Dam Construction Alternatives

A Major Qualifying Project

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Abstract

This project describes and assesses three different dam construction techniques: concrete-filled cellular sheet pile cell; float-in; and roller compacted concrete. A model was designed to help a client, entry-level engineer, and engineering firm understand the factors associated with specific site locations that help choose the appropriate dam construction technique. Stantec Consulting Service Inc. will use this model in the future during the preliminary assessment process for dam rehabilitation projects along the Kentucky River.

Acknowledgements

I would like to thank Professor Hart and Professor LePage with all of their assistance and guidance over the term while I was working on this project. The Stantec Consulting Service Inc. individuals in Lexington, Kentucky were of great importance when it came to resources. The project would not be complete without three Stantec employees; Daniel Gilbert, Brad Smiley, and Greg Yankey. Stantec's employee's vast knowledge on the Kentucky River Lock and Dam System assisted the project from start to finish. Thank you to those who helped during my project and Stantec for allowing me to use their company as an excellent resource.

Capstone Design Statement

The Civil Engineering program at WPI requires a capstone design that incorporates engineering analysis with real world concerns to meet the requirements for the Accreditation Board for Engineering and Technology (ABET). This MQP project coincides with the ABET qualifications by providing a product that focuses on economic, environmental, sustainability, and constructability constraints. The economic constraint is addressed through incorporating cost as one of the important factors associated with choosing the correct construction technique at specific locations. Economics are an important issue that helps the client when choosing the appropriate dam within their budget. Each dam construction technique impacts the environment in a different way and those impacts were then evaluated in this report. The model table will help Stantec Consulting Services Inc. with putting together documentation to make sure the owner, Kentucky River Authority, is satisfied with what they requested in terms of constructability. A user friendly model was created to allow the Kentucky River Authority and Stantec to use the model when evaluating dam construction alternatives in the near future for sites along the Kentucky River. The model is calibrated and tested with previously constructed dams to ensure that the correct dam construction technique is chosen for construction. The model was also used for testing a specific site that will call for dam construction in years to come. The model addresses constructability and sustainability issues that affect all three dam techniques. By addressing economic, environmental, sustainability, and constructability constraints, this MQP report achieves the Capstone Design requirements with the design of the dam construction model.

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1 Introduction

The 255-mile Kentucky River is one of the Ohio River's largest tributaries. The river begins in Beattyville, Kentucky and ends near Carrolton to discharge into the Ohio River.[1] Fourteen lock and dam structures are located along the Kentucky River. In the early 1800's the lock and dam system was used for transportation of coal and lumber from eastern Kentucky on barges. "The Kentucky River has shaped the culture, economy, and identity of towns across the Bluegrass Region for many years.[1]" These lock and dam structures are about 100 or more years old. Minor maintenance has been completed by the U.S. Army Corps of Engineers within the past 20 years. The Kentucky River Authority currently owns locks and dams 5 through 14 and is in the process of obtaining locks and dams 1 through 4 from the U.S. Army Corps of Engineers.[6]

Figure 1: Kentucky River Lock and Dam No. 8

The Kentucky River Lock and Dam No. 8 (see Figure 1) took two years to build when construction first began in 1898. The dam is currently owned by the Kentucky River Authority and is located 140 miles above the mouth of the Ohio River. Lock and Dam No. 8 is currently being used to supply Nicholasville, Kentucky with drinking water. The original dam is a timber crib structure, which helped sustain a seventeen and a half mile long pool of water.[2] The original lock is made from stone masonry. The dam was constructed as an enclosure with a timber frame on the outside and dirt/rock on the inside. In 2001 a concrete cutoff wall was placed inside of the lock chamber.[2] The dam has a maximum discharge of 5,700 cubic feet per second (cfs) and is 309 feet wide. The normal storage behind the dam is about 8,700 acre feet, but has a capacity to hold back about 14,020 acre feet.[3] Lock and Dam No. 8 drains an area roughly 4,414 square miles.[3] In late 2010 the Kentucky River Authority awarded the bid for Kentucky River Lock and Dam No. 8 to Stantec Consulting Services Inc. If plans go accordingly, construction should begin on Lock and Dam No. 8 by the end of 2011 and be completed in 2012. Once completed, Lock and Dam No. 8 will be one of three dams along the Kentucky River that Stantec will have constructed.

There are three dam construction alternatives that are assessed in this project; Concrete-Filled Sheet Pile Cells, Float-In, and Roller Compacted Concrete Construction. This project assessed the main components associated with each of the three dam construction alternatives. Many factors were considered in the evaluation process including cost, schedule, risk, constructability, quality assurance, and long-term performance. In order to efficiently evaluate the appropriate dam construction alternative for each location, a model was created. Once the model was constructed, it was calibrated with previous dam construction projects completed and then applied to Kentucky River Lock and Dam No. 8 to determine the best construction alternative. The Kentucky River Authority is planning to rehabilitate several lock and dam structures along the river and this user-friendly model will benefit the authority.

2 Background

There are currently 14 locks and dams along the Kentucky River. Kentucky River Lock and Dam No.8 was the focus for this project, and had similar site specifics to that of Lock and Dam No. 3., which is currently under construction and is scheduled to be completed in the summer of 2011. The Renovation of Kentucky River Lock and Dam No.3 consists of the construction of a new dam, two abutments, and a downstream training wall along with slope and scour protection features immediately upstream and adjacent to the existing structure. A similar Cell Dam was recently completed at Lock and Dam No. 9 in 2010.

A run-of-the-river dam is constructed across the entire width of a river or stream to control the downstream flow rate and allow the levels behind the dam to fluctuate accordingly. All of the 14 dams along the Kentucky River consist of the typical run-of-the-river dam, which provides a source of water for towns and also helps to control potential flooding along the river.

Navigation locks and dams are the most common example of run-of-the-river projects. Lock functions allow for the traffic of boats on the channel. Only locks 1-4 along the Kentucky River are usable for boat traffic during scheduled times of the year. The boat will drive into the lock and the water level will be adjusted accordingly by a lock operator to allow the boat to safely travel to the opposite side of the dam. The lock and dam structures that are included in this report along the Kentucky River are run-of-the-river dams.

There are a few different factors that influence the construction process at each dam location. Karst geology is an important concern for construction and can set the project back in terms of cost and schedule. Karst features are related to the terrain characteristics on the bottom of the river. The contractor can run into sinkholes, rocky ground, or underground rivers during construction. Karst geology is mainly caused by the effects of underground water on massive soluble limestone.[4] Along the Kentucky River, every dam location exhibited a noticeable amount of karst geology.

2.1 In-the-wet construction

In-the-wet construction, also known as offsite prefabrication, uses precast concrete segments that are fabricated offsite and then brought onto the site to be installed. "This innovation method uses precast concrete modules as the in situ form into which tremie concrete is placed directly without use of a cofferdam.[5]" These concrete segments are moved to their final position by either a lift-in or float-in construction technique. Lift-in construction involves heavy equipment to carry the precast modules from the factory to its final position. Float-in construction involves lowering these precast modules into place with a temporary floating structure. Concrete-filled cellular sheet piles cells involve pouring of tremie concrete directly into the water inside circular sheet pile cells that were driven down to the bedrock.

2.1.1 Concrete-Filled Cellular Sheet Pile Cell Construction

Concrete-Filled Cellular Sheet Pile Cells utilize cofferdam cell structures for in-the-wet construction. Typically, the main cells are evenly spaced across the river with arc cells connecting each main cell as sheet piles, driven down to the bedrock in the water, create structures to form these cells. After these cells have been placed, a special mixture of concrete is poured directly into the cell causing water displacement while simultaneously allowing the concrete to set.[5] The main cells are constructed first, followed by the arc cells in order to create a linear structure across the river channel. In order to maintain pool elevation along the Kentucky River, the new dams are placed in close proximity to the pre-existing dam. The new dam is constructed upstream of the pre-existing dam, which is left in place in order to protect the newest installment from damages caused by the flow of the river.[6] During the dam construction process, navigating the river around the dam may be required in order to avoid restriction on the flow of the river.

Design

These Concrete-Filled Cellular Sheet Pile Cells are designed across a river to not only withhold the water and allow the current to remain steady but also connect the dam to the existing lock structure. The evenly spaced cells across the river are the "main cells", which are connected by "arc cells". The main cells are in the shape of a circle and the arc cells are similar to the shape of a peanut (see Figure 2).[6]

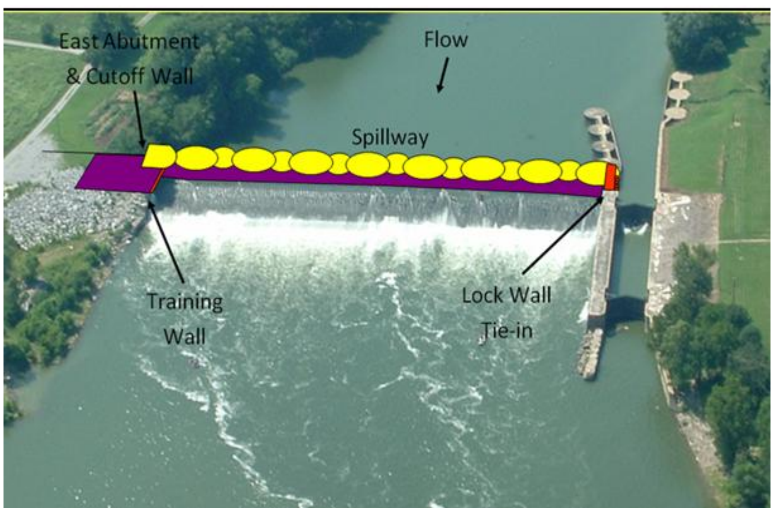

Figure 2: Lock and Dam No. 3 Stantec Plans

Steel templates, used in the construction of all cells, are intended to be reusable across the river to help save time and money.[7] Also, each cell, regardless of shape, is designed to have a crest elevation towards the surface of the river and is to be connected directly to the bedrock.[7]

Construction

Pre-dredging is the first step in the construction process of creating these cells for in-the-wet dam construction. Multiple reusable templates are then created to construct cells that will be built simultaneously across the river, in order to reduce construction time.[8] The concrete cells are constructed individually by means of placing the template in the preferred position in the river in an attempt to reduce the interference with the navigation of the river. The interconnecting, flat-plate, steel sheet piles are then driven to the bedrock by use of special hammer-like equipment. Each cell is then excavated down to the rock in order to prepare the proper foundation for the concrete. This process allows steel sheet pile cells to be filled with tremie concrete without requiring dewatering of the entire site for construction (see Figure 3). This results in a massive self-sustaining and efficient structure that can have cells constructed in any order across the river.

