Foundation Improvement Evaluation

Kentucky River

Lock and Dam No. 8

A Major Qualifying Project
for Stantec Consulting Services Inc.
submitted to the Faculty of
WORCESTER POLYTECHNIC INSTITUTE
in partial fulfillment of the requirements
for the Degree of Bachelor of Science

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Abstract

This project discusses and evaluates different dam foundation improvement techniques including two different positive cut-off walls, grouting, and a combination of these. These techniques were evaluated based on four different evaluation criteria: cost, environmental impacts, risk and constructability. A schematic design was created based on the most suitable foundation improvement. This report is intended to supply Stantec Consulting Services Inc. in Lexington, Kentucky with evaluation criteria that can be used at Lock and Dam No. 8 and other similar structures.
Acknowledgements

We would like to thank Professor LePage and Professor Hart for all their help throughout the entire MQP process. The resources and knowledge that Stantec Consulting Services Inc. in Lexington, Kentucky provided helped our project throughout the seven weeks. The help of individuals including Daniel Gilbert, April Welshans, and Adam Hacker was vital to the success of this project and we cannot thank them enough. Thanks to all the rest of the Stantec employees that helped us and made our stay in Kentucky all the more productive and enjoyable.
Authorship

Throughout the course of this project both group members worked on different sections of this paper. Specifically we would like to acknowledge Michael Kendall for taking an interest in the Grouting Programs and Karyn Sutter for taking an interest in the Cut-off walls. Although some sections were written by one member to begin with, all sections were edited by both members who contributed equally to this projects success.
Capstone Design Statement

The Accreditation Board for Engineering and Technology (ABET) requires that all accredited engineering programs include a capstone design experience. This requirement is met at Worcester Polytechnic Institute (WPI) through the Major Qualifying Project (MQP). The American Society of Civil Engineers (ASCE) specifies that this capstone experience must include the following considerations: economic; environmental; sustainability; manufacturability; ethical; health and safety; social; and political. The following is a description of how these considerations were incorporated into our design:

Economic

To aid in the decision making process of choosing an optimal foundation improvement program, a cost estimate of each foundation improvement alternative was prepared. This included the material, labor and equipment costs associated with each design alternative. This cost estimate was one of the primary factors in deciding upon a foundation improvement program to be recommended for at Lock and Dam No. 8.

Environmental

With the construction at Lock and Dam No. 8 there are concerns with disruptions to the Kentucky River. Two permits were investigated that address the discharge of materials from the excavations as well as any construction activity on the water.

Sustainability

By recommending a foundation improvement program that uses state-of-the-art techniques and includes aspects of redundancy, such as grouting and a cut-off wall, the anticipated lifecycle costs of the dam were reduced. Unsuccessful treatment programs were studied and used as guides to decrease the likelihood of needing future foundation treatments. There are numerous examples of inadequate or insufficient techniques being used which resulted in wasted materials and money.
Constructability

One of the key elements in our evaluation of each alternative was its constructability. This criterion involves applying knowledge of the construction process to assessing the practicality of a design. Several potential issues were considered such as site limitations and sequence of construction activity. Site issues, such as difficulty in accessing the site by land and in-the-wet construction, in the presence of constantly flowing water, eliminated several design options.

Health and Safety

Due to the uncertain nature of geotechnical related construction, much of the responsibility for safety resides with the contractor. However, by assessing the constructability of design alternatives, the likelihood of unsafe construction practices was reduced. Also, the structural capacity of the foundation was investigated to show that allowable stresses were not exceeded.

Social

One of the main reasons for the improvements being done on Lock and Dam No. 8 is to reduce seepage. During periods of drought, this seepage has resulted in a reduction of water quantity and quality for nearby communities including the city of Nicholasville.

This MQP has met the ABET and ASCE requirements by going through a “design process” where several of the above factors were used to evaluate the best alternative. These criteria were used to determine the most suitable foundation improvement to address water seepage issues at Kentucky Lock and Dam No. 8. Using previously prepared reports and industry reference material provided by Stantec Consulting Services Inc. (Stantec), we estimated the effectiveness of certain designs given the project’s geologic setting and construction approach. Once the most effective design was established, it was outlined, translated into schematic drawings and presented to Stantec for consideration.
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1.0 Introduction

Lock and Dam No.8 is located on the Kentucky River near the city of Nicholasville, KY between the Jessamine and Garrard Counties. The dam, which is 111 years old, was originally constructed between 1898 and 1900 by the U.S. Army Corps of Engineers. The dam consists of a rock-filled timber crib structure capped with concrete and a stone masonry navigation lock. While all previous dams built on the Kentucky River had provided a 15-ft. lift, Dam No.8 provided an 18-ft. lift which was carried through all subsequent dams on the river. Throughout its history, many repairs have been performed at the facility dating from 1907 to 2002; however, the facility still remains in poor condition (Stantec, 2011).

Figure 1: Dam No. 8 (Stantec, 2011)

A replacement structure for Kentucky River Dam No. 8 is currently in the design phase. After successfully completing two other dam renovations on the Kentucky River, Stantec Consulting Services Inc. (Stantec) was again retained by the Kentucky River Authority (KRA) to design and facilitate the renovation of Dam No. 8. Although the main dam construction method has been determined, several design decisions still remain. One of the most critical is how to improve the foundation.
Due to karstic geology in the region, a significant amount of seepage occurs through the foundation of the current Dam No. 8 in areas where significant voids or solution features exist. During periods of drought, this has resulted in a reduction of water quantity and quality for nearby communities including the city of Nicholasville. The karstic geology also raises concerns regarding the bearing capacity of the foundation. An evaluation of different foundation improvements addressing these concerns is required as part of the design process.

This MQP involves working with Stantec to determine the available foundation treatment options and suggesting an optimal design. The specific methods considered include grouting, positive cut-off walls and combinations of each. The evaluation criteria for each method depended on such considerations as: cost, risk, environmental impact and constructability.

After reviewing subsurface information at the renovation site from a recently performed geotechnical exploration program and applying the previously mentioned criteria, a report outlining a recommended design was prepared. In considering approaches, the cost of materials and labor necessary to perform the work was also evaluated. It should be noted that future dam replacements along the Kentucky River may require similar foundation improvements to those required at Kentucky River Lock and Dam No. 8. Therefore, our recommendation will be of value to Stantec and the Kentucky River Authority (KRA), not only by addressing the problems at the Lock and Dam No. 8 site, but also by serving as a guide in addressing similar foundation conditions at other facility locations.
2.0 Background

As stated in their mission statement, the first priority of the KRA is to manage the water resources of the Kentucky River Basin. Therefore, one of Stantec’s primary responsibilities to the KRA is to address water supply and quality concerns due to uncontrolled seepage. Seepage is a particularly important consideration at Lock and Dam No. 8 for two reasons. First, a majority of the rock in the region (limestone) is highly karstic. Karstic rock is characterized by frequent fractures and voids, sometimes several feet in height and width. Figure 2 shows features encountered in 1975 during the construction of a dam cut-off wall in southern Kentucky.

![Image](image1.jpg)

**Figure 2: Example of voids historically found in KY Limestone (Bomar, 2011)**

During a 2001 lock operation and leakage study on Lock and Dam No. 8 performed by Stantec, numerous karst features were discovered, ranging from 4 in. to 5.5 ft. wide, 3 in. to 1 ft. tall and 1 ft. to an undetermined length below the lock walls. The largest fissure observed, located in the lock chamber floor, was 10 to 12 ft. in length, 8 to 10 in. wide and over 4 ft. deep and oriented approximately northeast. From dye testing, the assessment estimated leakage to be 12.7 million gallons per day (Stantec, 2011).

The second reason seepage is an important issue is that the pool retained by Dam No. 8 (Pool No. 8) is a source of drinking water for a several nearby communities. The Nicholasville Water Department and Lancaster Water Works both actively draw from Pool No. 8. These systems directly supply populations of 20,552 and 5,254 people respectively. Additionally, several other suppliers purchase water from these systems including the Garrard County Water...
Association and Jessamine County Water District No. 1. These suppliers provide drinking water for 4,342 and 15,220 people, respectively (Kentucky Dept. of Environmental Protection: Division of Water, 2012).

2.1 Grouting

2.1.1 Overview

Grouting is a traditional approach to decreasing the permeability of a foundation and increasing its strength. In general, it is a process involving the filling of gaps and crevices with a low strength cement or chemical solution. The grout is injected under pressure through a drilled hole, usually 2 to 3 in. in diameter (Warner, 2004). In all grouting programs it is essential that the hole be thoroughly flushed with water before injection begins. In grouting designs, the standard unit used to measure the permeability of a foundation is the Lugeon (Lu). This unit, developed by Swiss geologist Maurice Lugeon, is calculated during pressure tests and equals 1 liter of water per meter of hole per minute at 10 bars pressure. It is impractical in most cases to reduce the permeability of a foundation below 1 Lu. In situations where water is highly valued, permeability between 1 and 3 Lu are recommended (Houlsby, 1990).

