency to match the natural frequency of the drill tooling, causing no dampening of the vibratory wavelength to the bit. Drill pipe acceleration exceeding 500g’s and forces up to 200,000 lbs are efficiently transmitted to the drill bit face to create an effective cutting action. The sonic vibratory action fluidizes the soil particles, destroying the shear strength and pushing the particles away from the tip of the drill bit. This localized liquefaction process allowed for the penetration of the overburden formation. Soil is forced into the drill string barrel creating a continuous soil core.

4” PVC casing was installed through the soil overburden and socketed a minimum of 2-feet into the underlying bedrock. The annulus between the casing and boring wall was grouted using a cement-bentonite grout.

Rock Drilling

Borings were extended through the underlying bedrock by rotary drilling methods. The project specification specifically prohibited the use of air to remove cuttings while drilling the rock foundation in compliance with Army Corps of Engineers Regulation ER-1110-1-1807. Rock drilling was performed by Geo-Con’s subcontractor, Armstrong Drilling. Primary and Verification borings were completed using high-speed coring with an HQ-sized triple-barrel wire-line drill string and water flush. Armstrong initially utilized diamond-destructive rotary drilling equipment to complete Secondary and higher order borings; however, coring was found to be equally time and cost-effective and had the added benefit of providing additional formation information in the form of rock cores, therefore the method was changed to coring.

All borings were installed at 15-degree from vertical inclinations with the exception of the abutment “fan” borings. The 15-degree angles were intended to maximize of chances of intercepting high-angled fractures within the formation. Fan borings were a series of grout curtain borings installed at an array of angles and were intended to provide a good contact between the grout curtain and the surrounding formation. It was necessary to employ drill rigs with full angle capabilities to accommodate the high-angle fan borings.

Borings were completed from top of rock to design depth unless significant drill-water loss was noted. If water loss was significant enough that drilling could not continue then drilling was ceased and the location was grouted to refusal as a downstage. Downstage grouting will be discussed in more detail in subsequent sections if this paper. Following sufficient grout cure, the boring was advanced to design depth or subsequent water loss.

Sonic drilling worked extremely well in the soils present in the embankment, and Prosonic had little trouble keeping up the desired project pace. The rock drilling presented slightly more of a challenge: Some anomalies were discovered in the expected gneiss/schist rock lithography during the course of the project. Rock with unexpectedly high quartz content was encountered in several areas of the dam foundation. These areas often resulted in core-run times (5’) of over 8 minutes, which was more than double the expected average run time. This resulted in erratic production rates for the rock drilling. Balancing the production rates of two inter-dependant drilling operations presented a unique challenge especially given the fluctuating production rates encountered with the rock drilling. We were able to balance the two by working with Armstrong Drilling to mobilize a second drill rig when necessary and coordinated some partial demobilizations with Pro-Sonic Drilling.
Water Testing and Grouting Equipment

Equipment used for water testing and grouting included:

- Self-Contained CG-600 Chem-Grouter Colloidal Batch Plant
  - 8-Cubic Foot mixing tank with bag breaker
  - 9-Cubic Foot agitated holding tank
  - On-board 2,000 RPM centrifugal mixing pump
  - On-board 3-stage size 6 closed-throat Moyno pump
  Used for mixing and pumping grout.

- Auxiliary Chem-Grouter Batch Plant
  - 3-Cubic yard total capacity
  - Auxiliary high-shear centrifugal mixing pump
  - On-board open throat moyno pump
  Used for water testing and backup for mixing and pumping grout.

- Davey Kent 725 – Used to assist operators in setting and pulling pipe and packer assemblies.

- 385 CFM Air Compressor – Used to power Chem-Grouter batch plants
- 25kw Generator – Power grouting trailer and grouting/movement monitoring equipment.
- 8’ x 10’ Ground Level “Grouting” Trailer – Served as “Control Center” for Real-time grout monitoring and movement monitoring.

- Grouting/Water Testing Header Assembly
  - Secondary flow meter and pressure gauges
  - Return line to batch plant
  - Control valves for down-hole grout/water flow and batch plant return
  - Emergency dump valve
  - Solution Grout Monitor
• All-Terrain Telescoping Boom Forklift – Used for transporting materials, and relocating batch plants and equipment.
• Skid Steer – Used to handle drilling and grouting spoils and maintain work platform.
• 4” Trash Pump – Used to pump water to the batch plant for water testing and grout mixing.