Figure 3: Concrete-filled cellular sheet pile cell

The bedrock foundation is then cleaned and prepped for the pouring of tremie concrete by divers. The tremie concrete is poured through tremie pipes under water, from the bedrock up, to within a few feet of the preferred crest elevation. Next, the top of the tremie concrete will be topped with a concrete cell cap, typically 2 feet high, in the dry.[8] The top of the cell will need to be dewatered and made water resistant when constructing the cell cap.[9] After the main cells are constructed, there will need to be a connection established between the main cells. At this time the arc cells are installed to ensure the gap is filled between each main cell.

Cost

Cell Dams can be inexpensive if the right circumstances are presented at the site. Costs can include a barge that will be used for placement of the cells, a crane to construct the cells, underwater diver work for foundation preparation, dewatering and placing a concrete cap on the top of the cell, and tremie concrete. Since the cells can be constructed in the water, there is no need for dewatering, thereby reducing the costs of construction for the contractor.[5] Overall, constructing a Cell Dam for a small scale project can save the client time and money.

Benefits

There are a substantial amount of benefits from using Concrete-Filled Cellular Sheet Pile Cells over the temporary cofferdam approach. Not only do these simple self-sustaining cells offer more options for construction when creating a dam but also, only standard marine construction equipment is necessary to complete these cells, which allows any average size contractors with minimal amount of marine equipment to complete the work.[6] From an economic standpoint, the availability of skilled contractors is high, allowing for a more competitive bidding process, reducing the costs overall. Readily available materials also prove to make Cell Dams a more desirable choice for clients.

During construction, time is of great importance to the owner. Less time results in less money being spent. The more time a section of work is exposed to the flow of the river, the more of a risk a contractor endures for the quality of the work. Concrete-Filled Cellular Sheet Pile Cell structures take on average about three to four weeks to construct.[7] Allowing the short window for construction of the cells reduces the amount of time the section of work is exposed to the environment of the river, which reduces risk for the contractor. Each cell can be placed directly on the bedrock regardless if there is an irregular rockline or not. Once the concrete is poured into the cells, the cells are stable and self-sustaining. By creating rigid cells, the damage of overtopping the cell with water is reduced. Karst geology and differing rock lines for construction is not of great concern, which reduces the risk for the owner.[7] The overall environmental footprint is reduced by construction that can be implemented without having to navigate the river during construction and not having to necessarily remove the old dam. The old dam more often than not is left in place to help protect the new dam from deterioration caused by the flow of the river.[6]

Overview

Concrete-Filled Cellular Sheet Pile Cells will be of use for constructing new dams along the Kentucky River in place of old existing dams. Replacing a prior timber crib dam with a new Cell Dam can help create a life expectancy of fifty plus years for the dam.[10] Cell Dams leave less of an environmental footprint and create a technique that can be used in a wide variety of site specific locations along the river. Cell Dams are a fairly new dam construction alternative and have been proven to be effective and inexpensive under the right circumstances.

2.1.2 Float-In Construction

Float-In Construction is a dam construction technique that uses prefabricated steel or pre-cast concrete segments. At an off-site location the prefabricated segments are prepared and then transported to a site to be put in place. Once at the site, the dam segments are placed in the water by dry dock facilities or casting basins in close proximity to the site.[11] These facilities need to be constructed prior to the arrival of the prefabricated segments. Each segment floats in the river to its precise location by means of ballasting to keep the segment level. The dam segments are then lowered into the water and into place to create the dam. Tremie concrete is used to seal the gaps between each of the dam segments to create a stable dam in-the-wet.[12]

Design

Design for site preparation is a main concern for Float-In Construction. Each of the dam segments is accurately sized ahead of time and the site has to be able to accept each dam segment that will be used. An area designed to accept these segments typically need to be constructed because these facilities are not normally available at the location (see Figure 4).[13]

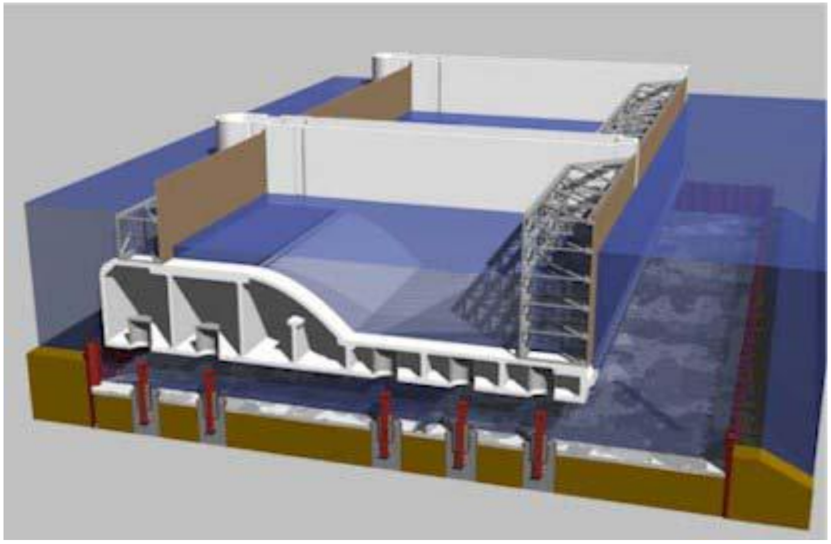

Figure 4: Typical Dam Segment Landing on Pre-installed Caissons (Ben C. Gerwick Inc., 2000)

An extensive amount of engineering is required for ballasting, lifting, and launching the segments because of the considerable amount of loads and the importance of each task performed.[11] The prefabricated dam segments are designed to be lifted by large equipment. Each segment is designed to meet the lifting capacity of the cranes that will be used at the site. The segments used for Float-In Construction usually are designed as large as possible to allow the need for fewer segments to construct the dam.[7] Float-In Construction normally requires a lot of engineering design work before the construction can take place.

Construction

Large cast and launch facilities may not be readily available for use at every site location. The large cast or launch facilities are created in close proximity to the site for the convenience of transporting the segments. Dredging of the site is required to create an infrastructure that will allow the prefabricated segments to be lowered into a dry area. The area is then flooded to make the segments float. Therefore, time, environmental impacts, and extensive site pre-development needs to be considered.[7] Pre-dredging of the site and installation of guides on a grid pattern or reinforced concrete drilled shafts are important for prepping the site.[11] No two sites are exactly the same for dam construction. Gravel I pads, leveling pads, and sheet pile cutoffs may be additional foundation elements that could possibly be included in the installation process to accept the prefabricated segments, depending on the site.[12] Bedrock preparation may also be required if the river is fairly shallow, which will allow the prefabricated segments to be placed directly on the bedrock. After the site is prepared for the dam segments, large construction equipment is needed to place these heavy segments in the water and into place.[12] The segments are placed in the launch facility or casting basin and then need to be brought to the dam location by means of floating (see Figure 5).

Figure 5: Floating segment for Braddock Dam

A larger size marine contractor with heavy machine equipment may be chosen to perform the work over an average size marine contractor because of the limited resources an average size marine contractor has with specialized construction equipment[14] (see Figure 6).

Figure 6: Crane Barge (Ben C. Gerwick Inc., 2000)

Underbase grouting and infilling the segments with tremie concrete is used to lock the segments to the foundation to create the dam.[13] The underwater positioning of these segments is dependent on underwater divers to get the correct alignment. More so than not, the diver can lose visibility in muddy waters and not have enough force to move objects underwater, which makes underwater diver work at times ineffective.[11] Having the correct alignment with every segment of the dam is important in constructing a stable dam.

Cost

Under the right circumstances, Float-In Dam Construction can offer significant schedule and cost savings.[7] The size and weight of dam segments can be reduced, potentially lowering the cost, that is, if the dam segment shells are fabricated in place. On the other hand, costs for Float-In Dam Construction can be substantially larger. For example, if the project size is small, then it would cost the contractor more money than what it is really worth to set up an infrastructure on site to build the dam. It would be beneficial to a large project, where the infrastructure would be of more use to the contractor. Float-In Dam Construction should be used for projects that are of large scale and have the proper amount of resources at the site to complete the construction. The important cost factors for Float-In Dam Construction are the prefabricated dam segments off-site, transportation of segments to the site location, access to large construction equipment, large cast or launch facilities, foundation preparation, and critical engineering analysis.[7]

Benefits

Float-In Dam Construction is beneficial by having less of a negative impact on the environment, but at the same time can increase the cost for the overall project due to increased engineering and site preparation. Under the right circumstances, Float-In Construction can offer cost and schedule savings. A project of this type can offer a reduced construction footprint and a reduced environmental impact to the area around the dam.[7] The geometry of the dam can be optimized because placement of the prefabricated dam segments can be designed any way the contractor/owner wants them. The segments being made off-site can speed up the construction process and allow for the segments to be created before construction begins. Float-In can also form to any irregular rocklines present at the location because of the area for construction being in-the-dry. Having all the segments essentially float into place without a whole lot of terrain adjustment, allows less of a karst geology impact. Karst geology treatment may still be conducted on site to allow a long performance of the dam.[7] The contractor may have to redirect the karst feature around construction or temporarily block the features to allow construction to continue without conflict.