One of the most important decisions in a grouting program is grout hole spacing. A typical grout program follows a split-spacing sequence where primary holes, spaced approximately 20 to 40 ft., are drilled first (Warner, 2004). Secondary and, if necessary, tertiary holes are then drilled and grouted between the holes of the previous iteration. The theory behind this practice is that the largest voids are filled through primary holes. This provides confinement allowing the secondary and tertiary holes to fill sequentially smaller voids and fractures.
Grout is injected into the ground at regular intervals known as stages. Stage spacing is typically a function of distance from the surface. Near the surface, stages should be every 1-3 feet (Warner, 2004). At lower depths stages can be every 6-10 feet. Injections can be completed in ascending stages (upstage grouting) or descending stages (downstage grouting) depending on the level of permeability desired and the mechanical properties of the rock. Upstage grouting is quicker and therefore more economical, but upper portions tend to fill with cuttings blocking the path of grout. Downstage grouting is more effective but time consuming since the drill must be removed at every stage and the hole rewashed.

2.1.2 Design Techniques

When single rows of closely spaced grout holes are specified, and the goal is to reduce seepage, the design is known as a grout curtain. Most experts agree that a grout curtain is most effective when multiple rows are used, though there is little benefit in using more than three (Warner, 2004). Row spacing should be roughly twice the estimated grout penetration distance (Houlsby, 1990). As with any grouting program, a split-spacing sequence should be used. Additionally, Weaver (2007) cites recommendations by The Swiss Committee on Large Dams to orient grout holes at inclinations greater than 30° in order to intersect the maximum number of features. This is a more substantial inclination than Warner’s (2004) recommendation to incline the holes at no less than 20° from vertical. Engineering judgment should be used to evaluate the best angle at a particular site. Warner further recommends three row curtains where the upstream row is completed first, followed by the row furthest downstream, followed by the middle row. In this way the grout in the middle row (in theory) fills all gaps between the two outside rows. Ideally, the rows should be inclined in opposite
directions to “intersect” paths.

In many dam foundation improvement programs, where fractures and insufficient rock exists near the surface, surface treatments may be required. When such treatments are performed to reduce rock permeability and increase strength below the footprint of the dam, it is known as blanket or consolidation grouting (Warner, 2004). Such grouting is often done in combination with a grout curtain. A blanket grouting design includes the layout of the holes and the hole depth (usually 20 ft. or less). Holes should be approximately 10 ft. apart and should be drilled in a split-spacing progression. If the surface is highly irregular and difficult to work on, but permeability is not a concern, regularizing or dental concrete should be used. These concrete mixes are no different than typical mixes with the exception that maximum aggregate size is limited to one-third the minimum gap being filled.

Surface treatment may also be required to improve the strength of the rock above a grout curtain in order to improve its restraining ability. This technique is known as a grout cap and it provides several benefits. A grout cap provides vertical confinement during grouting efforts, which forces grout to travel horizontally instead of vertically. In addition to providing confinement, the standpipe can be imbedded in the concrete to allow easier drilling. Warner (2004) recommends caps to be 2 to 4 ft. deep and to extend 2 ft. upstream and downstream of the curtain. It is also recommended that reinforcing and anchors are used to tie down the caps.

2.1.3 Materials and Additives Used in Grout

Although several types of grout exist, nearly all rock grouting programs are performed with Portland cement based mortar. By adjusting the water cement ratio and including admixtures, grouts with a wide variety of properties can be obtained. In some situations, chemical solutions have been used when the significantly higher cost is justified. When the goal of the grouting program is to reduce the foundation permeability, the grout mixture should exhibit:

- Good Pumpability
- Quick setting time
- High cohesion
- Low shrinkage
These desirable properties are all increased by including additives and admixtures (Warner, 2004). Including a high percentage of fly-ash and silica increases the pumpability and penetrability of the grout, though Warner advises not to include more than 10 percent by weight. Shrinkage can be dramatically reduced through the use of water reducers or superplasticizers. As with any cement compound, this will result in a lower water-to-cement ratio, which will decrease the amount of water required, and will increase strength. Most industry experts highly encourage the use of water-reducer for grouting applications. Antiwashout admixtures, though hard to find, will increase the cohesion of the mix and prevent ground water from washing out the grout before it hydrates.

Another important property of a grout mix is its mobility. This is a term describing the ability of a grout to travel through the delivery system and into the features being treated. Warner is quick to point out that a mixture’s mobility is independent of its slump or thickness. Low mobility grouts (LMG) are used in situations where the travel of the grout must be restricted and/or voids being treated are significant in size (greater than 3ft. in diameter). High mobility grouts (HMG) are used in reverse situations where grout must travel long distances and fill small features (Weaver, 2007).

2.1.4 Quality Control

Monitoring and inspection are essential to a successful grouting program. Warner (2004) recommends that real time monitoring and logging systems are used during every grouting operation. Careful visual inspection is important at all times in order to prevent hydraulic fracture and “jacking” of the surface. It is important to remember that injection pressure is directly proportional to pumping rate. When jacking is observed, grouting injection should be terminated.

In general, Warner recommends that the maximum safe injection pressure should be used. Historically, maximum grouting pressures are specified as a function of depth. A 1984 Engineering Manual released by the U.S. Army Corps of Engineers (2004) provides a basic guide on calculating grouting pressure (Figure 5). The manual states that a good “rule of thumb” is to increase grouting pressure 1 psi per ft. of depth. Figure 5 shows this recommendation graphically as well as adjusted pressures based on rock conditions.
One recent method of specifying recommended injection pressures is through the use of a Grouting Intensity Number (GIN). GIN is the ratio between volume of grout injected per unit length of hole and pressure applied (Warner, 2004).

![Figure 5: USACE Grout Pressure Guide (U.S. Army Corps of Engineers, 1984)](image)

![Figure 6: Parabolic GIN curve with recommended pressure volume relationships (Warner, 2004)](image)
GIN curves can be plotted in real time, allowing close monitoring and control of injection pressure. Figure 6 shows curves with GIN values of 1 through 5. In situations involving highly horizontal, near surface grouting, curves of GIN 5 or higher are recommended.

In order to further verify injection pressures and grout consistency and measure progress, water pressure tests should be performed in secondary (and successive stage) holes (Weaver, 2007). Grout temperature should be monitored at all times to help maintain normal strength gain and limit shrinkage. In most cases, specifications should limit curing temperature to less than 90°F and should be kept above freezing. Finally, testing should be performed frequently due to the inconsistency of common materials. Several standardized tests exist for the evaluation of grout properties. ASTM C939, “Standard Method for Flow of Grout for Preplaced-Aggregate Concrete” is used to measure the flow properties of a grout. Figure 7 shows available tests for specific grout properties.

<table>
<thead>
<tr>
<th>Grout Property</th>
<th>Test Method and Equipment</th>
<th>Most Typical or Practical Location of Test</th>
<th>Typical Phase or Frequency When Conducted</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Grout Plan/Field</td>
<td>QA/QC Laboratory</td>
</tr>
<tr>
<td>Cohesion or gelation</td>
<td>Lombardi plate, shear vane</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Apparent viscosity</td>
<td>Marsh funnel</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Bleed</td>
<td>Graduated cylinder</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Pressure filtration resistance</td>
<td>Filter press</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Washout resistance</td>
<td>Special assemblies</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Filler segregation</td>
<td>Clear cylinders</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>Baroid mud balance</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Set time</td>
<td>Vicat needle</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Strength</td>
<td>Cubes, cylinders</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Matrix</td>
<td>Triaxial permeameter</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Compatibility</td>
<td>Various</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

Note: This table excludes the routine (or mandated) testing and certification required for the individual HMG components. QA/QC means quality assurance and quality control.

Figure 7: Testing methods and recommended use for relevant grout properties (Weaver & Bruce, 2007)
2.2 Cut-off Walls

A common technique used to decrease soil and rock permeability and control seepage is the cut-off wall. A cut-off wall is a broad term for any underground vertical structure that serves as a barrier. Several different variations of cut-off walls have been designed and constructed. While typical concrete cut-off walls involve placing concrete within an excavated trench, variations such as secant pile walls and diaphragm walls were also evaluated for Lock and Dam No. 8.

Cut-off walls are constructed in foundations of nearly every composition. In general, the type of wall chosen greatly depends on the ground composition of the site in question. When the ground consists of rock, a concrete structure must be used. It also depends on the remediation goal. If the wall must withstand a pore water pressure difference (such as in the case of Kentucky River Lock and Dam No. 8) it is referred to as a positive cut-off. These walls consist of concrete or thick steel pile construction.

2.2.1 Secant Pile Walls

Secant pile walls are a form of cut-off wall that consists of shafts backfilled with concrete. Refer to Figure 8 below. Secant walls while not suited for all conditions are especially good in karstic features.

