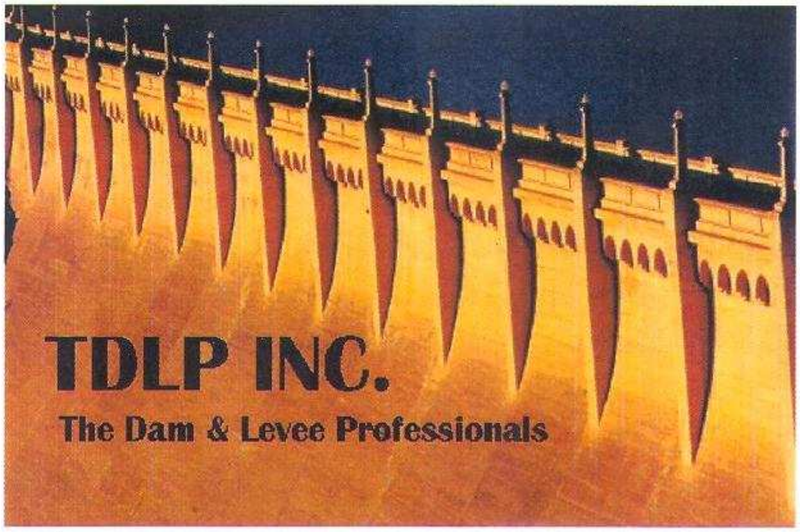
Protection from Floodwall Overtopping Scour



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Abstract

The objective of this project was to develop a method for sizing rip rap in order to prevent overtopping scour on the downstream side of floodwalls or other types of retaining walls. Initial investigation of current market products, related patents, and literature review of currently published data and research on the preventing this phenomenon was conducted. Design was then developed from research in order to perform scale model testing on several sizes of rip rap. Four distinctive rip rap sizes were chosen for testing including; 0.29 ft, 0.17 ft, 0.11 ft, and 0.05 ft D_{50}. Three model floodwall heights were selected for testing; 0.5ft, 1 ft, and 2 ft. A model flume was constructed and used to conduct tests. Rip rap beds were placed downstream of the model floodwall and analyzed as stable, minor movement, major movement, and failure dependent on movement during flow setting over the model floodwall. Results from observations are shown in a figure which can be used for engineering design analysis of rip rap beds for drop height to critical depth ratios up to 40. Length of rip rap bed downstream of the floodwall is established for the same drop height to critical depth ratios.

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Mission Statement

"TDLP Inc will be the innovator of dam and levee erosion control designs that will meet and exceed our customers needs to provide them with the safety and security we all deserve. TDLP Inc will go above and beyond industry standards to provide protection of property and quality of life by designing and maintaining top notch erosion protection structures."

-TDLP Inc

Introduction

The United States Department of Agriculture (USDA) chief scientific research agency Agricultural Research Service (ARS) specializes in developing solutions to agricultural problems that affect Americans every day. Stillwater is home to a division of the ARS this unit is called the Hydraulic Engineering Research Unit (HERU). HERU has been in continuous operation since it was established in 1940. The lab has had a major impact on soil and water conservation engineering and is recognized nationally and internationally as a significant contributor of sound design criteria for soil and water conservation structures and channels. Most notable is the pioneer work in the design concepts for vegetated channels.

The HERU conducts experiments and trials to develop criteria for the design and analysis of structures and channels for the conveyance, storage, disposal, and measurement of runoff waters. Also to develop fundamental knowledge of the hydraulics of surface flows for use in planning measures needed to control water for flood prevention, pollution abatement, and assessing the safety of existing measures. Other aspects the lab studies are the ability of vegetation and/or various natural and manufactured materials to prevent erosion when used to manage runoff waters.

Floodwall overtopping is an example of the type of project that the HERU laboratory would investigate. Overtopping is a result of intense storm events that under the right conditions produce runoff that overtops floodwall structures. The process of overtopping can be devastating in several ways. The excess water can flood property that was intended to be protected by the wall, and also the force of the water coming over the wall can scour and deteriorate the materials and foundation of the wall on the downstream side causing failure. In accordance with the mission statement of the HERU laboratory, we will be looking at what materials can be used to reduce this erosion phenomenon called scour.

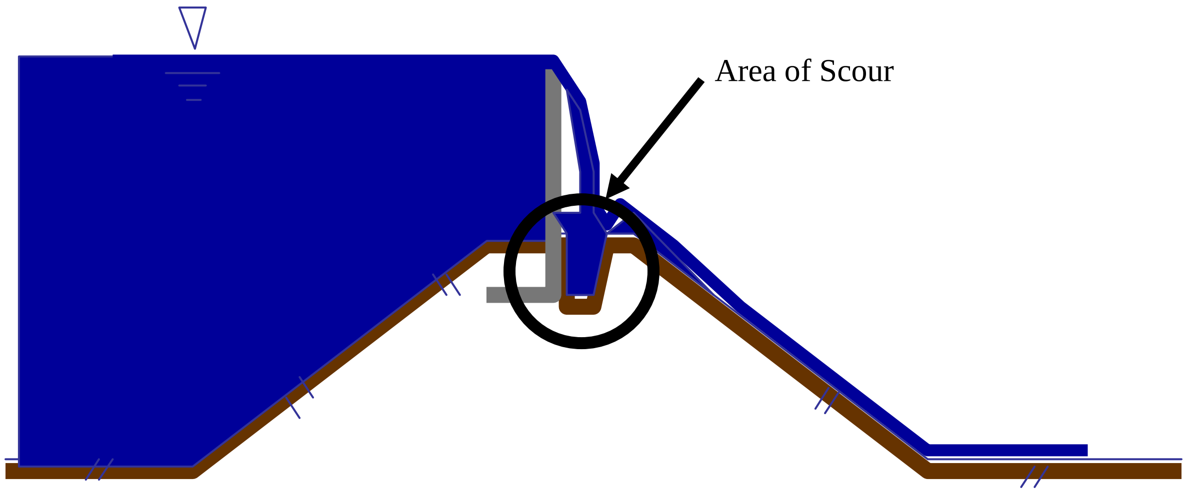


Figure 1. An illustrative example of floodwall scour.

