VERTICAL BARRIER WALL INSTALLATION USING THE VIBRATED BEAM METHOD; AN APPROPROPRIATE TECHNIQUE IN SELECTED APPLICATIONS

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The vibrated beam method of installing a vertical barrier wall is one of the least applied techniques, yet given certain site conditions and constraints, it is a cost-effective and proven method of controlling lateral groundwater flows. A recent full-scale application of this technique demonstrated its usefulness at an active manufacturing facility located in Northern Wisconsin. At this site, a 3,233 foot long cutoff wall was keyed into an underlying bedrock, which was located an average of 40 feet below the ground surface. Using a slag cement-clay based slurry, a 1E-7 cm/sec or less, nominal 4-inch wide cut-off wall was constructed using the vibrated beam method. Challenges included working around an active manufacturing facility with minimal access to the work area; installing the wall through a very dense glacial till; minimizing soil excavation volumes of potentially impacted soil; and, working around and adjacent to numerous active utility lines without impacting the facility operations. At utility locations, the vibrated beam wall was supplemented with a jet grout panel wall, without the need to bypass or otherwise interrupt any of the plant's utilities. Quality control consisted of the monitoring and measuring of slurry parameters, survey control, and real-time monitoring and documentation of all critical barrier wall installation parameters. A vibration monitoring plan was also implemented to measure vibrations at utilities and adjacent facility structures. Proper equipment selection, significant up-front planning and close coordination with the facility resulted in a safe and successful project. The work was completed ahead of schedule during the 2009 construction season.

Introduction

A manufacturing facility located in northern Wisconsin produced agricultural herbicides from 1957 until 1977. As result of the agricultural herbicide production process, waste salt containing approximately 2% arsenic by weight was generated, stored on site and subsequently entered site soils and groundwater.

A multi-phase vertical barrier wall system was ultimately proposed around the perimeter of the active manufacturing facility to control the lateral migration of groundwater. A contract was awarded for the installation of the initial 2,422 lineal feet (lf) of Vibrated Beam Slurry Wall (VBSW) at the facility. This wall surrounded the east and south side of the existing facility.

Upon completion of the initial contracted portion of the VBSW, a second contract was awarded for the installation of an additional 811 lf of VBSW the west side of the facility and directly down the middle of the main thoroughfare within the active facility. The balance of the barrier wall system consisting of a sheet pile bulkhead system with sealed interlocks along the northern side of the site and adjacent to navigable river was proposed for completion in 2010. The installation of other hydraulic control measures is also proposed to further enhance groundwater management.

Photo 1 - Overhead view of VBSW operations and proximity to facility structures.

Geology/Hydrogeology

Historic subsurface investigations at the facility indicate the following general stratigraphic units beneath the site:

- The upper soil layer generally consists of fill material. The depth of this non-continuous upper layer varied from approximately 0 to 15 feet below ground surface (bgs).

- Underlying the fill material is a water-bearing organic (peat) layer underlain by a layer of loose to medium dense alluvial deposits of fine-to-coarse sand and gravel with varying amounts of silt. The thickness of this layer generally ranged from 15 to 20 feet thick. Blow counts in this layer ranged from approximately 10 to greater than 50.

- Underlying the above layer are lacustrine and glacial till deposits of dense to extremely dense silt, sandy silt, and lean clay. At random locations, sand and gravel layers occur within the till; soil boring logs also indicated the presence of cobbles and rock fragments. The thickness of this layer generally ranged from 20 to 25 feet. Blow counts in this layer were generally greater than 50.

- Bedrock underlies the lacustrine and glacial till deposits at a depth of approximately 40 to 50 feet bgs.

Subsurface investigations also revealed that groundwater is generally encountered at depth of approximately five feet bgs. However, the groundwater level is generally dependent on precipitation, infiltration and the surface water level of the adjacent river. Groundwater was measured within three feet of the ground surface during high water levels in the river. Therefore, unsaturated soil sampling is typically limited to the top three feet of soils at the site. Groundwater encountered above bedrock beneath the site is considered a single aquifer with typical groundwater flow direction towards the river (to the northeast) across the site.