![Figure 8: Secant Pile Wall](image-url)
Design

The design of a secant wall includes excavation, shaft cleaning, concrete fill and sometimes a concrete cap. The wall is constructed in small segments to limit construction induced tensile stress on the dam face and to limit the potential for weak foundation rock to collapse into the open cut-off slot before concreting (Amos, 2007). The secant shafts are generally drilled with a 48-in. diameter bit with an overlap of up to 12 in. The shafts should be drilled to a depth that is further than the open features in the foundation and can be drilled to depths up to 280 feet (Bruce, 2012a). The walls are constructed by first drilling out alternating piles (refer to Figure 8, primary piles). Regular quality control checks are typically performed to make sure the shafts are being drilled vertically center. Once completely drilled out, the shaft is flushed with water and then filled with concrete using a tremie pipe which is lowered into the hole. It is important to note that the rate of concrete rise in the shaft should be closely monitored and controlled to monitor problems, such as wall collapse. Before the concrete is completely set in the primary shafts, the secondary shafts are drilled overlapping the primary piles. (Refer to Figure 8) Once completed, the wall can be covered with a concrete cap depending on project requirements. This cap might not be necessary if the dam does not serve as an overflow structure. However, run of the river structures, such as Lock and Dam No. 8, require a smooth concrete surface; therefore, a concrete cap constructed in the dry is necessary.

2.2.2 Diaphragm Walls

A diaphragm wall is a structure composed of multiple individual panels generally 3 feet in width and 60 feet deep. When finished, the walls end up being an assembly of elementary independent panels placed side by side. See Figure 9 below (Fell, MacGregor, Stapledon, & Bell, 2005).
Diaphragm walls are constructed by excavating and concreting in alternating panels. The walls are created first by constructing panels on either end of the wall and slowly moving towards the middle. Geotechnical features in the panels are excavated several different ways including a clamshell bucket, a scraping bucket or rotary drilling. Once excavated the panel is supported by a steel stop end, which is removed after the panel is filled with concrete. The hole left by the stop end is used as a guide for the adjoining excavation. The panels are cleaned out and then filled with concrete using a tremie pipe. Similar to secant walls, once filled with concrete, the panels may or may not be covered with a concrete cap depending on dam conditions (Fell, MacGregor, Stapledon, & Bell, 2005).

2.3 Typical Improvement Program

In many recent dam foundation improvement programs, grouting and a cut-off wall have been used in conjunction. This is particularly true for regions known to contain karstic features and dams used to retain water supplies. In order to determine the particular techniques and dimensions appropriate for a project, a thorough geotechnical exploration should be conducted. In fact, most experts agree a geotechnical exploration is essential to the success of a dam.
renovation. Water pressure tests are one effective way to determine if the cost of a particular
technique is justified.

One of the largest foundation improvement programs in which the ground conditions
were similar to those at Kentucky River Dam No. 8 (though to a much larger degree) was
included as part of the Wolf Creek remediation project. Wolf Creek Dam, located in Southern
Kentucky, retains Lake Cumberland and supplies water to nearly 200,000 people in addition to
supplying hydroelectric power (Bomar, 2011). The ground conditions at this site were similar in
that they featured a dam located over karstic limestone. Following a geotechnical exploration
which included visual inspection, pressure testing, and exploratory drilling, the decision was
made to install a two row grout curtain and then construct a new combination barrier (cut-off)
wall. The walls were constructed of concrete and consisted of 24-in. diameter piles joined by
precast panels. The project featured two walls, one approximately 270,000 sq. ft. in area and the
other approximately 261,000 sq. ft. The structure was imbedded into bedrock at an average
depth of 280 ft. (Bruce, Ressi di Cervia, & Amos-Venti, 2006).

2.4 Evaluation Criteria

There are a few criteria that need to be considered when creating a dam foundation
improvement plan. Such criteria include cost, environmental concerns, and any risks associated
with the construction and operation of the dam.

2.4.1 Cost

When doing any project there are expected costs that need to be considered. For dam
construction, these include the cost of labor, materials, and disposal. Labor costs include those of
the construction, contractor, and their employees as well as well as for the planning and
engineering design team. Material costs include machinery, any materials that will be used in the
construction of the dam itself and the transportation of these items to the construction site.
Disposal costs associated with excess materials and water treatment also need to be considered.
Grouting

The following are typical items to be specified in a grouting contract: Mobilization and Demobilization, Drilling and Redrilling, Special Flushing, Water-Pressure Testing and Grouting (Weaver, 2007). A standby crew provision could also be included. Table 1 indicates the typical payment method for each of these items. Representatives from industry contractors indicate that most grouting programs cost $75 to $100 per linear ft. of hole drilled. Mobilization and Demobilization costs can be estimated as $300,000 plus escalation, based on the ready mix plant at a previous Kentucky dam renovation project (Lock and Dam No. 9). When construction will follow an in-the-wet approach, additional items become necessary such as a working platform and barges. These items are shown in Table 2.

Table 1: Grouting Items and Associated Payment Methods

<table>
<thead>
<tr>
<th>Item</th>
<th>Recommended Payment Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mobilization and demobilization</td>
<td>Lump sum (typically 50-60% on mobilization and the balance on demobilization)</td>
</tr>
<tr>
<td>Drilling and redrilling</td>
<td>Per linear ft./meter (with provision for a reduced redrilling rate for hardened grout)</td>
</tr>
<tr>
<td>Special Flushing</td>
<td>Per crew hour</td>
</tr>
<tr>
<td>Water-Pressure Testing</td>
<td>Per crew hour for multiple-pressure or extended tests; per test for simple, short tests</td>
</tr>
<tr>
<td>Grouting</td>
<td>Per pump hour; Per kilogram for materials mixed; possibly per month for specified levels, quality assurance and quality control and monitoring, if not otherwise included</td>
</tr>
<tr>
<td>Standby Crew</td>
<td>Per crew hour</td>
</tr>
</tbody>
</table>

[Adjusted from Dam Foundation Grouting, Table 16-2 (Weaver, 2007)]
Table 2: Additional In-the-Wet Grouting Costs

<table>
<thead>
<tr>
<th>Item</th>
<th>2011 Unit Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working Platform</td>
<td>$25,000 EA plus $25,000 to design</td>
</tr>
<tr>
<td>Material Transport Barge</td>
<td>$4,000 EA</td>
</tr>
<tr>
<td>Work Barge</td>
<td>$5,000 EA</td>
</tr>
<tr>
<td>Crawler Crane Operator</td>
<td>$19,000 per month, and 59.76 per hour</td>
</tr>
<tr>
<td>Tugboat Operator</td>
<td>$3,550 per month, $33.10 per hour operating</td>
</tr>
</tbody>
</table>

These additional item costs are taken from 2011 Heavy Construction RS Means and historical cost information from previous Kentucky River Projects.

**Cut-off Walls**

For cut-off walls, including both secant walls and diaphragm walls, there are some costs that can be broken down. Laborers that will be involved are the project manager, the site superintendent, the head engineer on site or in the office, and any administration. For secant walls, construction costs include drilling the shafts, which on average cost $400/ft., quality control checks at $7,500/Check, mobilization and demobilization of the drilling rig and the barge mount, and then equipment costs (Stantec, 2012). For diaphragm walls, construction cost will include drilling and excavating the panels as well as the mobilization and demobilization of the drilling rig and barge mount, and all other equipment costs. Equipment that is typically used in both of these types of construction include: a transport barge, a work barge, a tugboat and captain, a crawler crane and operator, and a wheeled crane and operator. These pieces of equipment are generally rented for a set fee per month, some having additional fees for the hours they are in use. As with any work, there is waste that needs to be disposed of. An estimated cost can be calculated based on the weight of waste and miles traveled to and from the dump site (R.S. Means Company, 2011)

**2.4.2 Environmental Considerations**

For the any construction that will take place on a body of water there are certain permits that must be obtained. To implement the renovation design at Lock and Dam No.8 there are two
permits that must be obtained before construction can begin. A U.S. Army Corps of Engineers (USACE), 404 Section 10 permit for dredging and fill and a 401 Kentucky Division of Water (KDOW) permit to construct in or along a stream.

In accordance with the Clean Water Act, section 404 establishes “a program to regulate the discharge of dredge and fill material into waters of the United States” (United States. Environmental Protection Agency, 2005). The Environmental Protection Agency (EPA) and the USACE take joint responsibility for enforcing this Act. To receive a permit the applicant must demonstrate that the discharge won’t “significantly degrade the nation’s waters” and must also prove that there are no better alternatives.

Section 401 of the Clean Water Act provides a water quality certification for states to enforce their own water quality restrictions. This permit applies to “any activity including, but not limited to, the construction or operation of facilities, which may result in any discharge into the navigable waters” (United States. Environmental Protection Agency, 2010). Each of these permits can take months to acquire and can each be given a time limit for validity.