Figure 2. An example of the dangers of floodwall overtopping and scour. (Source: http://hsgac.senate.gov/_files/Katrina/Preliminary_Report.pdf)

Flood wall scour happens when the design recurrence interval is exceeded and the water overtops the structure causing erosion on the opposing side that can undermine and destabilize the structure.

Figure 3. A floodwall scour path along the base of an existing floodwall.

Figure 4. Floodwall scour along the base of an existing floodwall.

Figures 3 and 4 are examples of floodwalls that have experienced scour, however these structures have not sustained extreme damage. Numerous methods have been developed to potentially lessen the risk of destabilization such as geotextiles, sod, concrete, and riprap. Our group will be looking into finding a product that works under certain specified conditions. We will be testing our material in a scaled flume setting in order to determine what product works best. The definition of best is based on a number of factors including performance, economics, ease of construction and design, and availability.

One of the first steps in conducting a scaled flume study is to determine the appropriate size of model, model design, range of discharges, and series of tests to be conducted along with and estimated time-line. Below is an example of a system that we intend on using. With this system we will test scale sizes of gabion and riprap.

Figure 5. An operating flume. (Source: HERU, Stillwater, OK)

Figure 6. Floodwall with rip rap protection. (Source: http:www.uky.edu)

Problem Statement

Floodwalls are designed to provide additional storage and protection against flooding, but when floods exceed the design recurrence interval of the floodwall, waters will overtop the floodwall resulting in a waterfall effect on the downstream side. The resulting downstream impinging flow may cause scour and erosion that can undermine or destabilize the floodwall, potentially resulting in a catastrophic failure. Steps must be taken to reduce or eliminate this scouring and erosion in order to secure the integrity of overtopped floodwalls.

Customer Requirements

The main goal of TDLP Inc. is to successfully design a product in which the team and the sponsor/customer may be proud. The HERU laboratory requires TDLP Inc. to design a system which can be placed downstream of floodwalls to prevent scour and erosion from overtopping. In order to fulfill customer requirements, this new system must be more economic than pure concrete applications currently in use today, and also more stable than natural earthen systems. One condition also required by the customer is that the design be easily applicable in a variety of situations. In other words, a generalized approach for preventing scour from overtopping floodwalls is requested. This design must also have the ability to be directly packaged and sold to customers.

Statement of Work

TDLP Inc. met with the USDA-ARS HERU in September to discuss the logistics of the design problem at hand, and design objectives for a generalized approach for preventing scour and erosion downstream of floodwalls. As seen in the customer requirements section, the HERU laboratory has asked TDLP Inc. to develop a generalized approach with consideration of an optimal ground application that would decrease scour from water overtopping floodwalls, increase ground stability in order to protect the integrity of existing floodwalls, and remain within economic constraints in order to keep the product easily applicable and marketable.

TDLP Inc. will begin this process by investigating the specific issues and problems occurring with overtopping of floodwalls. In order for work to be considered complete for this project, TDLP Inc. is required to generate design concepts, build a model of floodwalls currently in existence using a flume provided by the HERU laboratory, determine experimental procedures for testing these concepts within the flume laboratory, model these concepts, and present concepts for evaluation.

Testing Determination

Before any experimentation is to begin, TDLP Inc. is assigned the task of creating a testing environment similar to actual environments encountered in the field. The main concern is creating a small scale model of a typical floodwall. Parameters involved when creating this design are drop height, overtopping width, flow rate, and flow area. TDLP Inc. has investigated existing floodwalls and the specific designs of those floodwalls, and will construct a model for simulating the floodwall environment. Rip rap sizing for a range of floodwalls is initially set using the following real world parameters which will be converted to model parameters:

Maximum floodwall height: 10 ft
Minimum floodwall height: 2 ft
Maximum overtopping flow: 2 ft
Minimum overtopping flow: 0.25 ft
Maximum rip-rap prototype size: 2 ft

It is understood that floodwall heights, overtopping flow, and rip-rap size could be greater than the designated values for this study. However, the values mentioned above seemed to be reasonable application ranges that could possible prove useful to engineers in the field.

Flow rate for the flume laboratory is discussed in the limitations section of the statement of work. The model is designed with a constant width. It is also designed to allow for variation in drop height and overtopping discharge. The initial plan is to develop a dimensionless approach similar to the approach used by Rice and Kadavy (1991). In their study, they related stable rip-rap size downstream of a straight drop basin to the critical depth of flow at the crest of the basin. An example problem of the developed equations and hydraulic parameters of importance is shown in the section "Initial Floodwall Design Calculations", presented later in this report. TDLP Inc. will work to solve a similar relationship and present our findings to the client for review.