Overview

Float-In Dam Construction requires an extensive amount of site preparation and engineering calculations to put the prefabricated segments into place. Prefabricated steel or concrete dam segments will be made offsite and transported to the site.[15] Once transported to the site, the segments will float to the location and be lowered into place. Due to the high set up cost and engineering cost, this type of construction should be used for large scale projects only. There will be a higher cost factor for preparation of the site with a small scale project than the actual cost of constructing the dam. Under the right conditions, Float-In Dam Construction can be an effective technique for saving time and money.

2.2 In-the-dry construction (cofferdam construction)

In-the-dry construction relies on a cofferdam, a temporary structure designed to keep water and/or soil out of the excavation in which a structure is built by enclosing the area around the dam.[16] This enclosure of the dam allows construction to be completed in-the-dry. There are five different types of cofferdams: braced, earth-type, timber crib, double-walled sheet pile, and cellular. This project will focus on cellular cofferdams used for Roller Compacted Concrete Construction. Cellular cofferdams are water-retaining structures that provide a sufficient amount of resistance to the flow of water, allowing no water to leak through the circular cells.[17]

2.2.1 Roller Compacted Concrete Construction

Roller Compacted Concrete (RCC) is a technique that involves construction of a dam to be completed in-the-dry. The cofferdams used in RCC Dam construction are temporary structures placed in the river by steel sheet pile cells in two, three or four sections across the river. Cofferdams are used to create water tight/resistant areas for construction.[18] The area where construction is going to be completed for each section will need to be dewatered after the cofferdams are in place. Once the area is dewatered, the concrete can rapidly be placed in-the-dry to create various types of dam structures.[7]

Design

Cofferdams are designed to keep water and/or soil out of an excavation area to allow a lock and dam structure to be constructed essentially in-the-dry.[18] Typically the contractor performs the design for these cofferdam structures. Factors included in the design are a sequence of construction, effective height of the cofferdam, scour protection, rate of overtopping, sediment transportation, passage of flows, stream flow characteristics, and safety.[7] If high water levels are present at a site, it is required that the cofferdam be designed at a greater height and stable enough to resist the increased water level. The cofferdams are placed across the river in sections to allow the river to safely flow around the sections during construction (see Figure 7). If the sections are designed in a way that creates a restriction on the river, then navigation of the river will need to be taken into consideration.[18] Stages are used across a river when there is not a designated area to navigate the river around the construction, which is very uncommon practice because it can harm the environment of the river.

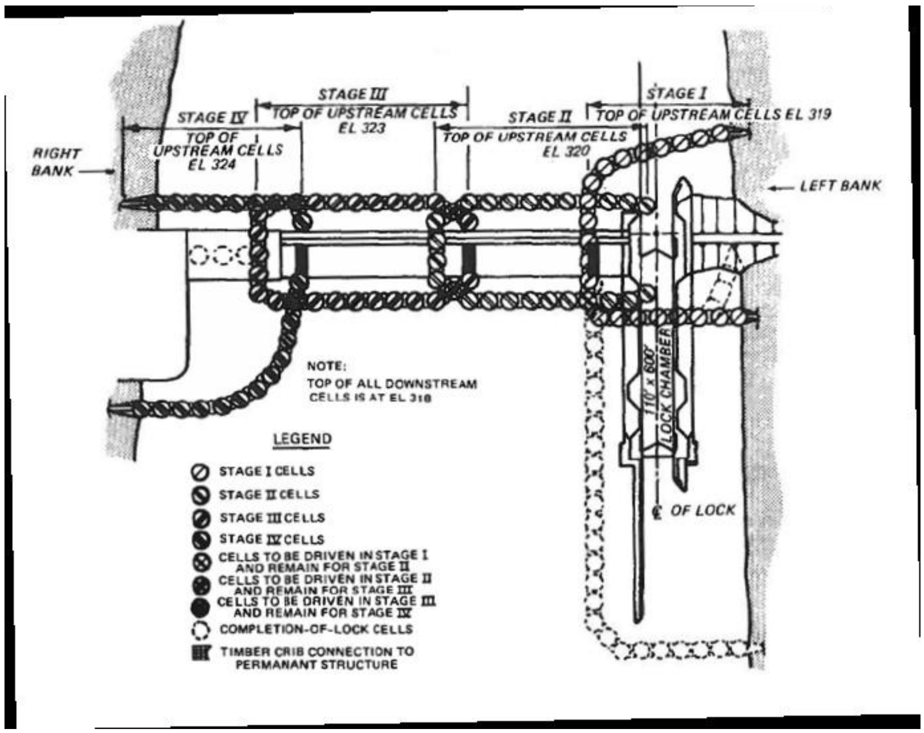

Figure 7: Four Stage Cofferdam Scheme to Construct a Lock and Dam

From a design standpoint, the placement of cofferdams is just as important as the actual design of the dam. Designing a dam in RCC construction allows a wide variety of dam types to be used. Typically, the contractor will suggest a few options and allow the owner to select their preferred alternative.

Construction

The first step in RCC Dam construction is to dewater the area where the construction is going to be taking place. Temporary cofferdams are driven down to the bedrock by means of cranes to create connecting circular steel sheet pile cells. The cells are then dewatered and filled with sand or dredged river material. The temporary cofferdam structures are created in sections across the entire river.[7] Each section is removed and a new section is added at the same time to allow the flow of the river to pass by the dam without needing to navigate the river. The areas inside of the cofferdam sections are dewatered to allow construction to essentially be completed in-the-dry (see Figure 8). RCC is most commonly used for in-the-dry construction compared to the traditional cast-in-place monolithic dam technique.[19] The main difference between in-the-dry cellular sheet piles and the cells for in-the-wet is that the structures for in-the-wet dam construction are permanent and backfilled with concrete.

Figure 8: Dewatered chamber at McAlpine

RCC is similar to conventional concrete because it has the same ingredients, but differs with the ratios that basically create no slump in the concrete mixture.[18] RCC can be placed at a fast pace and is more of an economical construction technique than the conventional placing of concrete. The procedure when using RCC is first transporting the concrete to the site in dump trucks, spreading the concrete by bulldozers, and compacting the concrete with vibratory rollers; similar to the technique of paving.[7] To reach effective consolidation, the RCC must be dry enough to support the weight of the equipment during construction. The concrete must also be wet enough to allow an even distribution throughout the mass during mixing and vibration of the past binder. Having an adequate amount of water in the concrete mixture will help achieve the compaction needed to prevent voids and unwanted segregation. The consistency requirements have a direct effect on the mixture proportioning requirements (ACI 207.1 R-87).[18] The concrete is allowed enough time to cure before it is exposed the flow of the river, making the dam a stable structure. Creating the cofferdams are more time consuming than the actual construction of the RCC Dam itself. The rapid placement of the concrete in an RCC Dam construction allows the process to almost counterbalance the extensive time it takes to construct and dewater the cofferdams.

Cost

There is an increase in construction cost for RCC Dams compared to other dam construction techniques. Constructing a dam at a large height can essentially increase the construction cost of the project. Taller cofferdams and more concrete for construction will be used when the height of the river is higher than normal. Within a river channel, the cost of constructing a cofferdam in stages for dam construction can amount to 20 to 40 percent of construction costs.[7] Another issue that can cause an increase in construction cost of a project would be if the site displayed karst geology. The cost could then substantially increase for the reason that additional dewatering of the site would be required. Cost for the design of the dam is minimal compared to the actual cost of constructing an RCC Dam.

Benefits

The use of RCC Dams seems to be more beneficial for allowing the construction in-the-dry to be completed at a rapid rate.[18] Numerous types of dams can be created because of the dewatered surrounding area where the construction takes place. RCC construction innovations have made gravity dams, dams that hold back water by the gravity of their own weight, more of an economically competitive alternative to embankment structures.[7] Factors such as material savings, spillways and appurtenant structures, diversion and cofferdam, shorter construction periods, reduced risk and damages associated with cofferdams overtopping, and cost advantages are a few areas that make RCC construction the leading technique implemented for in-the-dry construction.[18]

Overview

Roller Compacted Concrete (RCC) Dam Construction can only be completed in the dry across a river channel. The mixture for the RCC varies from concrete that is essentially placed in the water by use of tremie pipes for in-the-wet construction. RCC Dam Construction can be rapidly completed once the area around the dam is dewatered. An increased risk is associated with the owner and contractor for this technique because of the volatility of the river and karst geology that may be present. Although cost for constructing RCC Dams can be high, this technique allows the owner to choose from numerous types of dams.

3 Methodology

This goal of this project is to design a decision-making model for three dam construction techniques; Float-In, Concrete-Filled Cellular Sheet Pile Cells, and Roller Compacted Concrete. Float-In Construction and Concrete-Filled Cellular Sheet Pile Cells are related to an in-the-wet approach and Roller Compacted Concrete will be constructed by using the in-the-dry approach. An evaluation model for the dam construction techniques was created to show how cost, schedule, risk, constructability, quality assurance, and long-term performance affect the client when determining which dam construction to choose at a given location.

3.1 Dam Construction Alternatives

All of the information obtained is compiled into one document to conveniently allow a user to determine the appropriate construction technique for a dam at a specific site. This is important to the Kentucky River Authority as they are looking to rehabilitate several lock and dam structures in the near future. Below is a list of objectives that were compiled in order to achieve the overall goal for the research on the three dam construction techniques:

1) Research dam construction alternatives.
2) Develop an understanding of engineering aspects for marine construction.
3) Determine the appropriate factors involved in each dam construction technique.
4) Collect data associated with the factors from previously constructed dams to help construct a user friendly model.