2.4.3 Risks

An important part of any design evaluation is an evaluation of the types of risks involved and the likelihood of their occurrence. For civil engineering projects, these risks are associated with either the construction phase or operation and maintenance phase. Table 3 shows the major risks associated with the Dam 8 foundation improvement and probable causes. Design provisions will be analyzed for how well these risks are mitigated or eliminated. Historically, budgets for foundation improvement projects have been drastically exceeded when these risks were not correctly anticipated and addressed.
2.4.4 Constructability

The Construction Industry Institute (2012) defines Constructability as, “The optimum use of construction knowledge and experience in planning, design, procurement, and field operations to achieve overall project objectives” (Construction Industry Institute, 2011). It is considered to be a “best practice” in any engineering design process. Assessing the constructability of a given foundation improvement program (or any engineering design) is critical to its success when implemented. For projects taking place in-the-wet, such as Lock and Dam No. 8, constructability concerns are particularly great. River volatility and height directly influence the construction schedule and the feasibility of construction operations. The primary element affecting constructability at Lock and Dam No. 8 is the sequence of construction activities. Additional issues include site conditions and site accessibility.

Table 3: Foundation Improvement Risks

<table>
<thead>
<tr>
<th>Phase</th>
<th>Risk</th>
<th>Cause</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction</td>
<td>Cost Overrun</td>
<td>• Grout take exceeds expectations</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Cost of materials escalates</td>
</tr>
<tr>
<td></td>
<td>Environmental Destruction</td>
<td>(water quality, loss of wildlife)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Toxic substances are released into river</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Water table contamination</td>
</tr>
<tr>
<td></td>
<td>Foundation Damage</td>
<td>• Due to large voids, weight of poured concrete collapses foundation surface</td>
</tr>
<tr>
<td></td>
<td>Loss of Limb or Life</td>
<td>• Design is impractical, unsafe river level</td>
</tr>
<tr>
<td>Operation and Maintenance</td>
<td>Seepage is not reduced</td>
<td>• Injection holes Features/voids are missed</td>
</tr>
<tr>
<td></td>
<td>Seepage Increases</td>
<td>• Fracturing in rock or poor interface connection</td>
</tr>
<tr>
<td></td>
<td>Dam Failure</td>
<td>• Unlikely, run away equipment causes breach in existing dam</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Highly unlikely, fracturing of rock during grouting reduces stability of proposed dam</td>
</tr>
</tbody>
</table>
3.0 Methodology

The goal of this project was to create a preliminary design for a foundation improvement program for Kentucky Lock and Dam No. 8. To accomplish this task an evaluation was performed to narrow down the design alternatives. Three different methods for foundation improvements were considered and once one was selected a preliminary design was created. The following sections explain how each of the steps was executed to complete the MQP.

3.1 Design Selection

Before a design could be selected there were two steps that needed to be taken. These included evaluating the existing site conditions and preparing preliminary design options for each construction alternative.

3.1.1 Evaluate Existing Conditions

The first step in the process was to evaluate the existing dam conditions. This consisted of reviewing the November 15, 2011 geotechnical evaluation, all pertinent information from Stantec resources, interviews with Stantec staff, and a visit to the dam itself.

Geotechnical Study and Existing Conditions Report

The 2011 Geotechnical Report compiled by Stantec was essential to the design process. First, it was used to become familiar with the history and location of the site. Second, and more importantly, it summarized the results of the exploratory drilling study and water pressure testing. The report provided background into the size of karstic features and the estimated seepage rate. The calculated Lugeon values presented were used to determine the depth of the grout curtain and cut-off wall designs. Depths for the foundation improvement were determined corresponding to the geologically distinct regions indicated by the report. The horizontal limits of the curtain and cut-off wall were also determined using the test results of the borings along the right and left abutments. Additionally, the report provided the recommended bearing capacity and unconfined compressive strength of the foundation. These values were used to show that, assuming significant voids are grouted, the foundation can support the load of the planned dam structure.
In order to confirm the existence of karst features and determine locations with significant fractures or voids, borings were taken as part of Stantec’s 2011 Geotechnical Exploration. This consisted of thirty holes located 25 to 35 ft. upstream and downstream of the proposed dam centerline and in the right abutment. The location of these borings is shown in Figure 10.

The program revealed significant voids in borings B-13 and B-28 and several fracture zones throughout the foundation. The voids measured 1.4 ft. and 3.0 ft. respectively and were located within the top 8 ft. of rock. In order to measure permeability, water pressure tests were performed in each hole. High lugeon values were obtained for the top 10 ft. of rock in holes B-1 through B-7 and B-9 with most exceeding 100 Lu. As one would expect, Lugeon values exceeded 100 Lu in holes B-13 and ranged from 95 to 99 in B-28 down to 20 ft. below the rock surface. Significant water loss also occurred in Holes B-29 and B-30 down to 25 ft. below the rock surface (Stantec, 2011).

The water pressure testing results and bore logs indicated four distinct regions with similar geologic conditions along Baseline A. These regions are shown in Figure 10. As suggested by the geotechnical report, Region 1 was defined as spanning from the lock river wall (Station 12+50) east 175 ft. (Station 14+25). Region 2 was defined as from the lock river wall (Station 12+50) to Station 11+80. Region 3 was defined as between stations 11+70 and 10+50. Last, region 4 was defined as station 10+50 to 10+00.
Figure 10: Layout of Reconnaissance Borings (Stantec, 2011)
Water Pressure Test Parameters

The first step in determining the depth of the grout curtain and concrete cut-off wall was, using the recommendations discussed in section 2.1.1, defining rock of acceptable permeability as 5 Lu for the curtain and 1 Lu for the cut-off wall. Next, exact elevations were determined using results from water pressure tests as reported in the Geotechnical Exploration Report. For each boring within a particular region, the stage elevation for which the representative permeability was 5 and 1Lu was recorded. Then (discarding outliers) an average of these values was calculated and defined as the initial cut-off depth for a given region.

Stantec Resources and Interviews

While online research was beneficial to this project the help of Stantec employees was vital to its success. Once on site in the Lexington office, access to project databases was provided as research material. This included all relevant information from construction of previous dams to the working files of Lock and Dam No. 8. In addition to the information on their network, Stantec employees working on the project were also interviewed. These interviews were used to gain a better understanding of information provided in technical reports.

Visit to Dam

While the geotechnical evaluation on the dam as well as the project files included pictures of Lock and Dam No. 8, a visit to the actual dam site provided a better understanding of the existing dam. A visit to Lock and Dam No. 9 was also insightful as it showed what a completed dam renovation looks like.

3.1.2 Design Options

To better address the foundation problems at the dam, the construction was broken up into four different regions which were based on information found in the geotechnical evaluation as seen in Figure 10 above. By breaking it up it is easier to decide what foundation improvement is needed in which area. Based on the existing site conditions, three different foundation improvement designs were considered. These included using a grout curtain along the entire length of the dam, a grout curtain in addition to a secant wall in region two, and a grout curtain in addition to a secant wall across Regions 2, 3 and 4.
<table>
<thead>
<tr>
<th>Design</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design 1</td>
<td>Grouting in all regions</td>
</tr>
<tr>
<td>Design 2</td>
<td>Grouting in all regions, secant wall in region 2</td>
</tr>
<tr>
<td>Design 3</td>
<td>Grouting in all regions, secant wall in region 2, 3 and 4</td>
</tr>
</tbody>
</table>

Two cut-off walls were disregarded before the application of the evaluation criteria could even be applied. The first option that was not considered was placing a cut-off wall in Region 1. This area was about the same size as the other three regions and based on price alone was an unreasonable design. The other design option that was not considered was a diaphragm wall. The basic design of a diaphragm wall itself does not meet the positive cut off requirements because there is no overlap in paneling. Another problem was constructability, due to the location of Lock and Dam No. 8 it is unknown if the necessary equipment could even make it to the site. With narrow winding roads, sharp turns and a steep hill down to the dam site the roads leading to this site would be hard to maneuver or even fit machinery on. Wanting to make the design as feasible as possible was one of the goals of this project and therefore these design options were not utilized.

Grouting and cutoff wall techniques were then assessed for each of the four regions; information such as depth of the curtain and walls were calculated which were then compiled into tables for easier comparison.

3.2 Capstone Design

The capstone design section of this project includes analyzing the different design options based on the evaluation criteria and creating a preliminary design for the foundation improvement program that will be executed at Lock and Dam No.8.

3.2.1 Application of Evaluation Criteria

Four different evaluation criteria were researched in order to decide what foundation improvement techniques were best suited for the site. These included cost, environmental
impacts, risks and constructability. Once researched, the design options were evaluated using these criteria to determine which design option would be best suited for Lock and Dam No. 8.