Real-Time Data Monitoring/Quality Control

One improvement in grouting technology that has made a significant impact on the efficiency of grout curtain installation has been the use of computer-aided real-time monitoring and reporting. The production rate on a grout curtain installation depends heavily upon the ability of the contractor to accurately collect and report data so the Engineer/Owner can effectively evaluate and make decisions such as reducing split spacing on borings/adding higher-order borings, modifying grouting approach, identifying and troubleshooting anomalies or problem areas and “closing” sections of the curtain. Having an efficient method of collecting, evaluating, and distributing grouting information to everyone involved in the decision-making process is critical to the progress of the grout curtain.

The monitoring/reporting program enacted at Lake Needwood Dam was comprised of the following components:

Real-Time Data Collection and Display

A Solution Grout Monitor manufactured by RST was used for data collection. The Solution Monitor, which resided at the grouting/water-testing manifold, is a self-contained unit consisting of an electromagnetic flow meter (with local readout) and an electronic pressure transducer, which is interfaced with a data logger and RF radio unit housed in a weatherproof enclosure. The RF transmitter sends the signal to the nearby computer, housed in the “grouting Trailer”, equipped with custom software allowing the data to be both stored on the computer, and displayed graphically real-time. The computer displays the instantaneous flow rate and pressure with a real-time (scrolling) plot of each parameter over time, along with a plot line of the Lugeon Value over time. Data points are collected multiple times per second and stored to a raw-data file that is importable into MS Excel.

This system enabled instantaneous observation of grouting or water testing events and streamlined communication between Geo-Con’s Project Engineer, Superintendent, grouting/water-testing manifold Operator, and the Owner/Engineer’s on-site representative. Adjustments in grout mixing procedure or termination of a water test can be made quickly in response to trends in Lugeon values or trends toward refusal.
As-Built Drawing

An as-built drawing was maintained in the “grouting trailer” during grout curtain installation. The as-built was an excellent graphical tool that showed a scaled representation of the borings and their orientation in the curtain. Individual water testing and grouting stages were shown complete with water test lugeon values and grout takes - color coded according to low, medium, or high-take stages. The drawing allowed anyone on the project team to see individual boring results or Lugeon/Grout-Take trends across the alignment. Drawings were a valuable tool for progress meetings as well, allowing personnel that may not be intimately involved in the curtain installation to be brought quickly up to speed on progress.

Quality Control Reports

Quality control reports were generated daily for the project record. QC reports consisted of a daily accounting of activities onsite as well as the results of any water testing or grouting performed that day. Water testing and grouting charts were created for each completed stage from the reduced raw-data generated from the Solution Grout Monitor.

All reports could be generated in electronic format, which made distribution to team members quick and efficient. The only exception to this was the as-built drawing, which, initially, was hand-drawn. URS created an electronic gINT version of the drawing.

Real-Time Movement Monitoring

Geo-Con also performed real-time embankment movement monitoring on Lake Needwood Dam during grout curtain installation. A series of semi-permanent prisms were mounted along the dam embankment. An automated total station continuously monitored the prism locations and reported the 3-dimensional locations (accurate to one hundredth of a foot) in graphical format to a computer located in the grouting trailer. No embankment movement due to grouting was recorded during the course of the project.

Water Testing

Water testing was performed on all stages prior to grouting. Target water pressure was calculated as a 1 psi per foot of depth below rock surface (mid-stage elevation) corrected for hydrostatic head pressure:

\[(\text{Top of Rock Elevation} - \text{Midstage Elevation}) + (\text{Lake Level Elevation} - \text{Midstage Elevation}) \times 0.43\]
The Lugeon Value was used as the primary unit for hydraulic conductivity during water testing and grouting activities. 1 Lugeon is equal to a flow of 1 liter per meter of borehole being tested, per minute, as measured at a pressure of 10 bars, or roughly equivalent to 1.3 x 5e-10 cm/sec. Lugeon values for grouting and water testing were calculated as follows:

\[ L = \frac{[(\text{Cubic feet per minute}) \times 142]}{0.010762 \times \text{pressure in psi}} \]

Procedures for water testing varied by boring type:

**Primary/Exploratory and Verification Borings**

All primary/exploratory and verification borings were tested using the multi-pressure “Houlsby”-style water tests. Three pressure steps were used during the test as follows:

Houlsby described six basic conditions that could be recognized by comparing the Lugeon values returned at each pressure step:

1. Laminar flow
2. Turbulent flow
3. Dilation
4. Washout
5. Void filling
6. Hydrofracture

It is important to evaluate the results of the water tests to verify that chosen grouting pressures and parameters are appropriate for the formation, to help decide whether grouting is necessary or feasible, and to provide a basis for selection of the starting grout formulation.