Determination of Material at Scour

Literature reviewed for this design problem focused on studies looking at development of scour holes and size of material present at the hole. TDLP Inc. is asked to propose material(s), conduct tests on the material(s), and report findings for preventing scour or minimizing the size of the scour hole downstream of a floodwall. Bed stabilization is the major response variable under investigation. Possible material or product options recommended for initial study include rip rap of varying sizes, gabions, interlocking blocks, shingled blocks, and soil cement.

Rip rap is one of the more basic materials that could be used for protection downstream of a floodwall, and for that purpose is proposed as the material to be tested in this study. It meets one of the main customer requirements of easy placement and construction. Cost can also be very competitive depending on availability. Design and performance of rip rap is dependent on sizing required to attain a stable surface downstream of the floodwall. Because of the sizing variation, the objective of this study is to determine design criteria for rip rap sizing and placement that would achieve desired performance for application to functioning floodwalls.

Limitations

One limitation presented to TDLP Inc. is directly applied to the testing phase of our design. In nature, flow rates of waters overtopping floodwalls can vary in a wide range of flows. TDLP Inc. is limited in the flow rates allowed to be tested in our flume apparatus to a maximum of 4.21 cfs with an 8 inch orifice plate. Another limitation is flow length downstream of the floodwall. Since the laboratory basin within which tests will be conducted is only approximately 30 ft, downstream conditions will only be known to that length.

Limitations also arise from variation in actual floodwall design from place to place, availability of materials in different regions of the world, and geotechnical properties at individual floodwall sites. The HERU laboratory asked TDLP Inc. to determine specific ranges of protection needed for these varying floodwall conditions. However, there are cases that may fall out of the range being tested. TDLP Inc. is not responsible for developing design for every single possible case. For example, there are real world situations in which the design of the floodwall and the storm event may be in excess of the generalized approach presented by TDLP Inc. For cases such as this, the only solution may be direct application of concrete blocks which are out of the economic range of what TDLP Inc. is assigned to design.

Research & Literature Review

TDLP Inc investigated several methods to reduce flood wall scour. We discovered numerous methods and designs to reduce this process. Several journal articles were evaluated as well as individual market products. We also checked into several patents that are related to floodwall scour. The following are summaries from the articles that we found and the site at which they can be found.

Journal Articles

Michigan Department of Environmental Quality Riprap Guide

Riprap is rock cover used to stabilize stream banks and any other structure which can experience a large amount of erosion. The article is very descriptive in when and where to apply riprap, gives lists of sizes of riprap and their measurements.

The types of stones are discussed as far as what materials should compose them. Calculations are given in determining the depth of riprap, size of riprap, and length of the area. Tips on riprap around outlets are given, many details on designing riprap areas. Specifications for flows, depths of flows, and grades at which the rip rap should be laid. The article is very helpful it was written by the DEQ and provides lots of data and numerous equations to help find needed data (DEQ, 1997).

The Use of Gabion and Reno Mattress in River and Stream Rehabilitation

Gabions come from the Italian word for “Gabbione”, which means “Big cage” (Chayuck, 2005). Gabions have been a popular as well as easy way to secure structures for many years. The first industrial production of these structures began in 1894 in Italy used mesh to retain rocks (Chaycuk, 2005). This practice has continued and with the development of better techniques, their use continues. Gabions are an inexpensive and easy way to retain structures that can be subject to erosion. The article describes how they structures are used and work. Details on the wire and other material used are also given, as well as when to use certain wires and when not to because of the abrasive environment. The standard gabion was described as well as the Reno Mattress which is also very popular because of its construction. The Reno Mattress is more flexible because there are dividers every one meter this allows the structure to be maneuvered easier in changing slope conditions, making this structure great for scour protection and channel linings. The article describes construction of these structures as well as the preparation for them. Hints are given as to which system will better serve an individuals needs as well as designing the structure. Stone dimensions and mesh specifications are also given for the different varieties of gabions. Many images of the structures and installation are also given in the article that can be very helpful in setting up a good site. Even though gabions are simple they can be the best choice in reducing erosion conditions (Chaychuk, 2005).

Sediment Transport Modeling for Stream Channel Scour Below a Dam

In this journal article, Howard H. Chang (2001) investigates stream channel scour in California using sediment transport modeling. Although this study does not conform exactly to the study which is presented to TDLP, Inc., it has some helpful guidance for determining general scour and running various computations.

To determine the general scour, the FLUVIAL-12 model can be employed (Chang, 2001). This model takes a given flood hydrograph and simulates spatial and temporal variations in water-surface elevation, sediment transport and channel geometry. Even though Chang mainly discusses using this model for channel beds, we could investigate this model's application to flow over an embankment or levee. This article also discusses sediment delivery. Although sediment does not seem as it would be a concern in our problem (seeing as how the overtopping water will most likely be very dilute of sediments), sediment transport may be a concern on the side of the levee which shows scour.

Scour Below an Overfall: Part I. Investigation

The journal article entitled "Scour Below an Overfall: Part I. Investigation" (Robinson et al., 2002) is a very interesting article which could provide a lot of insight towards the problem assigned to TDLP, Inc. The authors realize that scour below an overfall contributes to headcut instability and gully advance and perform various tests to investigate factors which could reduce such scour. These tests included thirteen large-scale scour tests of water flowing over a horizontal approach onto compacted soil beds of differing soil moisture and soil density (Robinson et al., 2002).

