Pressure Grouting – A Multipurpose Solution for Dam Rehabilitation

By
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Abstract

Grout curtains continue to gain popularity as both an effective short-term, and a durable long term option for reducing seepage through fractured bedrock dam foundations. Similar pressure grouting techniques can be considered to address other dam rehabilitation needs as well. This paper will discuss the means and methods that were successfully used to install a grout curtain in the fractured bedrock foundation, and address defects in overburden soils using advanced pressure grouting techniques at the Lockington Dam in Piqua, Ohio. This information should be of value to owner/operators of similar problematic dam structures that may be evaluating pressure grouting as a means of improving overall seepage control.

Completed in 1921, the Lockington Dam stands 69-feet tall, 409-feet wide at the base and is comprised of 1.135 million cubic yards of earth with a concrete spillway structure containing two concrete drainage conduits. The dam manages a drainage area of approximately 255 square miles.

In 1999 the Miami Conservation District (MCD) launched a Dam Safety Initiative to address potential weaknesses in the existing flood protection system. Underseepage at Lockington Dam was identified as a primary issue. As a result of the hydraulic placement methods of the earthen fill during construction, some glacial outwash material was incorporated into the Dam embankment at the abutments. This material was found to contain well-graded sands, cobbles and boulders, also identified as a potential pathway for water seepage through the embankment.

Geo-Con, a trade name of Environmental Barrier Company, LLC., a specialty Geotechnical Contractor, was contracted by MCD to work with MWH Americas to install a grout curtain, intended to reduce seepage through the underlying fractured bedrock. Pressure grouting was also specified for use in the glacial outwash material overlying the bedrock. Both applications were to be completed using advanced grouting methods, including the use of balanced/stable grouts and real-time computer monitoring of the grouting parameters. The work began in May of 2010, and was successfully completed in November of the same year. This paper will detail key components of the grouting program as well as means and methods used to install the grout curtain and performance of the pressure grouting.

History and Background

In March of 1913, an estimated nine to eleven inches of rainfall fell over a three-day period in the Miami River valley and surrounding areas. The ensuing flood covered over 14-square miles and resulted in the loss of over 360 lives. The damage totaled over $100,000,000, which, in today’s economy, would equal nearly two billion dollars. In response to this, the Miami Conservancy District (MCD) was founded and
tasked with providing flood control for the Miami Valley. A total of 5 dams were constructed between 1918 and 1922. All 5 were designed to be “dry dams”, constructed strictly for flood control, with no permanent pool or reservoir. In their 90 years of operation, the five structures have stored water and reduced flooding downstream a total of 1,770 times, including 63 in 2011 alone.

Miami Conservancy District’s Board of Consultants, a group of world-renowned engineers, periodically meet with staff to critically review plans, data, technical investigations, and proposed solutions to various issues. As a result of the independent group of experts’ recommendations associated with MCD’s 1999 Dam Safety Initiative, underseepage, dam crest permeability, and concrete deterioration were to be addressed through a series of repairs and modifications to the 5 existing MCD dams. These projects were to include:

- The installation of relief wells and toe berms at the downstream base of the dams
- The construction of impermeable cut-off walls at the top of the dams
- The replacement of deteriorating concrete
- Grouting of Lockington Dam foundation

The Lockington Dam consists of an earthen embankment with a concrete spillway structure containing two concrete drainage conduits. The earthen fill was hydraulically placed in all of the MCD dams. While this was not a brand-new technique at the time, the collection of dams was, and still is, one of the largest applications of hydraulic fill placement in history. The construction of these dams also saw the very first use of a “hydraulic jump” to dissipate kinetic energy from the spillway discharge to prevent channel erosion.

During construction of Lockington Dam a borrow pit was excavated nearby to provide the required fill for the dam. Water was blasted into the borrow area to form a “slurry” and the material was pumped or sluiced out to the dam site. As the waterborne fill moves to the end of the sluiceways or pipelines, the larger cobbles and gravel settled out creating the free-draining shell of the dam while the finer clay and silt particles moved into the core pool where they settled and created the clay core of the dam. The hydraulic fill was brought up in lifts as the water gradually drained out to form the dam.