Challenges

The vertical seepage barrier installation at this active facility posed numerous challenges. Of primary importance to the facility owner were no interruptions to the active facility operations and no safety incidents. Due to the numerous active utilities providing service to the facility operations, successful implementation of activities associated with the utility investigation and subsequent crossings was critical. Other challenges included selection of the appropriate equipment to penetrate the extremely dense glacial till material and general planning of construction activities within the operating manufacturing facility.

Bench-Scale Grout Mix Design Testing

As part of the contract requirements, the Contractor completed bench-scale testing and submitted two slurry mix designs for the project; one for the VBSW installation and one for the jet grouting operations (to be used around the existing active utilities). The purpose of the bench-scale testing was to verify that the proposed grout mix designs could achieve the permeability specifications of a maximum of 1E-7 centimeters per second (cm/sec) and to verify compatibility of the proposed grout with site groundwater, which potentially contains high salt concentrations and arsenic. During the bench-scale testing, the Contractor also evaluated whether pre-hydration of the clay was necessary.

The Contractor developed and prepared eight slurry mix designs in a geotechnical laboratory. Six of the slurry mix designs were created with predetermined quantities of various reagents using hydrant water obtained from the site. One slurry mix was created with predetermined quantities of various reagents using a 50%-50% mixture of hydrant water and groundwater containing a medium concentration of arsenic, and one mix design was created with predetermined quantities of various reagents using a 50%-50% mixture of hydrant water and groundwater with a high concentration of arsenic.

Although not required by the project specifications, pocket penetrometer testing was performed on all mix designs during the first seven days of curing for a qualitative analysis of set time, and unconfined compressive strength (UCS) testing was performed at 7-days, 21-days and 28-days on samples from all mix designs for a quantitative analysis of strength. As samples with higher strength typically exhibit lower permeability, from 28-day UCS data, several samples were selected for permeability testing.

The permeant used for all permeability testing was the medium arsenic concentration groundwater.

In summary, one slurry mix design was selected for the VBSW installation and one mix design was selected for the jet grouting work. To determine if there were any deleterious effects on the cured grout permeability due to the use of site groundwater in the slurry, three of the slurry mix designs were further evaluated during the bench scale evaluation. The three mixes were identical in reagent proportion; however, one mix used 100% hydrant water and, as discussed above, site groundwater was used to prepare the other two mixes (i.e., medium and high arsenic concentration groundwater).

The permeability of all mixes tested was less than the specified maximum permeability of 1E-7 cm/sec. In addition, although the permeability of two of the mix designs which were created with site groundwater, exhibited slightly higher permeability values than the counterpart mix design that was mixed with just site hydrant water, the permeability of all samples were within the same order of magnitude (i.e., E-8 cm/sec range), which verified no significant effects from site groundwater. The bench-scale testing also confirmed that mixing the powdered clay with water for a 60-second period prior to the addition of the slag was sufficient to achieve the permeability specifications.

<u>Mobilization and Site Preparation</u>

Mobilization involved the movement of necessary equipment, materials and personnel to the project site and assembly/setup of the slurry batch plant and VBSW crane. The following equipment was used during the installation of the VBSW and jet grout diaphragm wall:

- Crane - A Terex HC 165, 165-ton crawler crane was used as the primary piece of equipment for the VBSW installation.

- Vertical Travel Lead (VTL) System - A 78-foot long VTL system was mounted to the crane. The VTL system supported both the vibratory hammer and the beam itself.

- Vibratory Hammer - An HPSI Model 1600 vibratory hammer was used to install the beam to the design depth. The hammer is rated at a frequency of 1,400 Hertz (vibrations per minute) and had an approximate suspended weight of 52,500 pounds. The hammer operated from a dedicated power pack and cooling system mounted on the rear of the crane.

- Beam - A 50 foot long steel wide flange beam with a web length of 30” and web thickness of 4” was initially used for the project. Because of the effectiveness of the vibratory hammer/beam combination in penetrating the dense glacial till, the Contractor switched to a larger beam with a 36” web thickness for full-scale production. Both beams were equipped with a 10-inch fin on the trailing flange that guided the beam into the previously installed panel to help maintain the beam alignment during installation. The beams were equipped with a steel pipe line and injection nozzle to transport the grout to the tip of the beam (Photo 2).