The study was conducted using a long flume of dimensions 1.8m wide, 2.4m tall, and 29.3m in length (Robinson et al., 2002). Sketches are found in the article which illustrate this flume. Such illustrations could be useful in the construction of a flume for TDLP's problem. The experimental procedure outlined by Robinson et al. (2002), could also be of use as a guidance tool for the specific problem presented to our team. The only differences that may occur would be due to using different materials than just soil as our test subject. This article is full of useful figures and instruction as well as results, but does not cover the full scope of what will be needed in our problem. It will serve mainly as a guidance tool for soil conditions and scour characteristics. Perhaps the main advantage of this article is that two of the authors did this research at the lab which we will be using for our testing and will be at our disposal for further questions and assistance.

Scour Below an Overfall: Part II. Prediction

The journal article "Scour Below an Overfall: Part II. Prediction" (Hanson et al., 2002) provides an extension to its previous journal article "Scour Below an Overfall: Part I. Introduction" (Robinson et al., 2002). The four main objective of this article were to:

> "*(1) utilize a previously developed excess stress parameter approach, with small modifications, for the free overfall jet; (2) develop similar excess stress parameter approaches for the submerged circular jet; (3) determine and compare excess stress parameters for both overfall and submerged circular jet scour test results; and (4) compare erodibility results for each experimental system.*"

All of the above objectives apply to TDLP's design problem. Although the main material of testing in this set of experiments was soil, TDLP can apply the concepts to the materials which we test. Excess shear stress concepts are also discussed and equations for computation are given. Hanson et al. (2002), also gives a comprehensive look into planar and submerged circular jets, and the extensive calculations used to define each. This article will give TDLP the knowledge to begin experimental setup and test procedures on the materials of our choice.

Velocity Field Measurements at an Overfall

One journal article which could prove to be beneficial to TDLP, Inc., as we begin our research into scour from an overfall is the article "Velocity Field Measurements at an Overfall" (Robinson et al., 2000). This article measures and characterizes the velocities and circulation patterns for flows in the vicinity of an aerated straight drop overfall, as is the condition of our design problem. Useful parameters tested by Robinson et al. (2000) are velocity vectors for multiple tail water levels at constant flow rates, and velocity vectors for multiple flow rates at constant tail water levels. A definite procedure for measuring these velocities is given and results are clearly outlined. With guidance from the procedures tested within this article, our team has a clear view of operations which might take place during our experimental testing. This article also gives insight to related work which could be functional for our team. Further investigation into the works referenced within this article may prove to be worthwhile.

Erosion of Fractured Materials

This journal discusses the natural fracture patterns that exist with in soil and rocks and how these fractures effect erosion. The objectives of the study were to investigate the dominant parameters that cause failure of a fractured block matrix. The study used matrix of blocks downstream of an overfall. They increased the discharge of water over overfall until the matrix failed. The block matrix failed due to the forces transmitted by the flow of water. The block size, block orientation, and overfall height were varied systematically over a range of flow rates. From the study the authors were able to describe a few of the parameters. Failure discharge was observed to decrease as the overfall height increased. The failure discharge was also observed to increase if the block was placed with its long axis oriented vertically. The orientation of the each block to where the weight was over a smaller area, thus requiring an increased pressure to dislodge the block. The article gives fundamental research information we need on scour holes formed in soil and rocks.

Lessons Learned using Laboratory JET Method to Measure Soil Erodibility of Compacted Soils

The article discusses a study cover the reason for accidents and failures of embankments for dams, lagoons, and levees. A key parameter that was focused on was the likelihood of the soil materials used in the building of the structures to erode. Soils are generally compacted to a certain specifications when being used for these structures. The jet erosion test (JET) was developed to study the erosion characteristics of soils. The laboratory version was used in the study to define the likelihood of compacted soils to erode. This article is good for project because it gives us a way to describe the erosion properties of compacted soils as well as the benefits of compacted soils. Also the JET is a good way for us to simulate the water overtopping the flood walls.

Plant Root Effects on Soil Erodibility, Splash Detachment, Soil Strength, and Aggregate Stability

This article covers a studied that tested in a laboratory the influence of dead roots on soil erodibility, splash detachment, and aggregate stability. The study used a rainfall simulator on a Mexico silt loam. The study found the difference in erosion and splash detachment when the type of cover was changed by type and amount. This article is helpful to use in that it gives us some insight on the type of covers and amount that are needed to significantly change erosion. However the study was only tested with rainfall so we will have to take in consideration the difference in the amount of water.

Physical Modeling of Overtopping Erosion and Breach Formation of Cohesive Embankments

This article discuses the processes and timing of dam embankment breach caused by flooding. The purpose of this study is to: (1) establish a better understanding of the erosion process of overtopped cohesive embankments, and (2) provide detailed data for future numerical model development, validation, calibration, and testing. The USDA-ARS has conducted 7 large scale tests with three different soils tested. The rate of the processes involved was observed to vary by several orders of magnitude and was dependent on the soil material properties. The study is good for our because of the modeling that is discussed in it.

Patents

Erosion control rolls

The patent number of this invention is 6,641,335. It was filed on January 7, 2000 with a current U.S. class number of 405/302.6. The reason for this invention was to control sediment and debris flow associated with soil erosion (Allard, 2000). These rolls are typically composed of fibrous materials such as straw or shredded wood and are held together with netting. These rolls are placed across a slope during construction to try and stop soil erosion and to dam as much as possible. They also direct and/or filter fluid flow as the fluid runs down the slope. Fiber rolls are more capable than silt fences because the silt fences collapse under heavy fluid flow and high winds. The construction of this patent consists of an open end, a second end, an interior space, and one more openings in the wall surrounding the interior space with the exterior of the core member (Allard, 2000). One or both ends of the core contain couplers or connectors for connecting multiple core members together (Allard, 2000). The exterior of the core member, which is a fiber roll, can be made of straw or shredded wood. Surrounding this is a porous covering material such as a woven cloth or netting (Allard, 2000). With this design an infinite amount of core members can be attached together depending on the size of the project (Allard, 2000).