Cost was analyzed primarily through the cost estimate prepared by Stantec for Phase A of Lock and Dam No. 8 as well as cost estimates for previous dam replacements on the Kentucky River. RS Means was also used to calculate materials and labor costs. Unexpected items were identified such as disposal costs and water treatment costs. Since cost is a huge factor in construction, the capital cost was evaluated for each design option which was then compiled in a table for easy comparison.

Stantec staff was very helpful in helping to identify applicable environmental issues. Concerns were largely similar for each of the improvement designs. Each of the alternatives involved a disruption to the flow of the river and construction on the river and therefore had the same permitting requirements.

Several risks were identified following advice from published materials and discussions with Stantec engineers. The risks identified were previously presented in Table 3 (Section 2.4.3). Risks were divided between those that are related to the construction phase and those that are related to the operations and maintenance phase. Most of these risks were applicable to all designs.

Constructability was assessed using guidance presented in textbooks, reports and discussions with Stantec employees. Potential issues were identified such as:

- Limited access by land to the site
- Necessity for all implementation to occur without the need for dewatering
- Foundation strength prior to grouting
- Practical tolerances available during construction

The four evaluation criteria were all given a numerical rating of 1-3, 1 being lowest and 3 being the highest, for each design option. These were compiled into a table to easily evaluate which design option would be best suited for the Lock and Dam No. 8 site.
3.2.2 Creation of Suggested Design

It was determined that the grouting program components of the project specifications should be flexible and are of a performance nature. This is particularly true for the mix design. As indicated by Warner (2004) it is highly logical to specify performance criteria for dam foundation improvement since one can simply specify the target permeability. This allows the contractor the flexibility to use proprietary techniques and familiar practices and will usually result in savings in cost and time. Specification flexibility is also important due to the uncertainty and variation involved in foundation treatment.

References were quick to point out, however, that certain aspects should be specified to ensure agreement between client and contractor and ensure accuracy of cost estimates. These include: Specification format, Mix design, scheduling and financial constraints, Supervision, quality assurance and verification and Method of measurement and payment.

Using recommendations from dam foundation improvement publications and discussions with Stantec engineers, a grout curtain was determined to be necessary regardless of other foundation improvement techniques also implemented at Lock and Dam No. 8. Additionally, since the foundation surface is highly fractured, surface treatments were also found to be necessary. The typical industry practice, in this case, would be blanket grouting and/or a grout cap. However, Stantec staff presented a more economical and effective solution. By completing a portion of the concrete cells and then commencing with the grout injection, the completed portion of the cell would act as “grout cap” providing a level work platform and providing confinement to the grout injection below.

The depth of the grout curtain was selected after comparing the results of two industry methods. The first dam foundation grouting programs typically specified hole depths as a function of the dam height. When used to control seepage from water retaining structures, the United States Army Corps of Engineers (USACE) recommends that grout curtains, under average conditions, be two-thirds to three-fourths of the headwater-tailwater differential (United States Army Corps of Engineers, 1995). Based on Stantec’s geotechnical study, the normal lift is 18.3 ft. suggesting a minimum depth of 13.73 ft. below the rock surface or elevation 486.
In all cases, in order to maximize the effectiveness of the grout curtain, grouting experts agree that the curtain should extend down to a zone of relatively impermeable rock. Using this method, various depths were obtained for each geological region. These values are tabulated in section 4.2.2. In a recent report, author Donald A. Bruce recommended that the cut-off extend to at least 50ft. beyond the expected insufficient rock (Bruce, 2012b). The final curtain length was chosen based on this recommendation. The decision to incline holes was also based on the advice of Bruce and other experts as mentioned in section 2.1.2. Although, several sources recommended inclination of 20° or 30°, the clearances presented by the cell walls minimized the range of practical angles.

Finally, the layout and spacing of holes and mix design recommendations were determined following guidelines from several textbooks and reports as presented in sections 2.1.1 and 2.1.3 respectively.

**Computer Aided Design**

AutoCAD was used to develop a plan view and profile view of the final treatment design. The drawings were created by layering the created design onto existing base maps and schematic representations of the proposed dam developed by Stantec. Plan and profile views (to scale) helped in visualizing the final design and avoid geometric constraints presented by the sheet pile cells and the existing lock. The plan view included the layout of the grout holes, including the direction of their inclination, and the layout of the secant cut-off wall. The profile view included a cross section of the upstream grout curtain and clearly showed the angle of grout holes and their depth as well as the length and depth of the secant pile wall.

In developing the cross section, it became apparent that the spacing between grout holes needed to be modified in order to avoid drilling into the base of the sheet-pile dam structure. Similarly, the secant pile wall could not be completely continuous, due to the sheet-pile walls of the concrete cell. The locations of the discontinuities in the secant-pile cut-off are in portions of the rock that do not exhibit significant fracturing, so this should not reduce the effectiveness of the cut-off.

The drawings were beneficial in two additional ways. In addition to allowing the visualization of errors and omissions in the design, the drawings helped to quickly and simply
communicate the design to Stantec. Also, the drawings were helpful in developing a cost estimate for the design.

3.3 Final Deliverables

There were four main deliverables for this project. The first deliverable that was presented to Stantec was a report on general evaluation criteria for dam foundation improvements as well as the suggested preliminary design for the foundation improvement to be implemented at Lock and Dam No.8. This report and design were also incorporated into a final MQP report that was presented to the WPI advisors for final review. The third deliverable was a presentation to Stantec outlining our findings and design that concluded our MQP. The final deliverable was a poster created to outline our project findings.
4.0 Results and Discussion

The results section of the report discusses the finding of both the application of the evaluation criteria as well as the creation of the capstone design. It includes an outline of the site geology and design options used in the application of the evaluation criteria. The capstone design results show how the best suited design option would be applied to the Lock and Dam No. 8 site.

4.1 Design Options

For Lock and Dam No. 8, three different design options were evaluated. These designs included using only a grout curtain the entire length of the dam, a grout curtain the entire length and a secant wall in Region 2 and a grout curtain the entire length and a secant wall across Regions 2, 3 and 4. The construction techniques and specifications for grouting and secant walls are outlined below before the evaluation criteria were applied.

4.1.1 Water Pressure Test Results

Based on the water pressure test results, elevations for both the grout curtain and cut-off walls were calculated. Table 5 below shows the average cut-off elevation values corresponding with each region and average top of rock.

<table>
<thead>
<tr>
<th>Method</th>
<th>Approx. Top of Rock NAVD88</th>
<th>Water Pressure Test Results</th>
<th>Depth from Top of Rock (ft.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1 Lu</td>
<td>5 Lu</td>
</tr>
<tr>
<td>Based on Water Pressure Tests</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Region 1</td>
<td>499.9</td>
<td>460.0</td>
<td>479.6</td>
</tr>
<tr>
<td>Region 2</td>
<td>499.6</td>
<td>475.4</td>
<td>475.4</td>
</tr>
<tr>
<td>Region 3</td>
<td>503.5</td>
<td>467.8</td>
<td>N/A</td>
</tr>
<tr>
<td>Region 4</td>
<td>517.5</td>
<td>484.0</td>
<td>493.5</td>
</tr>
</tbody>
</table>
The final grout curtain depths were established by subtracting an additional 50 ft. from the 5 Lu. averages. The final concrete cut-off depth was established by subtracting an additional 10 ft. from the 1 Lu. averages.

4.1.2 Grouting

Although the grouting components of the end project specifications should be of a performance nature, the following recommendations outline the aspects that should be specified.

Mix Design

Mix design specifications should include materials, testing standards and procedures. It is important that stable grout (i.e. minimal bleeding) is used consisting of ASTM Type I Portland cement, water and mid or high range water-reducer. It is typical for a range of permissible mix designs to be specified depending on the volume or rate of grout injected, but this is beyond the scope of this MQP.

At the discretion of the engineer, adjustments may be necessary such as using Type III Portland cement if the additional cost is justified by the need for a more penetrable grout. The engineer may also approve additives such as Ground-Granulated Blast Furnace Slag (GGBF) which has been shown to increase every desirable property of the grout (Weaver, 2007). The initial mix used for each hole should be highly mobile (HMG). If grout flow rates spike, indicating karstic features greater then 3ft in diameter, injection should switch to a lower mobility grout.

Finally, though it is becoming standard practice anyway, the use of a Data Acquisition system should be specified. The slight increase in cost is more than justified by the availability of real time take information and the automatic record generated.

Curtain Depth

Table 6 summarizes calculated recommended curtain depths for the grout curtain at Lock and Dam No. 8. Using the USACE convention, the calculated elevation was much too shallow. Instead, using the zone of relative impermeability method and a permeability standard of 5 Lu, the grout curtain should descend at least 21 ft. in region one and 25 ft. in region two and four.
Based on the water pressure test results, the rock in region 3 met or exceeded 5 Lu so no grouting is mandatory using that standard. The final depths follow the industry practice of extending the curtain an additional 50ft beyond the minimum cut-off length.