3.2 Capstone Design: Model

For the capstone design, a decision-making model was designed to help determine the best fit construction technique to choose at any given site location. The model has a list of questions for the client or entry-level engineer to fill out that are site specific. From the questions and other factors associated with each dam construction alternative, the best fit dam construction technique for that location will be output to a summary table for the client to review. Concrete-Filled Cellular Sheet Pile Cells, Roller Compacted Concrete, and Float-In Dam Construction each have different contributing factors that are more appropriate for one site location than another. Below is a list of objectives that helped construct the decision-making model:

1) Research the three different dam construction techniques: Concrete-Filled Cellular Sheet Pile Cell, Roller Compacted Concrete, and Float-In Dam Construction.
2) Determine what factors are closely related to all types of dam construction and what makes them different from one another.
3) Review site specifics at locations that may affect construction.
4) Create a list of site specific questions.
5) Consult with Stantec Consulting Services Inc. and Kentucky River Authority for additional information on creating a decision-making model.
6) Construct a decision-making model to help decide which dam construction technique best fits any given location.

3.2.1 Calibration of Model

A calibration of the model was conducted after the design of the model was finished. To ensure that the decision-making model was not biased towards any one dam construction technique but also remained sufficient enough to use, a series of tests at different site locations was completed for three different types of dams. Having three different types of dam construction sites was important to show that it will be useful at any site when determining the appropriate type of dam construction. The three different locations are listed below:

1) Ohio River McAlpine Dam: Roller Compacted Concrete Construction
2) Monongahela River Braddock Lock & Dam: Float-In Construction
3) Kentucky River Lock and Dam No. 3: Concrete-Filled Cellular Sheet Pile Cell Construction

Below is a list of objectives that helped calibrate the model at these specific site locations:

1) Review site specifics at location from external sources.
2) Complete the list of questions at the site and obtain more information of the site from previous dam construction completed at the site.
3) Input the answers into the questions in the model.
4) Review the decision that the model has chosen for each of the locations.
5) Edit the model by creating more of an impact for certain areas of the dam construction process with site specifics.
6) Find more questions for a site location that affect each of the construction techniques individually.
7) Complete the model to allow a client, entry-level engineer, or engineering firm to use as a resource when choosing a dam construction approach for a given site.

When calibrating the model, it was noted that there was a problem obtaining the outcome of Roller Compacted Concrete Construction at the Braddock Dam location. The question related to karst geology needed to include more of an influence for RCC Construction and less of an impact for the other two construction techniques. There was an error associated with question 8 "What is the maximum height of the river during a 50-year flood?" When answered, the question was not affecting the outcome of the summary model table. The model code was lost when completing the model and needed to be re-written to ensure that it affected each of the construction techniques properly. The last calibration required to complete the model was with one of the cells in the "summary model" tab. The cell was not linked to the proper tab and needed to be changed to the correct one. (Refer to the "Analysis" section of the report for more details on the model design)

3.2.2 Application to Lock and Dam No. 8

After completing the calibration section of the capstone design, the decision making model was incorporated into the report. Kentucky River Lock and Dam No. 8 is currently next on the list for construction of a new dam. The type of dam construction that will be used at this site has not yet been chosen. This is the best location to apply the model and to provide the Kentucky River Authority with a preliminary assessment of the construction approach that will be most suitable for the location. Below is a list of objectives that helped apply the model to the location of Kentucky River Lock and Dam No. 8:

1) Review site specifics at location from sources before heading to the site.

2) Complete the list of questions at the site and obtain more information of the site from previous dam construction completed at the site.
3) Input the answers into the questions in the model.
4) Review the decision that the model has chosen for the location of Kentucky River Lock and Dam No. 8 and then document the results.

For Lock and Dam No. 8, the client is currently looking at either renovation of the existing dam, Roller Compacted Concrete, or Concrete-Filled Cellular Sheet Pile Cell Dam Construction. The location has similar site characteristics to Kentucky River Lock and Dam No. 3. The most noticeable differences were that the lock chamber was almost twice as small at Lock and Dam No. 3 and the access roads to the site were not appropriate for any type of vehicle. Therefore, better site preparation would be necessary at Lock and Dam No. 8. From answering all the questions provided, the model concluded that Concrete-Filled Cellular Sheet Pile Cell Dam Construction should be used at this location.

3.3 Final Deliverables

The final deliverable for this project discussed construction approaches for dam rehabilitation for a run-of-the-river dam on the Kentucky River System and a recommendation of what construction approach should be used at the location of Kentucky River Lock and Dam No.8. This report includes a model analyzing the Kentucky River Lock and Dam No. 8, which will act as a preliminary design report for the analysis of this specific location. The Kentucky River Authority may use this report and model for future dam construction projects. The report also meets the requirements of an engineering capstone design for the MQP to return to WPI project advisors.

4 Analysis

The analysis component of this report consists of determining the appropriate dam construction technique for a specific site location by use of a model. During the course of the capstone design three dam construction alternatives, Concrete-Filled Cellular Sheet Pile Cells, Float-In, and Roller Compacted Concrete Construction, were analyzed to determine which factors are most important when determining which alternative is appropriate for a specific location. Cost, schedule, risk, constructability, quality assurance, and long-term performance were chosen to be the factors that are linked between each of the dam construction alternatives and to have the greatest impact on choosing which alterative best fits a site. To determine the proper alternative for a site location, mobilization/demobilization, site preparation, underwater diver work, construction approach, foundation treatment, river volatility, karst geology, river navigation, maintenance, and ability to perform testing were considered for the selected factors in the model.

4.1 Design Decision Model

The model was designed to help a client, entry-level engineer, and engineering firm to all have a clear understanding which factors associated with a specific site location can influence the decision on determining which dam construction alternative best fits the location. Each dam construction alternative has factors that are more appropriate for certain locations than others. For example, there may be factors at one location that are not present at the other location that will make on alternative more applicable to that location.

4.1.1 Cost & Schedule

Mobilization/Demobilization, site preparation, underwater diver work, and construction approach are the four subcategories that have the highest impact on the overall cost and schedule of constructing a dam. When deciding which approach would be appropriate for the situation, clients prefer cost effective, efficient, smart investments as opposed to the more expensive alternative. Each dam construction approach affects these subcategories differently and the model was designed to determine the best investment at each site.

Mobilization/demobilization refers to getting the equipment needed for the job to and from the site, and also setting up the equipment. For mobilization/demobilization, Cell Dams typically only use average size marine equipment to construct each of the cells including cranes, barges to hold the cranes, and tremie concrete equipment. Having a minimal amount of equipment needed to complete the job makes this dam construction alternative cost effective and require less of a time for setup. Float-In Dam Construction uses specialty equipment to place each of the prefabricated concrete segments into place on the dam. Precision for floating the segment out on the water in terms of ballasting, or leveling the segment to keep afloat, and determining the highest capacity a crane can hold for any given dam segment involves an extensive amount of engineering design work and cost. Roller Compacted Concrete Construction involves equipment that can be used to create temporary cofferdams, dewater the construction area, and to place the concrete at a fast pace in-the-dry. The equipment used in constructing a dam in-the-dry is similar to equipment used for paving.

When starting any type of dam construction, a general site preparation is needed for the construction to begin. There will need to be access roads to the site, real estate land to set up on, and proper facilities to complete the work. Because of the minimal amount of equipment needed for Cell Dam Construction, only a general site preparation is required. Float-In Construction will need construction of an infrastructure to accept these prefabricated dam segments, so that they can be floated into place. A large casting basin or launch facility will need to be created to accept each of the dam segments. The basin or launch facility is built in close proximity to the site, which is another element which can be costly to the client. The dam segments are placed in the basin or launch facility, flooded, and then barged out to the dam site. RCC Dams, unlike Cell Dams, require a significant amount of site preparation to allow construction to be completed in-the-dry. Temporary cofferdam structures will need to be driven down to the bedrock, formed in sections or stages across the dam, and then the site will need to be dewatered to allow work to begin.

Underwater diver work is important to all dam construction to ensure that concrete segments are placed properly and that certain structures are water tight/resistant. Underwater diver work can be expensive when there is a great deal of diver work needed to complete the work at a site. Since diver work cannot be completed as fast as one could work in a dry area, diver work greatly increases the total cost of a project. Although RCC Dams require diver work to ensure the temporary cofferdams are water tight/resistant, they are an economically smart alternative to the other two dam construction choices since it uses the least amount of diver work. One alternative, Cell Dams, require more diver work to guarantee water tight/resistant cofferdams; about 10-50% of the work is completed with underwater diver work. Divers inspect and prepare the foundation of the cell, so that the concrete can be poured and connected to the bedrock securely. The divers will then need to seal off the top of the cell to allow a concrete cap to be poured in-the-dry. Float-In Construction, another alternative to Cell Dams, requires greater than 50% percent of the work be completed underwater, increasing costs immensely. The divers align each and every dam segment that is placed in the water with the cranes as well as oversee the pouring of the tremie concrete after the dam segments are put in place. Because of the importance of the dam segments with regard to the rest of the dam construction, the divers assume a lot of responsibility during this stage of the project.

Every construction approach has a different technique that can affect the overall time required for a project. Each cell involved with a Cell Dam takes roughly a month to complete. Under ideal circumstances these dams would be the most time-efficient as compared to its alternatives. During Float-In Dam construction it requires a sufficient amount of time to dewater the area inside the temporary cofferdams used, but the concrete is placed at a rapid pace making up the difference. RCC Dams require an extensive amount of foundation preparation to allow the site to accept the prefabricated dam segments. Fortunately, there is more of a lead time on items coming from prefabricated facilities or dry dock facilities. Each segment will be created to a specific weight and shape, which can require a great amount of time and money.

Directly related to the schedule of a project is the cost necessary to fund it. Since the budget of a project dictates the amount of resources and time available for construction, cost is the most important factor when it comes to choosing the correct dam construction alternative for a specific site. Every client factors in cost differently into construction compared to the other factors associated with it, but more clients will want to save money with the work they want done. Although each client may hold stronger values for any one aspect of the project, often the cost is considered the most significant constraint.

4.1.2 Risk

The delays, karst geology, and volatility of the river are some common risks involved with any project. These risks can not only affect the client, but can affect the contractor as well. Both parties hope to avoid these possible risks by carefully evaluating their options during the first steps in the decision-making process for the appropriate dam technique. If any risk occurs, the schedule may be extended, more materials may be necessary, and more permits may be required, all resulting in higher costs.