Montgomery Watson Harza Engineers (MWH) had been involved in the Lockington Dam since as early as 1965 (then Harza). During this time they had performed a number of hydraulic and hydrologic studies and reports. In 2004 they published “Lockington Dam Foundation and Underseepage Report” which summarized a detailed exploration program conducted early in 2004 as well as previous explorations/findings. It also presented a detailed analysis of flow pathways through the dam and made recommendations to address these conditions.
The foundation underlying the Lockington dam primarily consists of Cedarville Dolomite bedrock overlain by thick glacial deposits. The dolomite layers were observed to be weathered and contained solution features and karst depressions with occasional infilling. A correlation between high pool levels and downstream bedrock piezometers also indicated that underseepage through the bedrock layers will continue to promote internal erosion of the dam. The glacial deposits overlying the bedrock contained layers of sand, gravel, cobbles and boulders (glacial till and glacial outwash plains). Except for the cutoff trench, which was excavated to bedrock, these deposits were left intact during dam construction and likely conveyed groundwater around and beneath the dam’s core directly adjacent to the hydraulic fill material. Wells within the downstream outwash plain were observed to respond to high pool levels. When exposed to high head-pressure, such as during a flood event, it was possible that these materials allowed water to pass through the abutments which contributed to further internal erosion of the dam.

To address seepage through both the weathered dolomite foundation and the glacial deposits, MWH designed a 2-line grout curtain to be installed through the existing embankment to the lower limits of the weathered dolomite bedrock. The goal of the grouting program was to reduce the hydraulic conductivity of the dam foundation to a target $K$ value of $10^{-5}$ cm/s.

**Figure 1a.** – Grout Curtain Alignment (East)

**Figure 1b.** – Grout Curtain Alignment (West)

**Drilling**

Drilling order, in general, was performed in a Primary, Secondary, Tertiary, etc. fashion beginning with the downstream curtain line followed by the upstream curtain line.
Soil Drilling

The hydraulic core material, which comprises most of the dam embankment, is extremely soft and prone to damage/deformation. Protection of the hydraulic core during drilling/grouting activities was a top priority on this project. To minimize the risk of damage to the core, Geo-Con chose Sonic Drilling methods to set casing through the hydraulic core. Sonic drilling uses high-frequency vibration, transmitted from a specialty drill-head through the drill string, to fluidize soil particles that are in contact with the bit. This allows for efficient penetration of the soil without the use of water or drilling mud. 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. A 4” or 3” PVC casing was installed through the soft hydraulic core to either the top of overburden or top of rock. The annulus between the casing and boring wall was grouted using a cement-bentonite grout.

Overburden Drilling

To isolate the overburden and protect it during rock drilling and grouting, Dual Rotary (Casing Advance) Drilling Methods were used. Dual rotary drilling allows the advancement of both an inner drill string and an outer steel casing. These can be advanced simultaneously or separately as needed which offers an advantage when drilling through variable soil conditions. The casing and inner string can be advanced simultaneously through softer formations, if cobbles or boulders are encountered, the inner drill string can advance ahead of the casing creating a “pilot hole” through the boulder. Conversely, in sandy soils or other formations that are prone to caving, the outer casing can be advanced ahead of the inner string to mitigate problems with stuck tooling due to caving conditions. This flexibility results in faster production and straighter boreholes. At Lockington Dam, the outer casing was left in place to protect the overburden during rock drilling and grouting. Following rock grouting, the casing was extracted in stages to allow grouting of the overburden as required.

Rock Drilling

Borings were extended through the underlying bedrock by NQ-size diamond (destructive) rotary drilling methods with water flush. Verification borings were completed using high-speed coring with an NQ-sized triple-barrel wire-line drill string and water flush.
The drilling methodology differed slightly depending on whether or not overburden grouting was specified for the boring. The borings scheduled for overburden grouting were located from Station 5+50 to 13+50 in the East and 6+85 to 13+00 in the West. For these borings the following procedure was followed:

1. Drill through hydraulic core to top of overburden using sonic drilling
2. Set 4” casing and grout in place
3. Drill through overburden leaving steel casing in place
4. Complete boring through rock to required depth

For all other borings:

1. Drill through hydraulic core to top of rock using sonic drilling
2. Set 3” casing and grout in place
3. Complete boring through rock to required depth

**Water Testing and Grouting Equipment**

Equipment used for water testing and grouting included:

- (2) 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
  o 3-Cubic yard total capacity
  o Auxiliary high-shear centrifugal mixing pump
  o On-board open throat moyno pump
  Used for water testing and PVC casing grout.