Water testing for primary/exploratory and verification borings was performed in 10-foot ascending stages using a straddle packer assembly. Straddle packer assemblies use two packers separated by a perforated pipe. The assembly is lowered to the desired stage depth and both packers are inflated effectively isolating the desired stage for water testing. Packers were inflated per manufacturers specification from the surface using pressurized nitrogen gas.
Primary/Exploratory boring water testing was completed on the downstream line, and results were evaluated revealing mostly tight borings near the center of the dam with and some large Lugeon values at each abutment, especially near the left abutment of the dam. This corresponded with the area of the observed seepage and where areas of highest takes were anticipated.

Secondary, Tertiary, and higher-order borings

Secondary, Tertiary and all higher-order borings not receiving multi-pressure “Houlsby” Tests were water-tested in 20-foot stages (to correspond to grouting stages) immediately prior to grouting using a single packer assembly and a single-pressure 5-minute water test. These water tests helped evaluate the necessity or feasibility of grouting that particular stage, provided some basis for selecting the starting grout mix, as well as provided information (in higher order borings) on the progress of the closure process.

Water testing was accomplished using the moyno pumps on either the primary or secondary Chem Grouter batch plants. Pressure and flow was controlled at the grout header and data was observed and recorded. Real-Time data monitoring and Quality Control will be discussed in subsequent sections of this document.

For both water testing and grouting, standard steel pipe was used down-hole. Steel pipe is more readily available, cost effective, and durable than aluminum pipe or hose. The primary disadvantage of steel pipe is the weight and inherent difficulty in handling. To overcome this, a Davey Kent 725 crawler rig was modified and used to assist water testing/grouting crew with setting and removing the pipe. Due to the relatively small size of the project and the availability of the continuous, level work platform, this system worked extremely well.

Grout Mix Design

Balanced, stable grouts are a key component in efficiently installing a successful grout curtain. URS specified three mixes for the project:

- Mix 1 – Marsh Value <40 Seconds
- Mix 2 – Marsh Value 50-60 Seconds
- Mix 3 – Marsh Value > 75 Seconds

Additionally, these mixes were required to meet the following criteria:

- Initial stiffening time of greater than 4 hrs
- Develop an unconfined compressive strength (UCS) of 500 psi or greater after 28 days of cure
- Each will be stable and demonstrate less than 5% bleed and a pressure filtration coefficient of 0.040 min $^{-1/2}$ or less
- Fall within a Water/Cement ratio range of 3:1 to 0.5:1

A “closer mix” was to also be proposed to bring any “runaway” takes to refusal.

We went into the lab to develop a suite of mixes that both met the specified requirements, and were “user friendly” and could easily be implemented and adjusted in the field. It was also important to consider materials that were locally available and in good supply.

Materials included:

- Portland Type III Cement (Locally available)
- Standard 90bbl yield Bentonite (From local supplier)
- Rheobuild 1000 Super-Plasticizer (Manufactured by BASF)

The approach was to develop a base grout mix meeting or exceeding the general requirements and the Mix 3 viscosity target. Once this was achieved, use the Super-Plasticizer to modify the viscosity to meet the
Mix 1 and 2 targets. This would enable the plant operator in the field to go between mixes without dumping or wasting any grout.

Bentonite and water were pre-mixed and allowed to hydrate before cement addition. This is important because it has been shown that adding cement before, or too closely following, the bentonite addition causes an interruption in the bentonite hydration process and will result in failing QC tests and poor performance of the grout. Cement was then added, along with a very small amount of Super Plasticizer (to aid fluidity and mixing/shearing). Grout mixing in the lab was accomplished by a drill-motor-type mixer to add and initially blend materials, followed by a high-speed blender-type mixer to impart the necessary shear to achieve thorough mixing and particle wetting.

Lab apparatus used for testing included:
- Marsh Funnel (Viscosity)
- Electronic Balance (Weighing materials)
- Mud Balance (Grout Unit Weight)
- Vicat Needle (Initial Set)
- Filter Press Apparatus (Pressure Filtration)
- 3 x 6 Cylinders (for UCS Testing)

Following multiple trials, a base mix was created that met the general requirements and had a nearly infinite viscosity (marsh value) without Super-plasticizer addition. By varying the Super-plasticizer addition any viscosity could be achieved. The mix developed the required strength within 7 days of cure.

Using the base mix formulation, we chose Type F fly ash as an admixture to increase the unit weight of the grout and create the required “closer mix”. While fly ash is less readily available and more difficult to handle than sand, it is not as abrasive and does not cause damage to mixing and pumping equipment, or valves.

The mixes performed as planned in the field. Having a quality colloidal batch plant is crucial to obtaining the desired results when transitioning grout mixes from the lab to the field. Lab mixes were easily duplicated in the field using the Chem-Grouter CG600 batch plant with the high RPM shear pump. We had to modify the auxiliary batch plant to increase the RPM to obtain the desired results.