Photo 2 - Close-up of beam tip showing 10-inch fin and injection nozzles.

- G&H Monitoring and Data Acquisition System - A G&H monitoring and data acquisition system was installed on the crane to collect and record quality control data during the VBSW installation. The G&H system collected and recorded the verticality of the beam, the flow rate and quantity of grout injected during the penetration and withdrawal cycles, and time for the installation of each panel.

- Scheltzke MPS-510 Automated Batch Plant - The batch plant was equipped with a water meter, mixing tank/colloidal mixer (~106 gallon capacity), reservoir tank (~370 gallon capacity) and feed pump. The batch plant operated using an integral diesel engine and power supply. The slurry was mixed in batches using the batch plant and pumped directly to the beam via one and one-half inch diameter high pressure grout hose.

- Reagent Silos - A 30-ton silo for bulk storage of blast furnace slag and a small bag hopper for storage of powdered clay were operated by the hydraulics on the batch plant.

- Vibration Monitoring - throughout the project, the Contractor collected and recorded vibration data proximate to the barrier wall installation and buildings within the facility using mobile monitoring equipment.

- Support Equipment - Other support equipment on the project included an all-terrain forklift, dozer, excavator, loader, dump truck and support crane.

The raw materials used for the grout for the VBSW and diaphragm wall installation were water, Grade 120 blast furnace slag and powdered clay. The blast furnace slag (aka, slag cement) was delivered via bulk tanker and stored on site in the 30 ton bulk storage silo. The powdered clay was delivered in one metric ton 'super bags' (2,205 pounds each) and stored on site on wooden pallets. The bags were transferred individually to the small bag silo using an all-terrain forklift. Water was obtained from an on-site fire hydrant and piped directly to the batch plant.

The Contractor set up the automated mix-pump station (i.e., batch plant) near the center of the wall alignment and was able to pump over 1,600 lineal feet to either extreme of the wall alignment. The water source for the batch plant was obtained from an on-site fire hydrant located approximately 400 feet to the west of the batch plant location. A water meter and backflow preventer were placed on the hydrant to meter water usage and prevent the backflow of water into the plant's water system. Four inch diameter HDPE pipe connected the batch plant to the hydrant. A one and one-half inch diameter output pump line connected the batch plant to the crane. The pump line was placed on the ground surface and the length was adjusted (i.e., 100 foot sections were added or removed) as the VBSW installation progressed along the alignment.

The Contractor cleared a portion of the VBSW alignment using a brush hog attachment on a mini-loader and constructed a working platform using clean off-site borrow material. The width of the working platform was approximately 30 feet. The platform was constructed with a small trench in the center to facilitate and manage excess slurry during installation of the VBSW. Construction mats were also utilized over the working platform to distribute the weight of the crane.

Utility Investigation & Crossings

As identified on the Contract Drawings, there were 11 active underground utilities that crossed the initial 2,422 lf of the VBSW alignment and an additional 10 underground utilities that crossed the 811 lf of the alignment along the main thoroughfare through the facility. At one location there were also overhead electric lines that crossed the VBSW alignment; these lines were temporarily relocated by the Engineer.

In lieu of the installation of the utility crossing/penetration detail initially proposed by the Engineer, which required the individual removal and temporary bypass of each utility while the VBSW was installed along the alignment, the Contractor proposed to install a concrete collar around each identified utility and install a thin diaphragm wall via jet grouting to complete the barrier wall at each utility crossing. This modified design resulted in a net savings of approximately $200,000.

The general plan for identifying the utilities consisted of an initial ground survey based upon the historical location from facility records. Each utility was located according to the information provided on the Contract Drawings and a stake and flagging was placed at each location along with the utility identification. Upon completion of the surveying activities, the Contractor requested that the utilities be field located via Wisconsin Digger's Hotline. Representatives of the city and utilities subsequently field located their known utilities based upon their available data. Upon completion of the field locating, the Contractor had the utilities surveyed again and all of the known utility data was complied in a table.

The Contractor then utilized the services of a non-intrusive investigation service that utilized ground penetrating radar to more accurately identify the location of all potential utilities. The Contractor then pre-trenched the entire proposed VBSW alignment utilizing a backhoe with a 12" wide bucket to a depth six feet to locate any other utilities or obstructions. As a result of the non-intrusive investigation and the pre-trenching activities, a total of 25 utilities were ultimately identified; 13 along the initial portion of the alignment and 12 within the facility.