Having more of a need for underwater diver work can significantly increase the risk of the project. With Float-In, lining up each dam segment into its proper place can be tough with the minimal amount of visibility the diver has underwater. If one dam segment is out of alignment, then the remaining dam segments will be out of line affecting the rest of the dam construction. The diver must make sure that the cofferdams in RCC and Cell Dams are water tight/resistant. If the cofferdams are not water tight/resistant, then the concrete will not be able to fully cure in the cell; and the area will not be completely dewatered and the seal around the cofferdam will not be properly secured. This can increase the likelihood of possible failure for the project.

Foundation treatment is required to be properly done to allow the dam to sit on a foundation and be secure enough to withstand the force of the river acting on the dam. Cell Dams do not require much of a foundation treatment because the tremie concrete can be poured onto any surface regardless of changing rocklines. RCC Dams are completed in the dry and the Roller Compacted Concrete can accommodate any changing rocklines present at the site. The technique that has the highest risk factor for foundation treatment is Float-In Construction. Float-In Dams required a surface that is level enough and stable enough to accept each dam segment with a proper fit. Each dam segment must fit into place properly without any restrictions from the bedrock. There is a greater risk with this alternative because there is more room for error when treating the foundation for construction.

The volatility of the river is the single most important risk factor for dam construction. If the river height changes drastically throughout the year, then overtopping can occur. Overtopping is most commonly present when the temporary cofferdams are built for RCC Dam Construction. If the height of the cofferdams is not tall enough to withstand the river increasing in height, then more dewatering will be required and construction can be potentially ruined. The cofferdams built for Cell Dams can experience overtopping, but will not impact construction nearly as much as RCC Dams. Cells may need to be reconstructed, but the positive side to Cell Dam Construction is that each cell is individually built. Each cell can have a risk of overtopping, but can only affect that one cell that is being worked on. Float-In Construction has the least amount of risk associated with river volatility and overtopping. The prefabricated dam segments can be lowered into place regardless of the height of the river.

4.1.3 Constructability

Constructability refers to the ability to perform tasks under certain conditions and to identify the obstacles before the project is actually being built. There is a review of the construction process from start to finish predicting what the contractor could potentially encounter during construction. Things such as river volatility, karst geology, and navigation of river can affect constructability of a dam.

The greater the volatility present in the river, the greater a change in constructability occurs. If the dam experiences high volatility throughout the year, then cofferdams will need to be constructed at greater heights to withstand the river overtopping them. Having to create a taller cofferdam can cost the client time and money. The higher the cofferdam, the more it costs to dewater the area inside. The contractor does not want the cofferdam to overtop and ruin what construction has already been completed.

Karst geology can be present at any location and not always easy to spot. If there is karst geology present at a site when using RCC Construction, then an extensive amount of dewatering will be required. It is not always possible to predict the amount of karst geology present at a site location until the construction has started. Cell Dams will require a temporary seal of the karst feature to allow the concrete to be poured and cured before the karst feature can affect the construction of the cell. Float-In Construction offers a reduced impact to karst geology features. The prefabricated dam segments are placed on the bedrock, using its own weight to stabilize the dam. The dam segments are already prefabricate and cured to a standard, allowing no impact from karst features to the segment when it is placed in the river.

Navigation of the river refers to a lock feature that allows boat travel throughout the year. The lock feature lowers or raises the water level to allow the boat to travel to either side of the dam. The only functioning locks along the Kentucky River are Locks and Dams 1-4, which are only accessible certain days throughout the year. If there is a lock present at any given site location, the client will have the contractor either find a way to tie the new dam into the existing lock, create a new lock, or eliminate the existing lock. The lock feature has site specific characteristics and affects the constructability for each of the dam construction alternatives the same.

4.1.4 Quality Assurance

Performing quality assurance helps ensure that the quality of service on the dam and the finished product is what the owner had requested. "The planned and systematic activities implemented in a quality system so that the quality requirements for a product or service will be fulfilled.[20]" Meeting the owner's request is of importance for the contractor. Each request must go through a series of quality assurance and control tests to meet all the requirements.

The diver inspection plays a significant role in determining the quality of a dam constructed under water. In-the-wet construction requires the use of diver inspection during the construction phase. Float-In Dam Construction uses the divers to guide each dam segment into place, Cell Dam Construction uses the diver to inspect the foundation and each cell, and Roller-Compacted Concrete Dam Construction uses divers to inspect the dam after water is introduced to the dam when construction is completed. Regardless of how a dam is constructed, the dam will need to be inspected by a certified diver to confirm that the dam is working to the correct specification. Visual inspections during dam construction can be implemented to in-the-wet and in-the-dry dam construction. After the concrete is placed for in-the-dry construction, the concrete can be visually inspected to make sure that it has cured to the required specifications. Core samples of the concrete are obtained from the job site and are later tested to ensure strength requirements are met. The core samples are taken during different phases of the concrete pour and are later tested in the lab to make sure that the concrete will have enough time to cure and become stable enough to hold back the forces of the river.

Quality assurance and quality control are important to the contractor, to show the owner that all the work they completed is quality work. Each job will have a list of workers who will conduct these quality assurance and controls to make sure the project goes smoothly without any interference from any outside sources. On-site concrete testing is required to obtain the correct specifications of the concrete such as the pressure test and slump test. If the concrete does not pass these simple tests, then the concrete will not be used at this construction site. These specifications are mandatory to meet for each type of construction because the right water to cement ratio will allow the proper curing time to take place for the concrete to reach its full strength. More so than not, meetings will be scheduled between the owner and contractor to make sure everything is running smoothly. Without quality assurance and quality control testing measures taken on a construction site every day, then the end product would not have a long life span and can cause a safety concern.

Once the construction is completed, there will be a review of all the work completed on the end product. Dam construction can be inspected to make sure what the owner requested was given to the owner and that all the construction went accordingly. The post construction verification is used to review the end product and make sure that the dam passes quality assurance controls. The contractor or owner can review the process of constructing the dam and see what could possibly be implemented in future construction to avoid any conflicts that may have risen during this project.

4.1.5 Long-Term Performance

Long-term performance relates to how long of a life the dam will have and what future maintenance will be required to keep the dam up and running. A longer lasting dam with less maintenance needed will result in less cost to the client throughout the years. It is hard to predict specific maintenance needs in the future, but yearly diver inspections help determine what feature of the dam may need some renovation. The owner of the dam wants the dam to last as long as possible.

Maintenance refers to the work that it will take the owner to keep the dam functional after dam construction has been completed. The main issue with regard to Float-In Construction is that the offsite prefabricated concrete segments are placed underwater with help of the divers and then tremie concrete fills in the voids between each segment to make a strong connection. The problem with having the segments placed underwater is that the segments can sometimes not be properly fitted into place because the diver does not have great visibility. If one dam segment is not in line, then more likely than not, the other segments are off as well. If this is the case then more maintenance will be needed. It will be hard to tell how well the tremie concrete sealed the gap between each segment. Yearly underwater diver inspections will be of necessity for all types of dam construction. Cell Dam construction is similar to the maintenance required for Float-In Construction. Yearly inspections by underwater divers will be required and possible engineering analysis will need to be conducted. If the curing for one of the cells did not go as the contractor had anticipated, then there will need to be future reconstruction of the concrete cell. Concrete segments or tremie concrete placed underwater can be hard to test when they are first placed, hence why Cell Dams and Float-In dams will require more of a focus on the maintenance aspect. All three dam construction alternatives will require the same type of maintenance over the years, but some will require less than other, depending on how well the dam was constructed. Underwater diver inspections, engineering inspections, and normal keep up will need to be conducted over the life of the dam.

4.2 Using the Model

To decide on the appropriate dam construction alternative for a specific site location, the user must bring the list of questions to the site chosen to be evaluated. Concrete-Filled Cellular Sheet Pile Cells, Float-In, and Roller Compacted Concrete Construction each have individual factors at a site that influence the construction process more so than others. Below is a list that goes through each question individually and describes what the user of this model is looking for at any given site:

1. Are there access roads available to the site?: Driving to the site the user must first inspect the road to determine if contractors or any average size car can make it safely to the site. If there is space on the road adequate enough for the construction workers and engineers to get out to the site, then answer yes to this question. If no, then there will be an increase for site preparation.
2. Are the access roads wide enough for transportation of large construction equipment?: The roads will need to be wide enough for transportation of large/heavy construction equipment to and from the job site. This question is directly related to Float-In Construction because there is a need for large construction equipment to lift the concrete segments and lower them into place. The road needs to have, at minimum, a 10-foot travel lane to allow the equipment to be transported to the site. If the road is wide enough for transportation of large construction equipment, then answer yes to this question. If the answer to this question for a given site is no, then there will be an impact for mobilization/demobilization of the equipment.

3. Is the distance to the site more than 2 miles from main access roads?: A measurement will need to be taken when leaving the main access road to where the dam construction is going to take place. If the site is at a greater distance than 2 miles away from a main access road, then answer yes to this question. Getting to and from the job site is important for saving travel time cost to get the equipment and the workers to the site. If there are main access roads close to the site, then there will be less of an impact to the cost of mobilization/demobilization of construction equipment.
4. Is there a sufficient amount of real estate for parking, setup, and storage of equipment?: Having enough real estate to setup the equipment, area to store the equipment, and an area designated for parking can affect the site preparation for any type of dam construction. There may be an area to set up on that the client already owns. If there is an area close to the site, but the client does not own it, then the land should be purchased or rented from the owner. If there is enough parking for at least two trailers, 15 cars, and an area to store the equipment then answer yes to this question.
5. Is the river system navigable? (lock chambers): Once arriving to the existing dam, examine the overall structure of the dam. The dam was either constructed across the entire river channel or part of the river channel with a structure connected to it. The connecting structure is called a lock chamber and allows for the travel of boats to either side of the dam. If there is a lock chamber, then answer yes to this question and constructability will be impacted if the new dam will need to be tied into the existing lock structure.
6. Are there any prefabrication facility or dry docks within 10 miles of the site?: This question can be looked up before or after going to the site for an analysis of the location.