• Drill Rigs – Included:
  o Sonic SR-17
  o Versa Sonic
  o Acker MP5
  o CME 45
  o Davey Kent DK50
  o Mobile B-6
  o Casagrande C7

• (2) Grouting/Water Testing Header Assembly
  o Secondary flow meter and pressure transducer/gauges
  o Return line to batch plant
  o Control valves for down-hole grout/water flow and batch plant return
  o Emergency dump valve

Water Testing

Water testing was done on a limited basis and mostly reserved for verification borings to evaluate the hydraulic conductivity of the completed curtain.

Water tests were a combination of “pump-in” type tests and “constant head” type tests and were performed to target “problem areas” within the foundation.

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 manufacturer’s specification from the surface using pressurized nitrogen gas.
Water testing was accomplished using the moyno pumps on either the primary or secondary Chem Grouter batch plants. Pressure and flow were 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.

**Grout Mix Design**

MWH tasked the contractor with the development of a suite of balanced, stable grout mixes for the project.

Geo-Con went into the lab and developed a suite of mixes that both met the needs for the project and were “user friendly” meaning they could easily be replicated 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)
- KelcoCrete DGS diutan gum (manufactured by CP Kelco)

Geo-Con targeted 3 viscosity variations (as measured by marsh funnel) for the grout mixes:
1. 34 Seconds
2. 50 Seconds
3. 80+ Seconds

We felt this range of viscosities would be appropriate to address a variety of subsurface conditions and would provide a good “progression” to bring grout takes to an effective refusal.

The approach was to develop a base grout mix meeting or exceeding the general requirements and the Mix 3 target viscosity. 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.

Other important properties that were targeted in the development of the mixes were:
- Low Bleed – Less than 3%
- Grout Durability – A UCS strength in excess of 500psi.
- Good Resistance to Pressure Filtration – A Kpf of 0.05 or less.
Final mixes were as follows:

**Mix Design Summary**

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<th>Mix A</th>
<th>Mix B</th>
<th>Mix C</th>
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<td>&lt; 3</td>
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<tr>
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<td>&gt;4&lt;24</td>
<td>&gt;4&lt;24</td>
</tr>
</tbody>
</table>

** - By Mud Balance

Using the base mix formulation, we chose Type F fly ash as an admixture to increase the unit weight of the grout and create a “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 were replicated during field trials and performed as planned on the project. 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.

**Grouting**

A Foundation Drilling and Grouting Test Section was specified to demonstrate means and methods to be used on the project and refine key procedures for drilling and grouting. The test section consisted of 24 total borings, which included 6 downstream primaries and 6 upstream primaries with an equal number of secondary borings associated with each line. At the conclusion of the test section the project team reviewed the results, evaluated the effectiveness of the grouting program and made recommendations for any changes to procedures including:

- Refusal Criteria
- Grout Mix Properties
- Grout mix viscosity progression during grouting
- Stage Lengths
- Threshold for addition of higher-order borings.

Geo-Con then issued a summary report as an addendum to the project work plan which set the final guidelines for the project.

While good grouting practices were to be followed at all times, there wasn’t a “set” procedure for the grouting of all stages. Some basic guidelines were established during the test section and procedures were continuously developed and improved as the project progressed and new information was obtained.

The primary goal of the grouting program was to grout the voids and conduits in the foundation by bringing each grouting stage to a gradual but efficient refusal.
In general, since no pre-grout water pressure testing was routinely completed, grouting was initiated with the thinnest mix at low pressure (gravity). Pressure was gradually increased and grout viscosity was progressively thickened until target pressure was reached and the “Apparent Lugeon Value” began to gradually show a smooth decreasing trend. Refusal for this project was generally defined as: Less than 5.0 gpm for 5 minutes at maximum allowable pressure. A slightly more conservative refusal criterion was used for the top stage, where the maximum pressure was held for 10 minutes instead of 5.