To physically locate the exact plan location, depth, diameter and construction material of each utility, the Contractor utilized vacuum excavation equipment to remove the overlying soil and expose each conduit. Once exposed, a concrete collar was formed and poured around each utility conduit. The purpose of the collar was to provide protection of the utility conduit during installation of the thin jet grout diaphragm wall. As necessary, the Contractor utilized the services of a local utility subcontractor with facility experience as part of the contingency plan should utility damage result from the vacuum excavation activities or during placement of the collars. As appropriate, the utility company was also on-site to observe the placement of the collars around the utilities.

<u>Vibrated Beam Slurry Wall Installation</u>

This section provides information on grout mixing and delivery operations, vibrated beam slurry wall panel installation, and data acquisition and quality control.

<u>Grout Mixing and Delivery</u>

The slurry for both VBSW and the jet grouting was mixed in batches using the automated batch plant (Photo 3). Initially, a predetermined quantity of water was added to the mixing tank. Based upon the mixing procedure that was used during the bench-scale testing, the powdered clay was added to the pre-measured volume of water and mixed for approximately 60 seconds; the cement slag was then added to the water/powdered clay mixture and the combined materials were mixed for approximately 60 additional seconds.

Photo 3 - Automated batch plant and reagent silos.

Both the powdered clay and slag cement were added to the mixing tank via an auger feed. A small 'super bag' feed silo, which was equipped with an auger feed, was used to add the powdered clay to the mixer. A 'super bag' of powdered clay was placed on top of the small bag feed silo. The 'super bag' was equipped with a draw string that when removed allowed the material to flow into the smaller silo. The auger feed for the slag cement was mounted directly on the 30 ton silo.

The batch plant was equipped with a flow meter to measure water, and also incorporated an integral scale to weigh the dry materials. The batch plant was programmed to add the three materials (i.e., water, powdered clay and blast furnace slag) to the mixer in the proportions according the bench-scale mix design study. Once a batch of slurry was sufficiently mixed, the slurry was transferred from the mix tank to the reservoir tank. Another batch of slurry was then mixed in the mix tank, transferred to the reservoir tank and the process repeated.

The following quality control testing was performed by the batch plant operator during the barrier wall installation and was documented on Contractor's Daily Slurry Batch Log:

- Date, time, batch number, beam insertion identification (or jet grout panel number), volume or weight of grout materials, and mixing time after addition of powdered clay and slag cement.

- Viscosity of slurry was measured a minimum of four times daily and was maintained at greater than 35 marsh funnel seconds in accordance with API RP 13B.

- The slurry temperature was measured a minimum of four times daily and was maintained at greater than 35 degrees Fahrenheit throughout the project.

- The unit weight of the slurry was measured a minimum four times daily and was maintained in the range of 68 to 75 pounds per cubic foot in accordance with API RP 13B.

<u>Vibrated Beam Slurry Wall Panel Installation</u>

The Contractor initiated the installation of the VBSW at the northeastern portion of the site adjacent to the river. The barrier wall alignment was field located by a licensed surveyor. Survey stakes were placed with stationing along the alignment at minimum 50 foot intervals and at turning points. The following was the general installation procedure that was used to install the VBSW:

- The crane was mobilized on the work platform and the leads, to which the beam was attached, was leveled and located to ensure that the beam was installed plumb and in the proper location along the alignment.

- Once the proper positioning was established, the crane operator notified the batch plant operator via radio communication to begin pumping grout. Once the flow of grout (~10 gallons per minute) reached the injection nozzles on the bottom of the beam, the beam was advanced using the vibratory hammer. The Contractor was provided a table by the Engineer that identified the approximate refusal depth along the alignment (based upon subsurface records) such that the crane operator could verify that the beam was driven to the approximate proper depth. Refusal at bedrock was easily verified based on the visual behavior of the beam rebounding on the bedrock surface and confirmed by the historical subsurface records.