Reinforced interlocking retention panels

The patent number of this invention is 6,851,889. It was filed on April 23, 2003 with a current U.S. class number of 405/32. The reason for this invention is for the prevention and/or elimination of scour beneath marine structures (Buchanan, 2003). The most common methods for preventing scour are the placement of rock protection or constructing a bulkhead (Buchanan, 2003). These methods may be efficient but will also have some disadvantages. This invention uses multiple interlocking panels to cover the area that is scoured. The panels are composed of resin impregnated carbon sheets on each side of fiberglass sheets (Buchanan, 2003). The thicker the carbon fiber is the stronger the sheets will be. Each panel that is used has a high-density polyethylene interlocks on each edge to allow each panel to slide together. The panels can be cut to a certain dimension to allow for a custom fit for each job (Buchanan, 2003).

Earth dam protective coverings

The patent number for this invention is 4,184,786. It was filed on March 6, 1978 with a current U.S. class number of 405/108. The reason for this invention is to protect earth dams from failure caused by overflow or internal erosion (Richards, 1978). This invention has a barrier that is placed below the dam and anchored down to prevent scouring. The barrier is made up of a flexible plastic sheet, or a combination of plastic sheets, capable of functioning as a water-tight barrier between the ground below the dam and the flowing water (Richards, 1978). Each section is anchored down with the embankment itself or with rock material

(Richards, 1978). The plastic material is relatively inexpensive, easily obtainable, and quickly laid out and anchored down. This protective covering should provide protection from scouring for years (Richards, 1978). If it should happen to become damaged it can easily be fixed or replaced.

Hydraulic energy dissipating offset stepped spillway and methods of constructing using the same

The patent number for this invention is 6,059,490. It was filed on May 5, 1998 with a current U.S. number of 405/108. The reason for this invention is to prevent scouring from happening below a dam which would eventually cause the dam to fail. When the dam fails the area downstream of the dam will be flooded. The material used to prevent scouring is made of concrete blocks. Each block is dimensioned and shaped so that water cascading down the steps is caused to flow in three dimensions. The three dimensional flow generates turbulence which dissipates the kinetic energy of the water (Kauppi, 1998). The blocks are arranged in rows then stacked on top of each other in a shingle like overlap (Kauppi, 1998). Each stacked row is offset laterally from the row below to try and prevent water penetrating through each level of the blocks. The bottom row is placed on top of the toe plates to prevent the bottom layer from shifting (Kauppi, 1998). The blocks are stacked and staggered until the desired height of the spillway and embankment is obtained (Kauppi, 1998). The stepping up of the blocks will help dissipate the kinetic energy of the falling water preventing scouring of the soil below the dam. This in return will keep the dam from failing and causing massive flooding downstream.

Hydraulic Energy dissipating offset stepped spillway

One very interesting patent that was found in our search involved a design for dissipating the kinetic energy of water flowing over the top of a spillway embankment (Kauppi, 2000). Even though this patent does not directly apply to the problem proposed by Dr. Hanson of the USDA ARS HERU, some of the concepts behind the design could be useful in guiding our team in the right direction. In this patent, Kauppi (2000) proposes that to build a spillway "comprising of a plurality of building blocks arranged in rows which are stacked upon each other in a shingle-like overlap such that … a series of steps are defined thereby" to generate enough turbulence within the water to dissipate kinetic energy. Although this patent offers one design detail which would assist the problem presented to TDLP, Inc., it also has some shortcomings. One claim of Kauppi (2000) is that the blocks used in the design must be fabricated from concrete. This is one material which will be avoided in our design due to the economics of the problem. In the background information of the patent, it does discuss a few interesting alternatives to scour. A few of these alternatives include riprap, geotextiles, and baffle apron drops. However, the most interesting alternative mentioned is gabions (wire baskets filled with rock which are anchored to the ground). Problems with gabions include deformation under certain flow conditions. This could be a possibility for future testing.

Market Research:

Aromorflex® Brochure

Armorflex is a product designed by Armortec™ . Armorflex is a flexible interlocking of concrete blocks which are interlocked by cables. They blocks are organized in a mat like fashion and placed on a prepared site on top of a permeable mesh. The driving force for this product is its available porosity, flexibility, and the fact that this product encourages habitat development and vegetation. The product is aesthetically pleasing and comes in a wide variety of sizes that make it easily used in all applications. This system is marketed as a articulated concrete block or ACB (Armortec, 2006).

Figure 7. **Aromorflex®** interlocking concrete.

Armorflex® Revetment System Specification for Overtopping Applications

This article was regarding the production of the blocks themselves and also the applications they can be used for. The article gave sizes of blocks and material composition. Standards for block inspection were also given and grounds on rejection. Information was also provided on the cables and which types of cables could be used and the diameter and strength of these cables. A detailed profile on site preparation and mesh specifications was also given. Sizing blocks for your particular application and finishing of the site location were given. The article was very beneficial from taking you from a start to finish in what all must be done in order to make a structure which can stand a dam overtopping. Equations and resources to find additional information on velocities of dam overtopping were also given (Armortec, 2006).