<table>
<thead>
<tr>
<th>Region</th>
<th>Recommended Grout Curtain Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Elevation (NAVD88)</td>
</tr>
<tr>
<td>Region 1</td>
<td>430</td>
</tr>
<tr>
<td>Region 2</td>
<td>425</td>
</tr>
<tr>
<td>Region 3</td>
<td>453</td>
</tr>
<tr>
<td>Region 4</td>
<td>443</td>
</tr>
<tr>
<td></td>
<td>Approx. Length @ 15° Inclination (ft.)</td>
</tr>
<tr>
<td>Region 1</td>
<td>72.5</td>
</tr>
<tr>
<td>Region 2</td>
<td>78.0</td>
</tr>
<tr>
<td>Region 3</td>
<td>52.5</td>
</tr>
<tr>
<td>Region 4</td>
<td>77.5</td>
</tr>
</tbody>
</table>

Stages

The grout holes should be drilled and injected using the upstage grouting method as explained in section 2.1.1. This method is always much more economical than the alternative downstage method since the time to complete each hole is much shorter and less material is wasted. The exact stage depths used should depend on encountered conditions and should be modified at the discretion of the engineer. However, it is recommended that three stage depth zones are used. The first four stages should be every 3 ft. (Zone 1). The following four stages should be every 8 ft. (Zone 2). The remaining stages should be every 10ft (Zone 3). As mentioned in section 2.1.1, the successful use of the upstaging method requires that the hole is thoroughly flushed with water before any grout is injected. Also, it is highly recommended that a packer is used to isolate the injection location and prevent hydrofracturing of the weaker, upper portions of the foundation.

Layout of Injection Holes

The recommended design will feature a two row grout curtain directly under the cells of the proposed dam. Two row curtains have historically been significantly more effective than single row curtains and locating them directly below the dam reduces the likelihood of seepage paths existing between the two structures. The standard spacing between each row was defined.
as 8 ft. and standard spacing between holes in each row as 6 ft. As described in section 2.1.1, the holes should be drilled in a split-spacing progression. The primary holes will be spaced every 24 ft., secondary holes will be spaced every 12 ft. and the tertiary holes will be at the final spacing of every 6 ft. The holes in each row will be inclined at 15 degrees in opposite directions. Where made necessary due to 90 degree angles, straight holes will be drilled to achieve spacing consistancy.

4.1.3 Cutoff Wall

For the conditions present at Lock and Dam No.8 a secant pile wall can help to remediate some of the seepage concerns. The general design of the wall in any region of the dam would consist of 4 ft diameter shafts. The shafts would have an overlap of a minimum of 1 ft on each side. The depth of the secant wall is dependent on the geological features that were found using the pressure test results from each region. For the secant wall the depths at which 1 Lu were achieved were used with the addition of approximately 10 feet. This was then rounded for design purposes, the values can be seen in Table 7 below.

Table 7: Recommended Secant Wall Length

<table>
<thead>
<tr>
<th>Region</th>
<th>Recommended Cutoff Depths</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Elevation (NAVD88)</td>
</tr>
<tr>
<td>Region 2</td>
<td>465</td>
</tr>
<tr>
<td>Region 3</td>
<td>455</td>
</tr>
<tr>
<td>Region 4</td>
<td>475</td>
</tr>
</tbody>
</table>

4.2 Application of Evaluation Criteria

To better understand which design would be the best suited for Lock and Dam No. 8; cost, environmental concerns, risks and constructability were applied to each design option. The results are presented in the sections below.

4.2.1 Cost

An exact estimate of the grout program cost is impossible due to the unknown volume of grout and time that will be needed. An approximate estimate of costs is possible, however, based
on typical equipment necessary and a standard industry unit cost per linear foot drilled and grouted. Appendix B shows the project cost estimate for the grout program design.

Construction of a secant wall includes a variety of costs. The cost of drilling was estimated based on linear feet. Appendix B shows the breakdown of the cost of installing the necessary piles, which were calculated using information from the Phase A Cost Estimate provided by Stantec as well as cost information from Lock and Dam No. 9. The unit price for a secant wall includes many of the other costs including a verticality check and all equipment. It is also important to note that the contractor who is doing the construction may choose what equipment is best suited for the job. These could include but are not limited to a material transport barge, a work barge, a tug boat and tug boat operator, a 150-ton crane, a crane operator, an oiler, a 75-ton wheeled crane and a crane operator. Another cost associated with the construction of the secant wall is the mobilization and demobilization of the drill rig and the barge mount, a separate cost which can also be found in Appendix B.

When only placing a cutoff wall in region 2, it is suggested that the wall overlap on each side by 10 ft. to make sure all geologic features are covered. Again this cost breakdown is in Appendix B.

A comparison of all three designs costs can be found in Table 8 below. These costs include total costs for each design. In the case of designs 2 and 3 these include both grouting and secant wall costs. As Table 8 shows, the cost of all three designs does vary, with Design 3 being considerably larger than the other two.

<table>
<thead>
<tr>
<th>Design</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design 1: Grout Curtain Along Entire Length</td>
<td>$2,435,746</td>
</tr>
<tr>
<td>Design 2: Grout Curtain Along Entire Length and Secant Wall in Region 2</td>
<td>$2,877,496</td>
</tr>
<tr>
<td>Design 3: Grout Curtain Along Entire Length and Secant Wall Across Regions 2, 3, and 4</td>
<td>$3,793,496</td>
</tr>
</tbody>
</table>
4.2.2 Environmental Concerns

With all three of the design options the same permits apply. These permits are required for any construction that happens in a body of water and for the dredging and fill that may occur in any water of the United States. However each design will have a different effect on the surrounding areas. With design options 2 and 3 there is more work that needs to be done in the river and this could potentially be more of an environmental concern. These two designs involve drilling parts of the foundation to fill with concrete in addition to the grouting program.

4.2.3 Risks

None of the treatment design alternatives eliminate all of the anticipated risks mentioned in section 2.4.3. The identified construction phase risks all were found to have similar chances of occurring. The opposite was found to be true for the operations and maintenance phase risks, as certain designs option were found to involve much greater risk than others.

Construction Phase

- Cost Overrun: Cost overruns due to unexpected grout takes, are equally likely to occur in each design option since the grout program is identical for each.
- Environmental Destruction: Neither toxic substances being released nor water table contamination, are likely to occur for any of the alternatives. Nontoxic grout and concrete mixes will be used. Also, the dam renovation will involve the use of a turbidity curtain as required by state and federal permits, reducing the likelihood that silt or debris from construction will spread.
- Foundation Damage: Improvements to the foundation of Dam No. 8 are necessary, firstly, to reduce seepage and water loss but, secondly, to help achieve sufficient bearing capacity. Using the 11,200 psi maximum compressive strength recommended by Stantec, the foundation can support the proposed dam with a Factor of Safety of 2.5. However, the report cautions that these recommendations are made assuming that any voids and significant fractures are grouted. Region 2 is of particular concern because the proposed design places an approximately 30ft. tall, 56.4 ft. diameter concrete filled cell over the area where significant voids were observed.
Each design option involves the same likelihood that this risk will occur. The risk is mitigated, however, by only filling the cells to a height of 10 ft. before grouting takes place. Also, by injecting the grout curtains before the secant pile wall, design options 2 and 3 are not any riskier due to the weight of the larger, heavier, equipment needed.

- **Loss of Limb or Life:** Each of the designs involves similar risk of injury taking place. Even with mandatory precautions such as life vests and hard hats, the nature of dam renovation involves a relatively high level of risk. Assuming that work is only performed during safe river levels, and conducting grouting and wall construction in dewatered sheet-pile cells both greatly improve construction safety.

**Operation Phase**

- **Seepage is not reduced:** One of the most significant distinctions between design options 1, 2 and 3 is that the likelihood of missing seepage paths greatly decreases with each additional secant wall component. The proposed grout program, in theory, should adequately fill voids and reduce the foundation permeability to acceptable levels. Nevertheless, there is no way to verify the success of the grouting program until after construction is complete. In contrast, by using secant walls in the regions known to have significant voids and fracturing to great depths, one can precisely verify the continuity of the cut-off, nearly eliminating the chance that seepage paths remain. Though beyond the scope of this MQP, it is even possible to model the effectiveness of such cut-off walls using commercially available software.

- **Seepage Increases:** In any grouting operation, there is a risk of injection pressure exceeding the tension strength of the rock causing additional fractures. Even though such cases have been greatly reduced in recent years by automatic computerized grouting systems and state-of-the-art procedures, the possibility remains. Design option 3 nearly eliminates this concern by providing a redundant (nearly) continuous barrier which will reduce permeability to a verifiable standard, regardless of further fracturing. Similarly, though to a lesser extent, design option 2 provides a redundant cut-off in region 2 eliminating the chance of seepage increasing in that region.
4.2.4 Constructability

In the end, many of the design decisions that led to the three design alternatives were the result of constructability related concerns. Each of the design options address anticipated construction issues and are, for the most part, equally feasible. From strictly a constructability perspective, Design options 2 and 3 are less advantageous since more effort, time and equipment are necessary to complete the secant-wall. However, as previously mentioned, secant-pile walls are by far the most constructible concrete cut-off wall technique at the Lock and Dam No. 8 site and allow the greatest precision and verifiability.