Stage lengths were specified to be a maximum of 20-feet, however most stages were set between 10 and 15-feet. A packer would be inflated at the top of the chosen stage to isolate that stage for grouting. After rock grouting was completed in any given boring, a drill rig would be brought to the boring location to extract the steel casing (left in place to protect the overburden during rock drilling and grouting). The casing would be extracted to expose the first stage of overburden for grouting. The packer would be inflated in the steel casing and the first stage of overburden would be grouted. This process would be repeated to grout the remainder of the overburden. The final stage would typically be grouted by inflating the packer in the PVC casing. Extra care was taken during grouting of the overburden to keep pressures and flow rates low.

**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 could be advanced. Conditions requiring downstage grouting were very infrequently encountered during completion of the project.

**Quality Control**

The quality control program at Lockington Dam included the following:

**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 computer, housed in the nearby “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. Because the measuring/recording unit resides at the collar of the grout boring, very little line-loss correction is necessary during data collection. 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 on site during grout curtain installation. The as-built was an excellent graphical tool that showed a scaled representation of the borings and their location within the curtain. Individual grout 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.

Grout Testing

In addition to a complete round of testing during the Field Trial, each grout mix was tested daily for Unit Weight, Viscosity, and Temperature and weekly for Pressure Filtration, Bleed, and Thixotropic Set to ensure they remained in compliance with the approved mix design. This was especially important since river water was being used for grout mixing and changes in water quality could affect grout properties.
Quality Control Reporting

Quality control reporting was comprised of the following documentation:

- Daily Quality Control Reports
- Water Testing Reports
- Grouting Reports
- As-Built Drawing

Quality control reports were generated daily for the project record. QC reports consisted of a daily accounting of activities onsite including drilling performed 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. An as-built drawing was maintained in the project trailer for review by the project team. A tabular as-built was also maintained and distributed periodically showing the status of all planned borings, dates and depths for each type of drilling and date grouted.

Conclusions/Lessons Learned

Following installation of the test program the following analysis was performed on the distribution of the grout placement over the different lines and orders of borings:
The observed reduction of grout takes in secondaries compared to primaries and upstream compared to downstream curtain lines is exactly what you would hope to see during a grout curtain installation. This indicates that the foundation and overburden are groutable and the means and methods used are appropriate and effective. This same net reduction in grout takes was observed during the completion of the remainder of the curtain as well.

A total of 675 borings were installed throughout the completion of the Lockington Dam grout curtain.

Drilling quantities included:
- 44,000 LF of casing installed through the hydraulic core
- 11,547 LF of drilling through glacial till/outwash
- 9,472 LF of rock drilling

Over 400 Tons of cement was placed during grouting of the foundation.

Nine (9) verification borings were installed across the alignment of the grout curtain. Five (5) were installed west of the spillway and four (4) were installed east of the spillway. While they were spread out along the alignment, placement was adjusted to target areas of high grout-take during curtain
installation. The water testing performed in the verification borings indicated that the grout curtain exhibited the desired hydraulic conductivity.

In general the drilling and grouting for the curtain installation went as planned without any major problems. Most importantly, it was completed safely with no incidents or accidents. Due to the configuration of the working platform (long and narrow) the logistics of coordinating 7 drill rigs performing 3 different types of drilling was extremely challenging. This was exacerbated by a significant underrun in the grouting quantity, necessitating increased production from the drilling rigs to maintain work for the grouting crews. This resulted in an overall extension of the curtain installation schedule and underutilization of the grouting crews.

Complete piezometer data won’t be available for years, but initial data points indicate that the downstream piezometers are no longer responding to increased pool elevations as they did in the past. This is an indication that advanced grouting techniques are an effective short-term, and a durable long term option for reducing seepage through embankment soils as well as fractured bedrock foundations.

REFERENCES:

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Websites:
http://www.miamiconservancy.org/flood/safety.asp
http://www.miamiconservancy.org/flood/dams_lockington.asp

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This paper is dedicated to the memory of Jeremy Wise.