Armorflex® Cellular Concrete Mat Specification for Erosion Control for Wave Attack

This article pertained more to protecting a flood wall from the opposing side rather than the overtop side. This information could still prove to be beneficial when considering maintaining the stability of the entire structure. This article gave information on the different types of waves to expect and sizing blocks for those applications. This article had information on site preparation, inspection, and a start to finish layout on how the setup would done. Material makeup of the blocks was provided as well as the makeup of the cables. Cable strengths and the application in which different sized cables were needed were also provided (Armortec, 2006).

A-Jacks® Brochure

A-Jacks® are another product by Aromortech, they differ from the articulated concrete block in that they look like a heavy duty concrete star or jack. They are designed to interlock and form a wall or structure that is rigid but yet highly permeable. They are popular in reducing bridge scour and stream bank erosion. They can be left with the voids to allow for marine habitat or can be back filled for plant life. These structures allow vegetation to be established by anchoring the vegetation down till it gets a strong start like trees and shrubs (Armortec, 2006).

Figure 8. **A-Jacks®** material.

Erosion Control Blanket Products Brochure

Erosion Control Blankets or ECBs are normally a short time fix to erosion problems. However, with better geo-textiles, the fabric will last much longer and help establish natural vegetation and help anchor that vegetation in. These mesh blankets are cheaper then the concrete and easier to apply. They can also help give a more natural look and are a quick fix to the problem. They are not quite as sturdy as the concrete but they can still be a good solution. The company Erosion Control Blanket out of Manitoba Canada markets several of these blankets from a short term blanket to a permanent blanket (ECBP, 2007).

Soil Erosion Control Mulches, Blankets and Mats

The article discusses several applications of erosion control blankets and turf-reinforcement mats (TRMs). The article regards the selection and installation process of theses erosion control methods. Several of the advantages that were given were protecting soil surface during and after land alteration activities. Others were raindrop impact and overflow protection. However, many other additional benefits were given as well as limitations to the blankets. Information that was also provided was design requirements and materials used.

A time table of the material life was provided and sketches of the installation. Overall the article is very helpful in the use and application of erosion control blankets.

LandLok® Supergro® Erosion Control Blankets Brochure

Propex, a geosynthetic company also makes erosion control blankets. They make blankets that are quickly biodegradable as well as some blankets that have a life span of three plus years. The fact that they are short term may not be beneficial but they could enable a good stand of vegetation to get in place. Also incorporating these textiles with other methods could prove successful. The article gave many examples of applications the fabric was used on. As well as installation facts and benefits, this fabric is very affective on steeper slopes and holds soil particles very well. The article gives the materials used in the nets such as straw, polypropylene, and even coconut. Several sizes are given as well as shear stresses and velocities that these fabrics can with stand (Propex, 2006).

Figure 9. LandLok® Supergro® Erosion Control Blankets

Kiciman Gabion Baskets, Mattresses, Sacks, Netting, and Razor Barbed Tape

Kiciman is a leading producer of Gabion structures. Gabions are rocks netted together using high strength wire. Kiciman sells several different structures and in their brochure they list these types as well as the sizes. Gabions are designed based on the customer's needs they can be very large, small, long, wide, and the wires can differ to as well as rock sizes. These structures have many advantages they are flexible, strong, durable, and very economical. Also, from a management prospective, they are easy to maintain. The article provides many details on the wire used and the sizes of the rocks however the size needed for certain applications was not given in the article. However, with other information size could be determined.

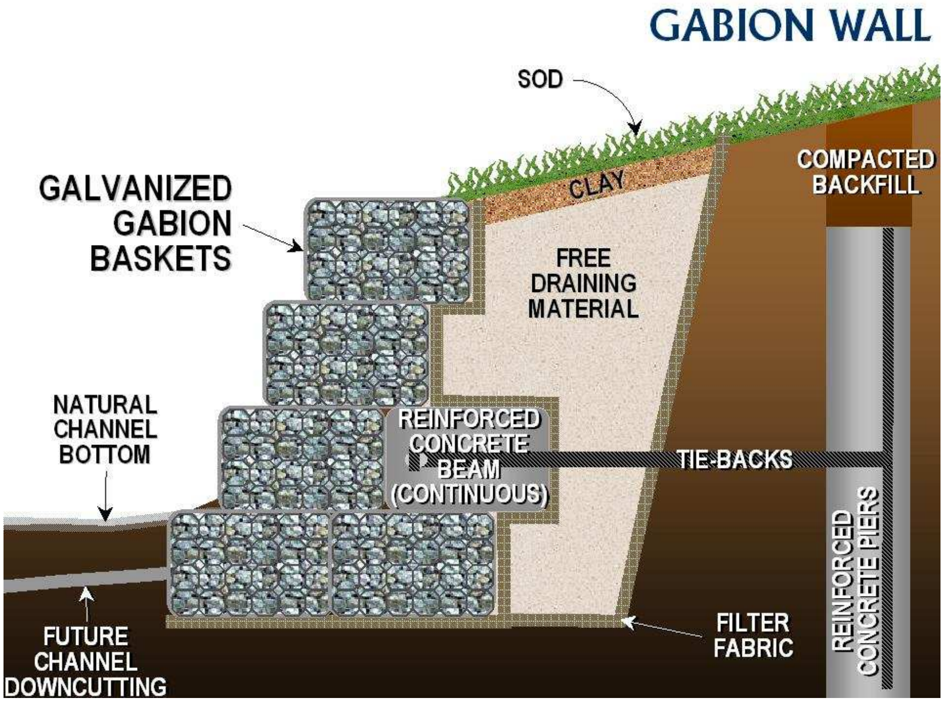


Figure 10. Example of Gabion initialization

<u>Introduction to Commonly Used Terms</u>

Knowledge of the following terms is required to understand equations and results of this project.