- Once the beam was driven to refusal, the crane operator communicated to the batch plant operator to increase the grout flow. The beam was then withdrawn while the grout slurry displaced the void created by beam penetration. The monitoring equipment (further discussed in this paper) in the crane allowed the crane operator to maintain a withdrawal rate based upon the grout pumping rate such that the withdrawal rate would not exceed the capacity of the grout pump to fill the void created by the beam.

- Once the beam reached the ground surface, the crane operator communicated to the batch plant operator to cease pumping.

Photo 4 - Excavated trench used to contain excess slurry.

- Upon completion of a panel, the crane moved to align the beam to the center of the next beam penetration location. Each beam insertion was overlapped by six inches. In addition, as previously discussed, the beam was equipped with a 10-inch fin on the trailing flange that guided the beam into the previously installed panel to help maintain the beam alignment during installation. The process of the beam installation was then repeated. The Contractor placed interim stakes between the 50 foot intervals provided by the surveyor, which represented each beam insertion location. The number of penetrations was checked along the alignment stationing as an added QC procedure to assure that the beam maintained the proper spacing.

- Along the VBSW alignment, a shallow pre-trench was incorporated into the crane platform to contain the excess grout slurry (spoils) as they came to the surface (Photo 4). Spoils from the pre-trench were managed and removed as needed. If, necessary, at the beginning of each production day, additional grout was placed in the trench to replace any grout slurry that may have been lost due to settlement.

The Contractor's Quality Control Manager maintained a Daily Driving Log and for each beam insertion and recorded the date, insertion start time, driving depth, approximate ground elevation, beam final tip elevation, withdrawal end time, and additional comments. The Daily Driving Log was attached to Daily Report and provided to the Engineer on a daily basis.

Data Acquisition & Quality Control

The Contractor's batch plant operator was responsible for the quality control of the slurry and maintained a Daily Slurry Batch Log. Additionally, The Contractor's Quality Control Manager maintained a Daily Driving Log and for each beam insertion.

The crane used for the VBSW installation was equipped with a data acquisition system to collect and record quality control data during the VBSW installation. The Contractor utilized equipment manufactured by Gamperl & Hatlapa (G&H). For each VBSW panel the crane operator entered the Panel number into the G&H system (Photo 5). As the panel was installed, the G&H system collected and recorded the verticality of the beam, the start time of the panel insertion and end time for the withdrawal, the total panel length, the total volume of grout injected during the insertion and withdrawal cycle, and the volume of grout injected only during the withdrawal cycle. On a daily basis, the G&H system also recorded the sum of the length of VBSW panels installed, the total volume of grout injected during the insertion and withdrawal cycles, and the volume of grout injected during only the withdrawal cycle.

Photo 5 - Data acquisition system display mounted in cab of crane.

On a daily basis, the Contractor's Quality Control Manager would download the data from the G&H system and attach the summary sheet to Daily Report.

Hydraulic Conductivity Testing

Laboratory hydraulic conductivity (i.e., permeability) testing was performed on slurry samples at the minimum specified frequency of one test per 300 lineal feet of VBSW.

During installation of the VBSW, wet grout samples were obtained on a daily basis, which represented each day's production. Each day, six three-inch diameter by six-inch high plastic preform molds were filled with grout slurry, capped, labeled, and stored on-site. The samples were stored at ambient temperature in plastic bins filled partially filled with water to represent 100% humidity in the container. The Engineering Oversight Manager was then presented with a list of samples and the corresponding date of collection and baseline collection location. The Engineer selected random samples within each 300 lineal foot interval along the entire VBSW alignment for hydraulic conductivity analysis.

The selected sample sets (two samples per set) were transported to a regional independent testing laboratory. The samples were maintained in an upright vertical position and protected from disturbance during transport. All samples were cured a minimum of seven days prior to initial transport. In some instances, the Contractor elected to begin permeability testing after a shorter curing time than the minimum specified 45 day cure time.

The specified confining pressures used for triaxial hydraulic conductivity testing (ASTM D5084) were between approximately 5 to 10 pounds per square inch (psi), and two permeability tests were performed for each sample set, using slightly differing confining pressures. All sample results were less than the specified maximum permeability of 1E-7 cm/sec.