Grouting

Grouting was accomplished in 20-foot-maximum ascending stages. Following the required water test, and based on the lugeon value of the test, an initial grout mix was chosen. The selected mix was batched in the Chem-Grouter while the grouting crews set the pipe and packers at the desired elevations.

Good communication is paramount during grouting operations. The Project Engineer/Engineer or Owner’s Rep. in the Grouting Trailer, Site Superintendent, Batch Plant Operator, and Grouting Operator (at the header) communicated continuously via Motorola Radio during grouting operations.

Geo-Con’s project engineer ensured that the real-time monitoring systems were in place and operational, maximum grouting pressures were calculated and this information was communicated to the Grouting Operator at the header. Once the appropriate mix was batched and pipe/packers were set and tested (boring was filled with water and the water level was observed to ensure it remained static) grouting commenced.

The primary goal was to bring each stage to a gradual but efficient refusal. Refusal for this project was defined as: Less than 0.5gpm for 10 minutes at maximum allowable pressure. While good grouting practices need to be followed at all times, there cannot be a “set” procedure for the grouting of all stages. Some basic guidelines need to be established during the first few stages of grouting and continuously developed and improved as the project progresses and new information is obtained. In general, the grout was progressively thickened until target pressure was reached and the “Apparent Lugeon Value” began to gradually show a smooth decreasing trend.
When presented with a stage that is taking grout, it is important to maximize the amount of grout that is effectively injected into the foundation from that location, but at the same time, keeping in mind the “reach” of the grout needs to stay within the confines of the foundation where it will be beneficial to the project. For this project, a maximum grout quantity limit of 1,800 gallons was set. This was based on an early “runaway” take that was brought to refusal. No subsequent borings reached that quantity. The Project Engineer and Engineer/Owner’s Rep. have to evaluate each stage’s progress and make the decision when to progress to the next step in grout viscosity. Because the grout mix viscosities were designed to be modified by Super Plasticizer addition, viscosity steps other than those specified were easily attainable. This flexibility in grout viscosities was taken advantage of and the following general progression was followed:

- 2:1W:C Starter Mix (the use of this mixed will be explained further)
- 30 seconds
- 32 seconds
- 35 seconds
- 37 seconds
- 40 seconds
- 42 seconds
- 45 seconds
- 50 seconds
- 55 seconds
- 60 seconds
- 65 seconds
- 70 seconds
- Closer Mix

Approximately 2 batches of each were injected as grouting progressed. The batch plant operator and Engineers would communicate as batching continued so the Operator knew to continue the progression or stay with a given viscosity if the stage was showing signs of refusal. The Batch Plant operator would then inform the Grout Header Operator when a thicker batch was being sent so the Grout Header Operator was prepared to adjust the pressure to maintain the target.

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**Example Grout Chart – Bringing a Grout Stage to Refusal**
Early on in the project a peculiarity was observed: During water testing, certain stages (predominantly top stages near soil/rock interface) would return a lugeon value that would suggest a grout take would be expected. However, during grouting, these stages would refuse even the 30-second mix. It was speculated that this could be due to a large network of very small fractures, possibly due to bedrock weathering. It was decided that a very thin 2:1 Water to Cement mix would be used to attempt to get some cement into these fractures.

**Downstage Grouting**

Borings that resulted in significant water loss during drilling were grouted as downstage borings. Downstage borings were grouted by seating the packer at the top of the hole and grouting the stage to refusal. Grout was then allowed to cure for a minimum of 24-hours, and drilling continued.

Overall, the center of the foundation had very low grout takes, and the majority of the grouting effort was spent on the abutments, especially the left abutment. Following the installation and grouting of the primary and secondary borings, a reduction was shown between the two in lugeon values and grout takes, and it appeared that the curtain could be quickly brought to closure. However, upon the drilling and water testing of the third order borings some of the highest lugeon values were returned to date. Some of the borings even required downstage grouting. Despite this somewhat discouraging data, the grouting program was adhered to and higher order borings were added as necessary, some areas requiring up to 6th order borings to attain closure. Although still remaining somewhat unpredictable, even during upstream curtain installation, the trend progressed toward lower lugeon values and grout takes, and eventually closure was attained.

Verification was accomplished by installing eight (8) borings located between the upstream and downstream grout curtains. The verification locations intentionally targeted the most “problematic” areas of the dam, or the areas that had the highest initial lugeon values and grout takes, or presented the most difficulty in attaining closure. These borings were water tested using the Houlsby method. Four (4) of the verification boring locations required limited additional grouting. Two (2) of these locations required grouting and re-verification, the remaining two locations required additional borings, grouting, and re-verification.

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