- Unit Discharge (q) – Rate of fluid flow per unit width of floodwall
- Critical Depth (dc) – The depth of water flowing in an open channel or conduit, partially filled, corresponding to one of the recognized critical velocities.
- Drop Height (h) – Height from top of rip rap surface to top of floodwall
- Flow Rate (Q) – Rate of fluid flow
- Flume Width (b) – Total width of model flume at floodwall
- Gravity (g) – Force due to the gravitational pull of the Earth
- Head (H) – Total height of water from ground level
- Length to Impact (L) – Distance from floodwall to impact point
- Rip Rap Bed Length (Ls) – Length of rip rap downstream from floodwall
- Rip Rap Nominal Diameter (D_{50}) – Average diameter of a set of rip rap

Floodwall Design Calculations

Flow Rate:

$$Q = CH^{3/2}$$

C is a constant taken from the calibration chart in Figure 21.

Flow Rate per Unit Length:

$$q = \frac{Q}{b}$$

Critical Depth:

$$d_c = \frac{q}{\left(g^{1/2}\right)^{3/2}}$$

Length of Riprap Bed:

$$L_s = 5 \times d_c$$ (Rice and Kadavy, 1991)

Design and Setup of Experimental Flume

The number of tests and variations that could be tested is nearly infinite therefore the research team had to limit the number of variations that would be tested. The USDA Hydraulics lab presented us with two possible test setups. The first setup was to find rock sizes that were stable at predetermined flow conditions. Two drop heights and three flows would be used, then the group would simply have to determine what size of riprap would withstand these flow and drop conditions. This would result in 6 variations and a minimum of three rip sizes to be tested with at least 18 tests being run. Riprap size would play as the variable in this experiment. The second setup was to establish drop height and riprap size and test which flows each individual riprap size could withstand. This would result in test 2 drop heights and 4 riprap sizes; a third median drop height would be used as verification for the test. Flow was the variable in this setup, TDLP chose this setup because flow was easier to control than rock size and was also quicker from a test setup to alter. The figure shown below is an example of the experimental setup that was developed from the second suggested test setup.

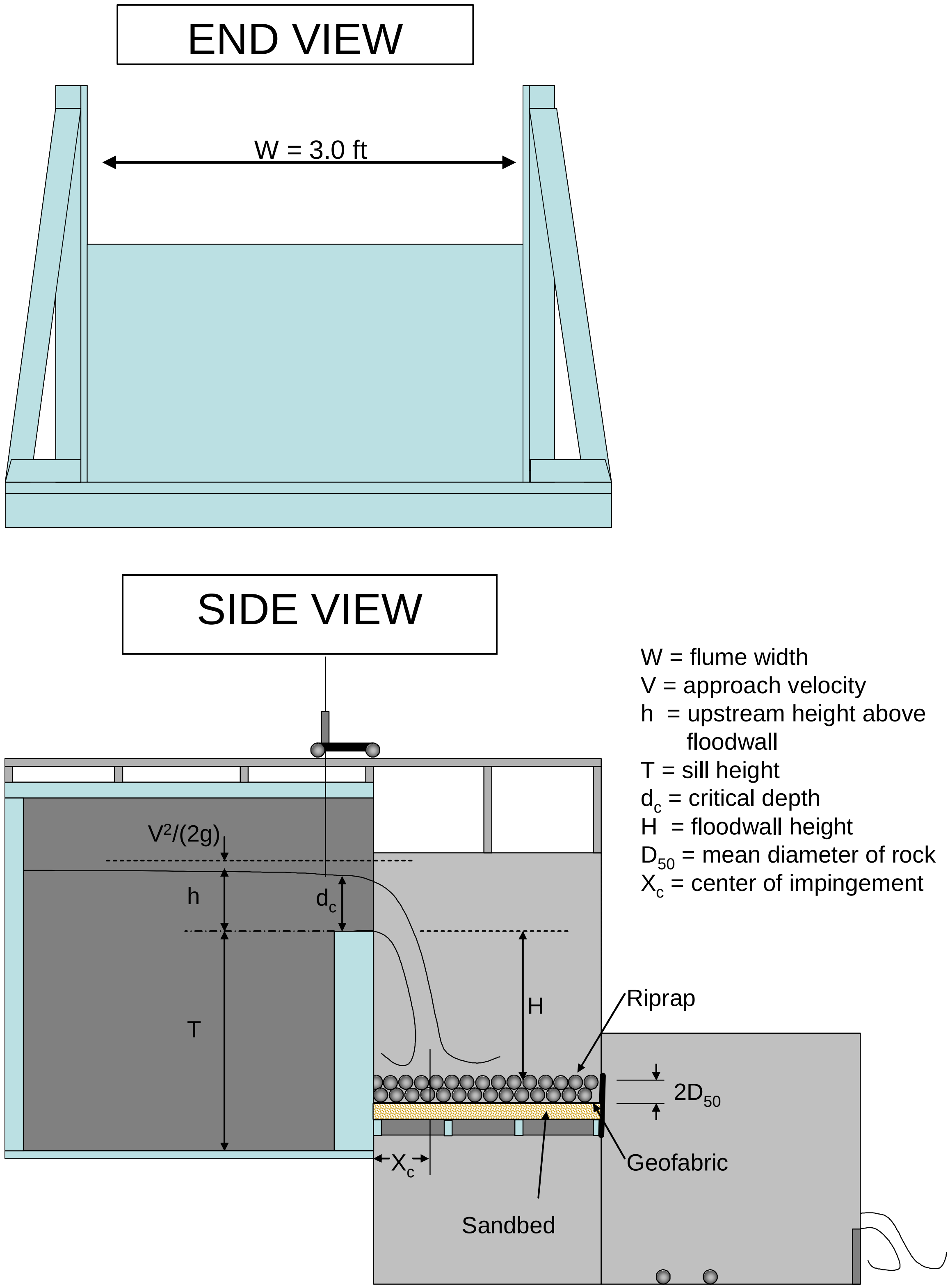


Figure 11. Test setup presented by Dr. Greg Hanson.