There will need to be some research to determine if a prefabrication facility or dry dock facility is within 10 miles of the site. These facilities help create the precast concrete segments and allow them to float down the river to the location needed. If a facility is located within 10 miles, then answering yes will allow for Float-In Construction to be more efficient and cost effective to allow the travel of dam segments down the river to the site.

7. Casting basin or launch facility located on river?: Similar to question number 6, this question deals mainly with Float-In Construction. This question can also be determined at any point of reviewing a dam by determining if there are any current casting basins or launch facilities along the river. At the site, one may see an area that is sculpted out of the land and connected to the river. This area can allow for precast dam segments to be placed into the water to help achieve flotation of the segments. If there is a casting basin or launch facility, then there will be minimal amount of site preparation for the river to accept these dam segments.
8. What is the maximum height of the river during a 50-year flood?: The maximum height of the river affects the volatility of the river, which affects the construction approach. There are usually statistics showing the height of the river at any given time throughout the year on the United States Geological Survey USGS website. The USGS monitors the height of the river and other factors daily, and provides this information on their website. If this information is not readily available, a hydrologic analysis should be conducted to determine the expected river stage for the 50-year storm event. The height of the river during a 50-year flood will directly impact the probability of overtopping during construction.

9. If the river is navigable, what is the lock chamber width?: If question number 5 was answered yes, then you will need to get the dimensions of the existing lock chamber at the site. You can measure the length of the structure with a tape measure or obtain the dimensions of the lock from previous documents for the construction. The lock will affect constructability; when needing to determine the best way to tie into the existing lock structure or to demolish the lock structure. If deciding to do away with the lock chamber, then you will need to check local regulations to see if it is a requirement to keep the lock up and running.
10. What is the lift of the dam?: The lift of the dam can also be measured from the USGS website. The lift is the difference between the upper pool level and the lower pool level on the dam. You can measure the height of the pools at the site if you have a diver team or you can review the specs of the dam to see what the dam was designed to hold for a pool level. This will affect the construction of the new dam to maintain the proper pool levels on either side of the dam.
11. What is the height of the existing dam?: The height of the existing dam can be measured with a team of divers or previous documentation of construction of the old dam. The height of the dam will help allow the contractor to decide the required height of both the new dam and the cofferdams. The taller the cofferdams, the more dewatering will be required at the site. With a greater area to be dewatered, the overall cost of construction will increase.
12. What is the width of the river at the dam site?: The length of the river can be measured by a team of divers or by previous documentation of construction. Adding the length of the lock chamber and the length of the dam can give you the width of the river channel.

Having a wider channel will call for cost and risk of dam construction to increase with the need for a greater area of construction.

13. Is there alluvial material at the dam site?: Alluvial material relates to the soil that is present at the location of the site. It can be difficult when determining what those characteristics of the soil are unless there are core samples taken. At the site you will be able to measure from the top of the soil down to the bedrock by a team of divers. You can also take samples of the soil in the river at a different location along the river to come up with the same conclusion about soil characteristics. If there are alluvial materials present at the site, then the cost of removing these materials will increase.
14. Is there an irregular rocklines present?: Irregular rocklines are another thing that can be hard to measure before starting construction. Roller Compacted Concrete and Cell Dam Construction can accommodate irregular rocklines, but Float-In Construction can run into problems with setting the dam segments down on the foundation. A geological study can be conducted by a specialized engineering team to see what the contractor will run into upon reaching the bedrock.
15. Is there karst geology present?: Karst geology will need to be measured by a team of underwater divers. There can be karst geology present at any dam site location without knowing until construction begins. The divers will be able to conclude if there is indeed karst geology at a site, but will not know the extent of the features until construction begins. Karst geology can affect RCC and Cell Construction because an extensive amount of dewatering or temporary stops to the karst feature will need to be considered. If yes, then you will run into a greater risk for the contractor and the client during construction.

After completing the list of questions above, the user will need to determine the relative importance for each of the factors. Cost, schedule, risk, constructability, quality assurance, and long-term performance are weights chosen by the client. For example, the client may want the construction of the dam to focus more on schedule than cost.

After completing the list of questions and filling in the chart, the user can view the outcome of the model on the "summary model" tab. If the numbers are close between two construction techniques, then a more extensive engineering study will be needed for evaluating the site for construction of a new dam.

4.3 Run Through Questions

Each question is factored into the model with a series of "if" and "and" statements that affect each cell and each construction technique differently. As you change the answers for the questions, you can see how each question affects each of the cells individually. The total column for each construction technique tab is then linked to a summary table, which allows the model to rank each of the construction techniques from 1 to 3. Below is a run through with a few of the questions from the questions tab in the model:

Question #2: Are the access roads wide enough for transportation of large construction equipment?

- Answering Yes: The cell that shows a relationship between cost and mobilization/demobilization with Float-In Construction will be affected. If there are roads wide enough for the large construction equipment, then there will be less of a cost for mobilization and demobilization of the equipment. This will subtract one point from this cell when answered yes.

- Answering No: The cell that shows a relationship between cost and mobilization/demobilization with Float-In Construction will be affected. If the roads are not wide enough for the large construction equipment, then there will be an increase in cost for mobilization and demobilization of the equipment. This will add one point to the cell when answered yes.
- Model Code: +IF((AND(A1="Float-In Construction",Questions!C4="N")),1,IF((AND(A1="Float-In Construction",Questions!C4="Y")),-1,0))

Question #5: Is the river system navigable? (lock chambers)

- Answering Yes: The cell that is the overall total for constructability within a specific construction technique is affected by answering yes. There is an addition of one point to show that there will be more of focus on constructability during any type of construction. To tie into the existing lock structure or demolishing the structure will cause the increase of constructability during construction.
- Answering No: There will not be an affect to constructability for construction of a dam when this question is answered no. The constructability for all the types of dam construction will not be affected when answering this question.
- Model Code: +IF(Questions!C7="Y",1,0)

Question #8: What is the maximum height of the river during a 50-year flood?

- Answer ≤ 5 ft: There will be an increase of one to underwater diver work to all types of dam construction techniques. With the least amount of diver work required for any type of dam construction, the company will save with cost, schedule, risk, and quality assurance for construction.
- Answer 5 < 10 ft: There will be an increase of two to underwater diver work to all types of dam construction techniques. With an average amount of diver work required for any type of dam construction, the company will focus less on cost, schedule, risk, and quality assurance for construction.
- Answer ≥ 10 ft: There will be an increase of three to underwater diver work to all types of dam construction techniques. With greater amount of diver work required for any type of dam construction, the company will see an increase for cost, schedule, risk, and quality assurance for construction.
- Model Code: +IF(Questions!C12<=5,1,IF(Questions!C12>=10,3,2))

Question #11: What is the height of the existing dam?

- Answer < 10 ft: The value will remain the same within cost and constructability for Roller Compacted Concrete and Concrete-Filled Cellular Sheet Pile Cell Dam Construction if the height of the existing dam is less than 10 ft.
- Answer > 10 ft: There will be an increase of one point for both Roller Compacted Concrete and Cellular-Sheet Pile Cell Dam Construction. The increase will affect the cost and constructability of the project. With a taller dam you will need to take into consideration that there will be a greater need for taller cofferdam structures during construction.
- Model Code: +IF(Questions!C15>=10,1,0)

Question #15: Is there karst geology present?

- Answering Yes: An increase to the relationship between risk and foundation for Roller Compacted Concrete construction will occur if answered yes. For the relationship of constructability and karst geology for all three dam construction alternatives there will be an increase of three points to each. The increase is because there will be more of an impact with karst geology features, than any other factor associated with construction. Also if this question is answered yes, then there will be an increase of five for Roller Compacted Concrete. Because there is such a high risk with constructability if karst geology is present at site, in-the-dry can have more of an influence from these features.
- Answering No: There will be a decrease of five for the relationship of constructability and karst geology for Roller Compacted Concrete. This is because not having karst present at the location, will essentially requires less of an impact to the construction process.
- Model Code: + IF(Questions!C21="Y",3,1)+IF((AND(A1="Roller Compacted Concrete Construction",Questions!C21="Y")),5,IF((AND(A1="Roller Compacted Concrete Construction",Questions!C21="N")),-5,0))

4.4 Site Data

Each site location was analyzed to determine the site specifics at each location. The calibration of the model was conducted with data from Kentucky River Lock & Dam No. 3, Monongahela River Braddock Lock and Dam, and the Ohio River McAlpine Dam. Then, the model was applied to the Kentucky River Lock and Dam No. 8 to see which dam construction would be appropriate to choose for that location. Below are the answers to each of the questions for the locations and figures of the outputted summary tables:

4.3.1 Kentucky River Lock and Dam No. 3

	Site Specific		
#		(Y/N)	
1	Are there access roads available to the site?	y	
2	Are the access roads wide enough for transportation of large construction equipment?	n	
3	Is the distance to the site more than 2 miles from main access roads?	y	
4	Is there a sufficient amount of real estate for parking, setup, and storage of equipment?	y	
5	Is the river system navigable? (lock chambers)	y	
6	Are there any prefabrication facility or dry docks within 10 miles of the site?	n	
7	Casting basin or launch facility located on river?	n	
	Measurements	(Value)	(Units)
8	What is the maximum height of the river during a 50-year flood?	26	ft.
9	If the river is navigable, what is the lock chamber width?	38	ft.
10	What is the lift of the dam?	13.3	ft.
11	What is the height of the existing dam?	21.5	ft.
12	What is the width of the river at the dam site?	478	ft.
	Foundation Conditions	(Y/N)	
13	Is there alluvial material at the dam site?	y	
14	Is there an irregular rocklines present?	y	
15	Is there karst geology present?	y	
	Client Specific Weighted Values	(Weight)	
	Cost	16.67%	
	Schedule	16.67%	
	Risk	16.67%	
	Constructability	16.67%	
	Quality Assurance	16.67%	
	Long-Term Performance	16.67%	