4.2.5 Comparison of Evaluation Criteria

The four different evaluation criteria were applied to the design options to determine which option would be the best for Lock and Dam No. 8. The results can be seen in Table 9 below. The rating system is based on a 1-3 scale, 3 being the highest and 1 being the lowest score.

<table>
<thead>
<tr>
<th>Design:</th>
<th>Cost</th>
<th>Environmental Impact</th>
<th>Risk</th>
<th>Constructability</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design 1</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>3</td>
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<td>Design 2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
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<tr>
<td>Design 3</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>1.75</td>
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</table>
With cost being an important factor the highest score was given to the design that cost the least amount. Environmental impacts were the same for all three design options and therefore received the same score. Seepage reduction was one of the main concerns for this project; the designs that had the potential for the most reduction received the best scores in the risk category. Finally constructability was also a concern. The designs taking a longer time to build were given lower scores.

As Table 9 shows Design 1 had the highest score and Design 3 the lowest. While this provided a best design option based on a numerical rating, this was only one factor in deciding which design option would be best for the Lock and Dam No. 8 site.

4.3 Capstone Design

By weighing the advantages and disadvantages of each design according to Cost, Environmental Impact, Risk and Constructability, two designs were determined to be less optimal then the third. As shown in the figures below and in the drawings found in Appendix C, design option 2 was determined to be the best alternative. The recommended design features a “Composite” Cutoff in region 2 and a two row grout curtain along the alignment of the proposed dam. The curtain will turn ninety degrees up the cell-lock wall connector and then continue to the east abutment along the upper lock sill.
Figure 11: Layout of Grout Holes and Secant Pile Wall

Figure 12: Profile View of Grout Holes and Secant Pile Wall
The proposed sequence of construction activities is:

1) Installation of cell sheet-piles and lock wall connector piles
2) Laying the first 10 ft. of concrete in each cell
3) Completing the upstream grout curtain row
4) Completing the downstream grout curtain row
5) Installation of the secant pile wall

Completing construction activities in this order is advantageous for several reasons. First, as mentioned in section 4.3.3, grouting through a section of the dam cells improves the effectiveness of the grouting program by allowing greater injection pressure and a level working surface. Furthermore, completing the upstream curtain row first reduces the likelihood of washout occurring in the downstream row. In region 2, water pressure testing the primary and secondary holes during the grout program will determine if the size of the proposed secant pile wall is adequate. Finally, by treating the karstic features prior to drilling the piles, far less loss of drilling fluid will occur.

4.4 Capstone Design Conclusions

The final foundation improvement design that was chosen compared cost, environmental concerns, risks and constructability. Based on these evaluation criteria the design that was chosen was design option 2 which included a grout curtain with a secant wall in Region 2. This design was decided to be the best option for Lock and Dam No. 8 for the following reasons. One of the most important pieces of evaluation criteria that was considered was cost. While design option 2 was not the cheapest option it was only slightly more expensive than option 1 but provided more foundation improvements. Region 2 was found to have the worst foundation problems present and by placing a secant wall in this region it will help to further reduce the seepage problems. While environmental permitting is the same for all design options this option had less of an impact on the river than option 3 which would involve disturbing the area more.
5.0 References


Stantec. (2011). *Geotechnical Study and Existing Conditions; Kentucky River Lock and Dam No. 8.*


Appendix A: Proposal

Renovation of Kentucky Lock and Dam #8

Major Qualifying Project Proposal

Michael Kendall
Karyn Sutter

December 15, 2011
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Introduction

A replacement for the Kentucky River Dam No. 8 is in the final stages of design. Although the main dam construction method has been determined, several design decisions still remain. One of the most critical is how to improve the foundation. Because of karstic geology in the region, a significant amount of seepage occurs through the foundation of the current Dam No. 8 in areas where significant voids or solution features are encountered. This has resulted in a loss of drinking water for the nearby community including the city of Nicholasville. The karstic geology also raises concerns regarding the Bearing capacity of the foundation. An evaluation of different dam improvements that would address these concerns is needed.

Project Description

Our Master Qualifying Project will involve recommending foundation improvements as part of the renovation of Kentucky River Dam No. 8. The specific methods we will consider are grouting, positive cut-off walls, aprons and combinations of the three. The evaluation criteria for each method will depend on such considerations as: cost, risk, environmental impact and effectiveness.

After studying the extent of the karstic features present at the renovation site using a recently performed geotechnical evaluation and applying the previously mentioned criteria, we will develop a report outlining a proposed design. In considering approaches, we will also estimate the cost of materials and labor necessary to perform the work. It should be noted that future dam replacements along the Kentucky River will likely need similar foundation improvements to those which are required at KY River Dam No. 8. Therefore, our recommendation will be of value to Stantec and the Kentucky River Authority, not only by addressing the problems at the lock and dam No. 8 site, but also by serving as a guide in designing the improvements to those future projects.
Background

Positive Cut-Off Wall

A common technique used to decrease soil permeability and control seepage is the cut-off wall. A cut-off wall is a broad term for any underground vertical structure that serves as a barrier. Several different variations of cut-off walls have been designed and constructed. Types of structures include sheet pile (steel, wooden), concrete and soil-bentonite. (Bruce, Ressi di Cervia, & Amos-Venti, 2006). While typical concrete cut-off walls involve placing concrete within an excavated trench, variations exist such as secant pile walls and diaphragm walls.

![Figure 13: Free body diagram of sheet pile cutoff wall; (Singh, Mishra, Samadhiya, & Ojha, 2006)](image)

Cut-off walls are constructed in foundations of nearly every composition. In general, the type of wall chosen greatly depends on the ground composition of the site in question. When the ground consists of rock, a concrete structure must be used. It also depends on the remediation goal. If the wall must withstand a pore water pressure difference (such as in the case of Kentucky River Dam No. 8 and in the diagram above) it is referred to as a positive cut-off. These walls consist of concrete or thick steel pile construction.

One of the largest examples of cut-off walls in which the ground conditions were similar to those at Kentucky River Dam No. 8 was included as part of the Wolf Creek remediation project. The ground conditions at this site were similar in that they featured fill over karstic limestone. The
walls were constructed of concrete and consisted of 24-inch diameter piles joined by precast panels. The project featured two walls, one approximately 270,000 sq. ft. in area and the other approximately 261,000 sq. ft. The structure was imbedded into bedrock at an average depth of 280 ft (Bruce, et al., 2006).

**Grouting**

Grouting is a general term for the process of filling gaps and crevices in the subsurface with a low strength cementous material. There are several different types of grouting techniques including but not limited to grout curtains, grout caps, grout galleries, and blanket grouting (Weaver & Bruce, 2007). Grout curtains are used to control seepage by injecting grout into areas of the ground with high permeability. This method only reduces permeability and cannot be precisely controlled. Blanket grouting is similar however it is typically applied to the shallow area directly under the dam. In addition to reducing the permeability, the blanket increases the bearing capacity of the ground underneath. Each of these techniques can utilize a variety of grouting materials with either high or low mobility. High mobility grout mixes (HMG) are useful in situations where voids are small and difficult to access (Warner, 2004). Low mobility grout mixes (LMG) are preferred for larger openings and to ensure that only the intended area is grouted.

**Combinations**

In many if not most cases grouting and a cut-off wall are used in dam construction. However, the particular technique, type and dimensions of each method used vary from project to project and are unique to each site.
Methodology

The following tasks will be completed throughout the 8 weeks to complete the project.

Task 1. Evaluate and Analyze the Existing Dam Conditions

To evaluate the existing site conditions we will go over the November 15\textsuperscript{th} 2011 geotechnical evaluation, hold interviews with Stantec staff, as well as visit the dam itself. The main goal of the visit(s) will be to familiarize ourselves with the layout of the dam and surrounding geography and compare observations taken during the geotechnical evaluation with up-to-date observations (to the extent necessary or possible).

Task 2. Research Evaluation Criteria/Considerations

There are four criteria/considerations that will be researched in order to decide on what foundation improvement techniques are best suited for the site. These include effectiveness, cost, environmental impacts and risks. Each of these evaluation criteria will be applied to the different foundation improvement techniques.

a. Effectiveness
   i. Will the methods, reduce the seepage occurring through the foundation to acceptable permabilities?

b. Cost
   i. What will the anticipated labor and supply costs be?
   ii. What are the estimated maintenance costs?
   iii. Will the capital costs exceed the budget allocated by the Kentucky River Authority?

c. Environmental Impacts
   i. Based on existing conditions, how will each improvement method affect the surrounding area?
   ii. What permits would be applicable?

d. Risks
i. What happens if we miss a seepage point?