Vibration Monitoring

In accordance with the Project Specifications, both a pre-construction survey of site structures and vibration monitoring at structures within 75 feet of the VBSW operations using seismographs were required. A seismic survey subcontractor performed the pre-construction survey of the site structures and additionally provided the portable seismographs and trained the Contractor personnel on their use.

The Contractor utilized two Instantel Minimate Plus portable vibration monitors (Photo 6) to measure the ground vibration as particle velocity in accordance with the Project Specifications. Each of the vibration monitors was equipped with wireless cellular modems that transmitted and downloaded the vibration data to the seismic survey subcontractor's office on a daily basis. As specified, the monitors measured and recorded particle velocity in three directions. The maximum specified allowable peak particle velocity limit was one inch per second (1 in/sec) as measured in either one of the three directions or as the sum of the three velocity vectors.

As the VBSW installation progressed, the two monitors were moved and placed proximate to structures, utilities, or other potentially sensitive objects. Typically, one monitor was placed proximate to the VBSW operations and the second would be placed along the VBSW alignment ahead of the VBSW operations. The locations of the two monitors were recorded in the Contractor's Daily Report. During the vibration monitoring period, pre-determined particle velocity trigger levels were set in each monitor such that if the particle velocity trigger levels were exceeded, the wireless cellular modems within the monitors would send an electronic mail message to notify the Contractor's personnel of the exceedance. The individual velocity triggers were set at 0.02 in/sec, which were far below the maximum specified allowable value.


Photo 6 - Portable vibration monitors.

During the monitoring period, there were a total of three days when the total peak recorded particle velocity exceeded 1 in/sec at only one of the monitors. Additionally, there were no individual vector particle velocity measurements greater than 1 in/sec at either monitor during the recording period. During two of the three days when the total particle velocity exceeded 1 in/sec, there were a total of five instantaneous readings that exceeded the peak allowable velocity. Because the readings were not consecutive, not sustained throughout the day, nor measured proximate to any of the structures within the facility, it was judged that no modifications to the VBSW operations were warranted. The third day that the total peak recorded particle velocity was exceeded was a day when no VBSW operations were conducted. The elevated readings were likely caused by other construction equipment operating proximate to the monitor.

Thin Diaphragm Wall Installation

The Contractor used dual phase jet grouting using high pressure grout and air with dual nozzles to build the thin diaphragm wall panels between the VBSW windows at each utility crossing and parallel to a water main where it was impractical to install the VBSW.

The jet grouting also included the installation of two jet grout tie-in columns where the VBSW alignment intersected an existing steel sheet pile wall near a former backfilled boat slip.

Site Restoration and Demobilization

Site restoration included activities that were conducted on the project site to ensure that the site was restored to its condition as approved by the Engineer. These activities included permanent fence reinstallation; placement of topsoil; seeding; installation of erosion control blanket; fertilizing; and, maintenance. Additionally, the Contractor repaired asphalt paving proximate to the boat slip area that was either removed or damaged as part of the VBSW installation. The Contractor was also contracted by the Owner to complete the full-width restoration of the asphalt pavement along the thoroughfare within the facility.

Demobilization included removal of all temporary construction items in areas where the VBSW and thin diaphragm wall barrier walls were installed; decontamination and cleaning of equipment; demobilization of all temporary trailers, equipment, and excess materials; and, final site cleaning.

Conclusions

As previously discussed, the challenges on this project were numerous. Of primary importance to the facility owner, the project was completed without interruption to the active facility operations and with no recordable safety incidents. The proper selection of equipment to penetrate the extremely dense glacial till allowed the project to be completed approximately six weeks ahead of schedule. In addition, an alternate solution to the specified utility crossing methodology decreased the likelihood of a facility interruption and ultimately reduced the overall project costs.

The vibrated beam construction at this facility allowed for work in confined areas with limited space for staging or above-ground mixing that would be required for more traditional slurry wall construction. The final unit cost for the VBSW was approximately $21 per vertical square foot, which is somewhat higher than a traditionally installed cement-bentonite slurry wall. However, because minimal excavation of site soils was required for installation, this technique minimized soil transportation and disposal costs, which can be costly when dealing with contaminated sites. The VBSW was successfully installed to a depth of 50 feet with a final grout hydraulic conductivity of less than 1E-7 cm/sec.

Reference list

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