Figure 9: Kentucky River Lock and Dam No. 3 Questions Answered

Summary Table	Cost	Schedule	Risk	Constructability	Quality Assurance	Long-Term Performance	Total	Rank
Concrete-Filled Cellular Sheet Pile Cell Construction	0.83	0.50	1.50	1.83	1.00	0.17	5.83	1
Float-In Construction	3.33	3.00	2.00	1.83	1.50	0.17	11.84	3
Roller Compacted Construction	1.33	1.83	0.50	1.83	1.00	0.17	6.67	2

Figure 10: Kentucky River Lock and Dam No. 3 Summary Table

4.3.2 Monongahela River Braddock Lock and Dam

	Site Specific		
#		(Y/N)	
1	Are there access roads available to the site?	y	
2	Are the access roads wide enough for transportation of large construction equipment?	y	
3	Is the distance to the site more than 2 miles from main access roads?	n	
4	Is there a sufficient amount of real estate for parking, setup, and storage of equipment?	y	
5	Is the river system navigable? (lock chambers)	y	
6	Are there any prefabrication facility or dry docks within 10 miles of the site?	y	
7	Casting basin or launch facility located on river?	y	
	Measurements	(Value)	(Units)
8	What is the maximum height of the river during a 50-year flood?	22	ft.
9	If the river is navigable, what is the lock chamber width?	720	ft.
10	What is the lift of the dam?	11.8	ft.
11	What is the height of the existing dam?	21	ft.
12	What is the width of the river at the dam site?	1080	ft.
	Foundation Conditions	(Y/N)	
13	Is there alluvial material at the dam site?	y	
14	Is there an irregular rocklines present?	y	
15	Is there karst geology present?	n	
	Client Specific Weighted Values	(Weight)	
	Cost	16.67%	
	Schedule	16.67%	
	Risk	16.67%	
	Constructability	16.67%	
	Quality Assurance	16.67%	
	Long-Term Performance	16.67%	

Figure 11: Braddock Lock and Dam Questions Answered

Summary Table	Cost	Schedule	Risk	Constructability	Quality Assurance	Long-Term Performance	Total	Rank
Concrete-Filled Cellular Sheet Pile Cell Construction	2.00	1.67	1.50	1.50	1.00	0.17	7.83	3
Float-In Construction	0.67	0.33	2.00	0.67	1.50	0.17	5.33	1
Roller Compacted Construction	1.50	2.00	0.33	0.67	1.00	0.17	5.67	2

Figure 12: Braddock Lock and Dam Summary Table

4.3.3 Ohio River McAlpine Dam

	Site Specific		
#		(Y/N)	
1	Are there access roads available to the site?	y	
2	Are the access roads wide enough for transportation of large construction equipment?	y	
3	Is the distance to the site more than 2 miles from main access roads?	n	
4	Is there a sufficient amount of real estate for parking, setup, and storage of equipment?	y	
5	Is the river system navigable? (lock chambers)	y	
6	Are there any prefabrication facility or dry docks within 10 miles of the site?	n	
7	Casting basin or launch facility located on river?	n	
	Measurements	(Value)	(Units)
8	What is the maximum height of the river during a 50-year flood?	55	ft.
9	If the river is navigable, what is the lock chamber width?	600	ft.
10	What is the lift of the dam?	37	ft.
11	What is the height of the existing dam?	35	ft.
12	What is the width of the river at the dam site?	1800	ft.
	Foundation Conditions	(Y/N)	
13	Is there alluvial material at the dam site?	y	
14	Is there an irregular rocklines present?	y	
15	Is there karst geology present?	y	
	Client Specific Weighted Values	(Weight)	
	Cost	16.67%	
	Schedule	16.67%	
	Risk	16.67%	
	Constructability	16.67%	
	Quality Assurance	16.67%	
	Long-Term Performance	16.67%	

Figure 13: McAlpine Dam Questions Answered

Summary Table	Cost	Schedule	Risk	Constructability	Quality Assurance	Long-Term Performance	Total	Rank
Concrete-Filled Cellular Sheet Pile Cell Construction	2.00	1.67	1.50	1.83	1.00	0.17	8.17	2
Float-In Construction	2.17	1.83	2.00	1.83	1.50	0.17	9.50	3
Roller Compacted Construction	1.50	2.00	0.50	1.83	1.00	0.17	7.00	1

Figure 14: McAlpine Dam Summary Table

4.3.4 Kentucky River Lock and Dam No. 8

	Site Specific		
#		(Y/N)	
1	Are there access roads available to the site?	n	
2	Are the access roads wide enough for transportation of large construction equipment?	n	
3	Is the distance to the site more than 2 miles from main access roads?	y	
4	Is there a sufficient amount of real estate for parking, setup, and storage of equipment?	y	
5	Is the river system navigable? (lock chambers)	y	
6	Are there any prefabrication facility or dry docks within 10 miles of the site?	n	
7	Casting basin or launch facility located on river?	n	
	Measurements	(Value)	(Units)
8	What is the maximum height of the river during a 50-year flood?	26	ft.
9	If the river is navigable, what is the lock chamber width?	72	ft.
10	What is the lift of the dam?	18.3	ft.
11	What is the height of the existing dam?	33.3	ft.
12	What is the width of the river at the dam site?	326	ft.
	Foundation Conditions	(Y/N)	
13	Is there alluvial material at the dam site?	y	
14	Is there an irregular rocklines present?	y	
15	Is there karst geology present?	y	
	Client Specific Weighted Values	(Weight)	
	Cost	16.67%	
	Schedule	16.67%	
	Risk	16.67%	
	Constructability	16.67%	
	Quality Assurance	16.67%	
	Long-Term Performance	16.67%	

Figure 15: Kentucky River Lock and Dam No. 8 Questions Answered

Summary Table	Cost	Schedule	Risk	Constructability	Quality Assurance	Long-Term Performance	Total	Rank
Concrete-Filled Cellular Sheet Pile Cell Construction	1.00	0.67	1.50	1.83	1.00	0.17	6.17	1
Float-In Construction	3.50	3.17	2.00	1.83	1.50	0.17	12.17	3
Roller Compacted Construction	1.50	2.00	0.50	1.83	1.00	0.17	7.00	2

Figure 16: Kentucky River Lock and Dam No. 8 Summary Table

4.3.5 Results of Kentucky River Lock and Dam No. 8

When applying site specifics for Kentucky River Lock and Dam No. 8 to questions in the model, the "summary matrix" tab ranked Concrete-Filled Cellular Sheet Pile Cell Construction as the top choice at this location. With the results from the model, an in depth engineering analysis should be done at this site to confirm that the correct construction technique was chosen and determine what other factors may influence construction of the a new dam.

Appendix

Appendix A: Rubric Tab

Cost			
	Average Size Equipment	Large Marine Equipment	Specialty Equipment
Mobilization/Demobilization	1	2	3
	General Site Preparation	Significant Site Preparation	Construction of Infrastructure
Site Preparation	1	2	3
	≤ 10%	10% - 50%	> 50%
Underwater Diver Work	1	2	3
	In-the-wet: limited foundation elements	In-the-wet: significant foundation elements	In-the-dry: cofferdams/dewatering required
Construction Approach	1	2	3
Schedule			
	Average Size Equipment	Large Marine Equipment	Specialty Equipment
Mobilization/Demobilization	1	2	3
	General Site Preparation	Significant Site Preparation	Construction of Infrastructure
Site Preparation	1	2	3
	≤ 10%	10% - 50%	> 50%
Underwater Diver Work	1	2	3
	In-the-wet: cell dam	In-the-wet: cofferdam construction	In-the-dry: fabrication of elements offsite
Construction Approach	1	2	3
Risk			
	0 - 5 ft	5- 10 ft	> 10 ft
River Volatility	1	2	3
	≤ 10%	10% - 50%	> 50%
Underwater Diver Work	1	2	3
Constructability			
	0 - 5 ft	5- 10 ft	> 10 ft
River Volatility	1	2	3
	Reduced Impact	Increased Impact	
Karst Geology	1	3	
Quality Assurance			
	One Technician Required	Extensive Testing / Multiple Technicians Required	Special / Unique Dam Elements
Quality Control / Quality Assurance Testing & Observations	1	2	3
	≤ 10%	10% - 50%	> 50%
Underwater Diver Work	1	2	3
Long-Term Performance			
	Periodic Above Water Inspections	Periodic Above Water & Below Water Inspections	Periodic Above Water & Below Water Inspections with Instrumentation Monitoring
Maintenance	1	2	3

Appendix B: Construction Tabs

Concrete-Filled Cellular Sheet Piles Cell Construction

Concrete-Filled Cellular Sheet Pile Cell Construction			<--------------------	Change Construction Technique Here									
	Weight	Mobilization/ Demobilization	Site Preparation	Underwater Diver Work	Construction Approach	Foundation Treatment	River Volatility	Karst Geology	Navigation River	Maintenance	Ability to Perform Testing	Total	Weighted Total
Cost	**16.67%**	1	2	5	-4							**6**	1.00
Schedule	**16.67%**	1	2	5	-4							**4**	0.67
Risk	**16.67%**			5		1	3					**9**	1.50
Constructability	**16.67%**						3	3	1			**11**	1.83
Quality Assurance	**16.67%**			5							1	**6**	1.00
Long-Term Performance	**16.67%**									1		**1**	0.17
Total	**100%**												

Float-In Construction

Float-In Construction			<--------------------	Change Construction Technique Here									
	Weight	Mobilization/ Demobilization	Site Preparation	Underwater Diver Work	Construction Approach	Foundation Treatment	River Volatility	Karst Geology	Navigation River	Maintenance	Ability to Perform Testing	Total	Weighted Total
Cost	**16.67%**	4	5	6	4							**21**	3.50
Schedule	**16.67%**	4	5	6	4							**19**	3.17
Risk	**16.67%**			6		3	3					**12**	2.00
Constructability	**16.67%**						3	3	1			**11**	1.83
Quality Assurance	**16.67%**			6							3	**9**	1.50
Long-Term Performance	**16.67%**									1		**1**	0.17
Total	**100%**												