In order to determine answers to these research questions we will hold interviews with Stantec Staff, analyze reports of previous dam renovations conducted in the area/areas with similar characteristics, use textbooks such as Geotechnical Engineering by Donald P. Coduto, and follow design guides. In the case of costs, it may be necessary to contact vendors/firms if information from other projects is not available or sufficient.


task 3. Create report or table summarizing criteria research

Advantages and disadvantages for each improvement technique will be compiled as applied to rock foundations.

Task 4. Select and recommend a foundation improvement program at the site.

A brief discussion will be provided as to why this approach is best suited for this site based on the evaluation of the alternative.

Task 5. Outline proposed foundation improvement design alternatives

Create schematic outlining an appropriate design(s) by combining the results of the criteria study with design calculations and recommendations. Applicable calculations and guidelines will likely be found as print materials at Stantec, textbooks, or online materials such as those supplied by the Army Corp of Engineers. This final component of the MQP will complete the requirements of a capstone design.
## Schedule

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<th>1/22/11</th>
<th>1/29/11</th>
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</table>
Deliverables

The final deliverables of this project will include a report on general evaluation criteria for dam foundation improvements as well as a schematic design for improving the foundation of Kentucky Dam #8. The design will likely include schematics specifying the layout of the proposed design. The evaluation will look into areas that include effectiveness, cost, environmental impacts and risks. The capstone design component of the project, which is the final design for the foundation improvements we recommend, will be presented in a report that will be submitted to both Stantec and WPI.
Appendix A (Proposal): Capstone Design Statement

The Accreditation Board for Engineering and Technology (ABET) requires that all accredited engineering programs include a capstone design experience. This requirement is met at WPI through the Major Qualifying Project (MQP). The American Society of Civil Engineers (ASCE) specifies that this capstone experience must include the following considerations: economic; environmental; sustainability; manufacturability; ethical; health and safety; social; and political. This MQP will meet the ABET and ASCE requirements by going through a “design process” where several of the above factors will be used to evaluate the best alternative. More specifically, they will be the criteria that determine the optimal level of improvement to address the water seepage issues at Kentucky Dam No. 8. Using models developed by Stantec Consulting Services Inc., applicable calculations and historical reports outlining current improvement techniques, we will estimate the anticipated effectiveness of certain designs. We will then evaluate the alternatives in terms of financial costs, environmental impact, and constructability. This will most likely be an iterative process resulting in the optimal design to be recommended by Stantec Inc. to the Kentucky River Authority.
Appendix B (Proposal) : Tasks by Week

Week 1:
* Get acclimated
* Begin to evaluate existing dam conditions
  o Geotechnical Evaluation (recommendations, significant findings)
  o Discussions with Stantec staff
* Meet with Stantec advisors
* Contact WPI advisors on weekly basis updating on progress

Week 2:
* Continue evaluating existing dam conditions
* Continue research from B term
  o Evaluation Criteria
  o Solution methods
  o Structural/Hydrology Equations
* Visit Dam #8
  o Become familiar with layout and how it relates to schematics/pictures
* Begin writing up background to be used in final report
* Meet with Stantec advisors

Week 3:
* Finish compiling existing dam conditions
* Continue Researching
* Finish writing up background
* Meet with Stantec advisors

Week 4:
* Finish major researching tasks
* Begin outlining specifications of proposed designs based on evaluation criteria
  o May include computer drafting
* Begin writing up methodology for final report
* Meet with advisors

Week 5:
* Research as needed
* Continue outlining design specifications(s) based on evaluation criteria
* Begin drafting final report including writing up deliverables
* Meet with advisors

Week 6:
* Continue work on design
* Continue working on final report
* Meet with Advisors
Week 7:
* Finish design
* Finish final report and send to advisors for review
* Draft poster
* Work on presentation

Week 8:
* Present Project to Sponsors
* Submit MQP
Appendix C (Proposal) : Bibliography


# Appendix B: Cost Calculations

## Table 10: Secant Wall Drilling Costs

<table>
<thead>
<tr>
<th>Drilling Cost:</th>
<th># of Shafts</th>
<th>Diameter</th>
<th>Depth</th>
<th>Cost</th>
<th>Total</th>
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<tr>
<td>Region 2</td>
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**Total Cost:** $1,336,000

## Table 11: Region 2 Secant Wall Drilling Costs

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<tr>
<td>Region 2</td>
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## Table 12: Additional Secant Wall Costs

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<td>$14,500</td>
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<td>Barge Mount</td>
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**Total Cost:** $21,750
Table 13: Estimated Base Cost of Grout Program

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<tr>
<th>Location</th>
<th>Total Borings</th>
<th>Total Length</th>
<th>Rate* ($/LF)</th>
<th>Total Cost</th>
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<tr>
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<tr>
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<td>78</td>
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<td>$130.00</td>
</tr>
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<td>525.0</td>
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<tr>
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<td>West Abutment</td>
<td>15</td>
<td>77.5</td>
<td>1162.5</td>
<td>$130.00</td>
</tr>
<tr>
<td>West Bank Fan</td>
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<tr>
<td><strong>Total Cost</strong></td>
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<td></td>
<td></td>
<td><strong>$1,363,245.00</strong></td>
</tr>
</tbody>
</table>

* Note: Contingency of 30% added in the event that additional grouting is needed.
Table 14: Approx. Duration of Grout Program

<table>
<thead>
<tr>
<th>Drilling</th>
<th>Total linear ft.</th>
<th>Mins per ft.</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10000</td>
<td>1</td>
<td>10000</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Water Testing</th>
<th># Primary and Secondary Holes</th>
<th>Mins per test</th>
<th>Number of tests per hole</th>
<th>Total</th>
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<tbody>
<tr>
<td></td>
<td>75</td>
<td>20</td>
<td>4</td>
<td>6000</td>
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</table>

<table>
<thead>
<tr>
<th>Grouting</th>
<th>Total # Holes</th>
<th>Stages/Hole</th>
<th>Mins per stage</th>
<th>Total</th>
</tr>
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<tr>
<td></td>
<td>148</td>
<td>12</td>
<td>20</td>
<td>35520</td>
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</table>

*Note: Assumes 173 working hours per month*

Total Minutes 51520

*Total Months 4.96
Table 14: Estimated Additional Grout Program Costs

<table>
<thead>
<tr>
<th>Mob/Demob Grout Plant</th>
<th># of Plants</th>
<th>Rate ($/EA)</th>
<th>Total Cost</th>
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</thead>
<tbody>
<tr>
<td>Mob, Demob, &amp; Setup</td>
<td>1</td>
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</table>

<table>
<thead>
<tr>
<th>Engineering &amp; Constructed Platform</th>
<th>Total</th>
<th>Rate ($/LS)</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design</td>
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<td>Platform</td>
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<td>$50,000.00</td>
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</table>

<table>
<thead>
<tr>
<th>Casing for Overburden</th>
<th># of Borings</th>
<th>Depth</th>
<th>*Rate ($/ft)</th>
<th>Total Cost</th>
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<tbody>
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<td>Casing</td>
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<td>$16,010.29</td>
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*Note: Escalated from 2008 to 2011 using USACE Cost Index for Dams

<table>
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<tr>
<th>Equipment</th>
<th>Expected Usage</th>
<th>Rental (month)</th>
<th>Operating (hr)</th>
<th>Months</th>
<th>Hours/Month</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
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<td>Material transport barge</td>
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<td>$20,000.00</td>
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<tr>
<td>Work barge</td>
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<tr>
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<td>$43,333.33</td>
</tr>
<tr>
<td>150-ton crawler crane</td>
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<tr>
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<td>$ -</td>
<td>$50.00</td>
<td>5.0</td>
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<td>$43,333.33</td>
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<tr>
<td>Oiler</td>
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<td>$43,333.33</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Labor</th>
<th>Unit Cost/Worker</th>
<th>Months</th>
<th>Hours/Month</th>
<th>Estimated # Workers</th>
<th>Total Cost</th>
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<tbody>
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<td>Cost</td>
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Total Cost $1,072,501.00
Table 15: Total Costs Separated by Region

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<tr>
<th>Design</th>
<th>Secant</th>
<th>Secant extra Costs</th>
<th>Grout</th>
<th>Grout extra Costs</th>
<th>Total</th>
</tr>
</thead>
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<tr>
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<td>1,072,501</td>
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</tr>
<tr>
<td>Design 2</td>
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<td>21,750</td>
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<tr>
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<td>1,072,501</td>
<td>$3,793,496</td>
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Appendix C: CAD Drawings
FOUNDATION TREATMENT PLAN
# Appendix D: Injection Hole Coordinates

## Grout Hole Location and Inclination

<table>
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<tr>
<th>Label</th>
<th>Northing</th>
<th>Easting</th>
<th>Inclination</th>
<th>Label</th>
<th>Northing</th>
<th>Easting</th>
<th>Inclination</th>
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</thead>
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