Roller Compacted Concrete Construction

Roller Compacted Concrete Construction			<--------------------	Change Construction Technique Here									
	Weight	Mobilization/ Demobilization	Site Preparation	Underwater Diver Work	Construction Approach	Foundation Treatment	River Volatility	Karst Geology	Navigation River	Maintenance	Ability to Perform Testing	Total	Weighted Total
Cost	**16.67%**	2	3	4	3							**9**	1.50
Schedule	**16.67%**	2	3	4	3							**12**	2.00
Risk	**16.67%**			4		-4	3					**3**	0.50
Constructability	**16.67%**						3	8	-4			**11**	1.83
Quality Assurance	**16.67%**			4							2	**6**	1.00
Long-Term Performance	**16.67%**									1		**1**	0.17
Total	**100%**												

Appendix C: Project Proposal

(Project Proposal is after the Endnotes)

Endnotes

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Cost-Analysis of Dam Construction

Major Qualifying Project Proposal

Prepared By:

Jason Butler

December 8th 2010

Table of Contents

Description

This project will identify the benefits, advantages and disadvantages, of two dam construction approaches, in-the-wet construction vs. in-the-dry construction. The different construction approaches will be evaluated in suitability for use in dam construction on the Kentucky River System in terms of cost, schedule, risks, and potential construction issues. All of this information will be compiled into one document that will allow a user to determine the best construction approach for a dam. This is important to the Kentucky River Authority as they are looking to rehabilitate several lock and dam structures in the near future. Part of this evaluation will be possible benefits of uplift sensor technology for the life-cycle of these facilities to perhaps offer an insight to the Kentucky River Authority.

The final deliverable for this project will be a technical report discussing construction approaches for dam rehabilitation for a “run of the river” dam on the Kentucky River System and an evaluation of each approach. This report will include an evaluation of the possible benefits with installing uplift sensors in future dam rehabilitation projects. The Kentucky River Authority may use this report for future dam construction. The report will also meet the requirements of an engineering capstone design for the MQP to return to WPI project advisors.

Background

The Renovation of Kentucky River Lock and Dam No.3 consists of the construction of a new dam, two abutments, and a downstream training wall along with slope and scour protection features immediately upstream and adjacent to the existing structure. There are currently 14 locks and dams along the Kentucky River. This project will cover what goes into the engineering phase during the renovation of Kentucky River Lock and Dam No.3. The project will assist with construction submittal review and responses, project documentation, preparation for progress meetings, review contractor invoices for payments, and schedule management along with other construction issues that may arise. The Kentucky River Authority is looking at rehabilitating several lock and dam structures along the river in near future and information on different construction approaches will help benefit the authority in determining the appropriate approach to choose.

In-the-wet construction

In-the-wet construction, also known as offsite prefabrication, uses precast concrete segments that are fabricated offsite and brought onto the site to be installed. “This innovation method uses precast concrete modules as the in situ form into which tremie concrete is placed directly without use of a cofferdam” (US Army Corps of Engineers, 1999). These concrete segments are moved to their final position by either a lift-in or float-in construction technique. Lift-in construction involves heavy equipment to carry the precast modules from the factory to its final position. Float-in construction involves lowering these precast modules into place with a temporary floating structure.

In-the-dry construction (cofferdam construction)

In-the-dry construction relies on a cofferdam, a temporary structure designed to keep water and/or soil out of the excavation in which a structure is built by enclosing the area around the dam (Standard Handbook of Heavy Construction, 1996). This enclosure of the dam allows construction to be completed in the dry. There are five different types of cofferdams: braced, earth-type, timber crib, double-walled sheet pile, and cellular. This project will focus on cellular cofferdams. Cellular cofferdams are water-retaining structures that provide a sufficient amount of resistance to water flow so that no water leaks through the circular cells (Foundation Analysis and Design, 1996).

Run of the river dams

A run of the river dam is constructed across the entire width of a river or stream to maintain the normal flow levels. Run of the river dams have little or no storage behind the dam and are constructed to allow the water to flow over the dam. Navigation lock and dam is the most common example of run of the river projects and allows for the traffic of boats on the channel.

Uplift Sensor Technology

Uplift pressure is one of the dominating loads on the dam's structure; therefore a big concern is to measure the amount of uplift pressure on concrete dams. It is difficult to measure the overall uplift pressure of concrete dams because uplift sensors are confined to one point for a measurement reading. Therefore, theoretical models are used to describe the uplift distribution (US Army Corps of Engineers, 2009).

Scope of Work

The scope of this project includes the evaluation of different dam construction approaches on the Kentucky River System in terms of cost, schedule, risks, and potential construction issues. A look at possible benefits of uplift sensor technology will also be implemented into this project.

Deliverables

The final deliverable for this project will include an evaluation document on the different dam construction approaches. This evaluation will look closely at comparing the cost for each approach, length of the projects for scheduling purposes, possible risks that could occur for the different approaches and potential construction issues for prior, during, and even after the construction phase. An additional section will be devoted to the evaluation of uplift sensor technology and what benefits it could contribute to the Kentucky River Authority for future dam rehabilitation projects.

A Capstone design will be incorporated as part of the project to show the Kentucky River Authority the different types of construction approaches on dams. Since the Kentucky River Authority is looking to rehabilitate several lock and dam structures in the near future, they can use the evaluation of these different types of dam construction approaches. A MQP report, including a background, literature review, methodology, results, and conclusions will be submitted to WPI. This report will include all the research that was used to develop the evaluation on the different types of construction approaches on dams and the uplift sensor technology.

Methodology

The goal of this project is to provide Stantec with an evaluation report of the different types of approaches that could be used when constructing a dam and also an evaluation on uplift sensor technology. The evaluations conducted will be of use when determining what approach to use for constructing a dam. This document will be of use to the Kentucky River Authority and Stantec for future rehabilitation of lock and dam structures on the Kentucky River. To create this document the following steps will be taken.

1. Research and compare advantages and disadvantages of in-the-wet construction vs. in-the-dry construction for lock and dams.
2. Develop an understanding of engineering aspects for marine construction.
3. Research and develop an understanding of uplift cells and their uses/applications.
4. Evaluate dam construction approaches.
    a. Overall Cost.
    b. Length of project in terms of scheduling.
    c. Possible risks in the project.
    d. Potential construction issues that may arise.
5. Evaluate uplift sensor technology.
    a. Use/application costs.
    b. Benefits of installation in future dam rehabilitation projects.
6. Compile evaluated dam construction approaches and uplift sensor technology into a user friendly template.

Appendix A – Preliminary Schedule

Week	11/22/2010	11/29/2010	12/6/2010	12/13/2010	1/18/2011	1/24/2011	1/31/2011	2/7/2011	2/14/2011	2/21/2011	2/28/2011
Activity											
Draft Proposal											
Research											
In-the-wet Construction											
Dry Construction											
Dam Sensors											
Cost Analysis on Dams											
Complete Proposal											
Call Project Contacts (Set Time and do it)											
Revise Project Proposal											
Get Approval From Stantec for PQP project											
Arrive in KY											
Get Acclimated											
Get Project Status Update											
Project Meeting with Stantec											
Sensor Implementation											
Evaluation of Cost-Benefits											
Draft Poster											
Final Draft Submitted											
Create Presentation											
Practice Presentation											
Final Report Submitted											

Appendix B – Tasks

Week 1

- Main Objective:
    - Develop knowledge base of Stantec's project
- Tasks:
    - Research types of in-the-wet dam construction approaches (tremie concrete)
    - Become familiar with dam construction for the Kentucky River Lock and Dam No. 3
    - Begin literature review and bibliography
    - Start write up for different dam construction approaches and uplift sensors (to be done throughout every week)
    - Add to annotated bibliography

Week 2

- Main Objective:
    - Other construction techniques besides in-the-wet and begin deliverables
- Tasks:
    - Research in-the-dry construction approaches
    - Finish up background research
    - Find lock and dam construction studies completed for other rivers
    - Continue literature review and background for MQP
    - Arrange for interview with Stantec employees
    - Add to annotated bibliography

Week 3

- Main Objective:
    - Start creating template for items evaluated in the project
- Tasks:
    - Complete researching on in-the-wet and in-the-dry construction
    - Begin looking into uplift sensor technology
    - Format template for evaluating the different dam construction approaches and uplift sensor technology
    - Complete literature review and background
    - Interview with Stantec Employees
    - Add to annotated bibliography

Week 4

- Main Objective:
    - Finish research, start to compile evaluation template, and work on MQP write-up
- Tasks:
    - Finish uplift sensor technology research
    - Start entering information acquired into the evaluation template (cost, schedule, risks, potential construction issues)
    - Start writing the evaluation out into a document
    - Work on Methodology – MQP
    - Add to annotated bibliography

Week 5

- Main Objective:
    - Continue working on template and write up
- Tasks:
    - Finish up template and start write up to go along with it
    - Work on write-ups for different dam construction approaches and uplift sensors
    - Work on compiling everything into MQP

Week 6

- Main Objective:
    - Continue work on template and MQP Capstone
- Tasks:
    - Work on evaluation template – submit preliminary draft for review
    - Decide on capstone
    - Work on MQP – Results and Discussion

Week 7

- Main Objective:
    - Complete evaluation template
- Tasks:
    - Finish template and review material
    - Begin the capstone design project
    - Finalize draft and submit for review
    - Begin thinking about presentation
    - Work on MQP – should complete draft – submit for review

Week 8

- Main Objective:
  - Presentation, Capstone Design, MQP
- Tasks:
  - Present the evaluation template and other knowledge gained to Stantec
  - Present Stantec with final deliverable
  - Complete capstone design problem
  - Complete final draft of MQP