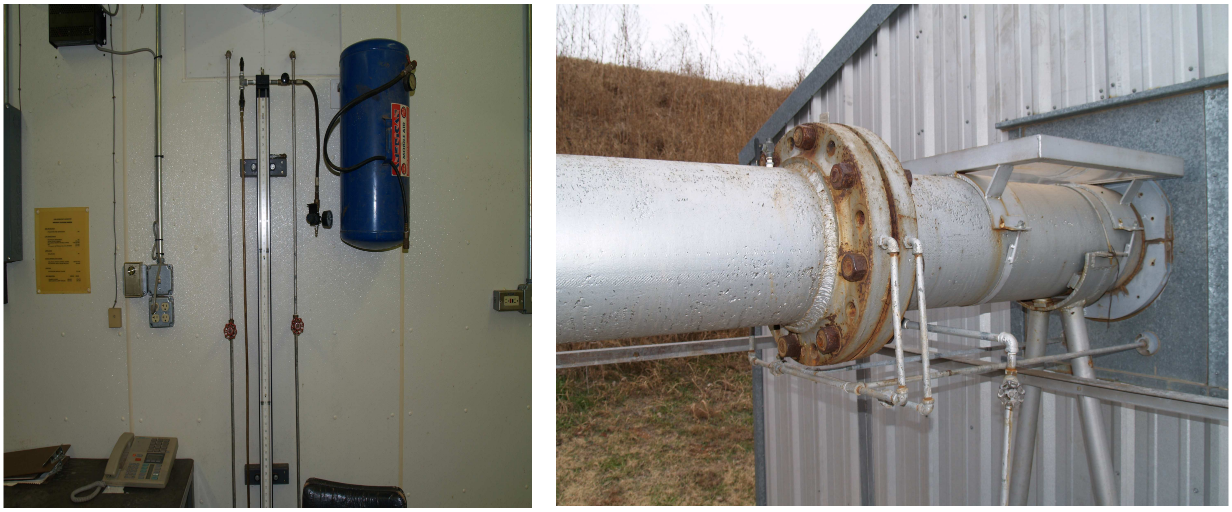
The following information explains structures already existing and our test set up.

Existing Structures

The USDA HERU provided an experimental laboratory in which TDLP Inc. conducted its tests. The laboratory building and all incoming pipes are not insolated; therefore, experiments could only be run whenever the ambient temperature was expected to remain above freezing. The floor of the lab included a walking/observation area and a basin with 2.5 foot high walls that run 40 feet the length of the laboratory. Inside this basin was the structure to support the flume. Large, 12 inch diameter pipes ran into a large storage tank which made the flow consistent. The frame was not sloped which matched the design of real world floodwalls. Its dimensions were 16 feet long, 4 feet wide, and 5 feet tall.
These structures can be seen in Figure 12. The basin/floor slanted towards a drain so that when water reaches the floor it will flow towards the drain and out of the lab.

Figure 12. Pre-existing flume support structure and drainage basin.

The water for the laboratory was siphoned directly from Lake Carl Blackwell. Flow within the transfer pipes was measured using a manometer shown in Figure 13. Flow inside the flume was regulated with the use of orifice plates of varying sizes. This manometer was located on the south wall of the laboratory and the orifice plate slot was located just opposite of the manometer outside of the building.



(a) (b)

Figure 13. (a) Manometer used in testing procedures. (b) Orifice plate slot located just outside flume laboratory.

Flume

The flume was built out of wood. Its dimensions were 3 feet wide, 2 feet deep, and 16 feet long. Wood was the building material of choice because was easy to work with and inexpensive. The width and length of the flume were determined simply by the dimensions of the framing that was available at the lab. The depth was chosen so that we could achieve all of the critical depths over our floodwall with out overfilling the flume. At the end of the flume there was a one foot high wall representing the flood wall or weir. The weir that was chosen was classified as a sharp crested weir. This was done to ensure that highly accurate discharge measurements could be obtained. Figure 14 gives a view of the complete flume. A detailed drawing is available in Appendix B.

Figure 14. Model flume used in testing.

Rock Box

The Rock Box housed the actual experiment and its cad drawing is in Appendix B. Its dimensions were 3 feet wide, 4 feet deep, and 8 foot long. A view of the completed box is shown in Figure 15. The width was again based on the existing framing. The depth was based from on platform which was placed below the rock box to control drop height. The length was chosen to be 8 feet in order to give the rip rap length to move or be pushed down the direction of flow and to direct the overtopping water towards the drain. For example, when overflow from the flume hits the rip rap bed, the rip rap placed in the rock box has a possibility of moving and we wanted to be able to watch this happen. We had to see if displacement would take place, so there had to be enough room for this to occur without falling off of the rock box into the drainage basin. One side of the rock box is made out of plywood while the front and the other side is made out of ¾ inch Plexiglas so that we can observe what is happening inside the rock box.

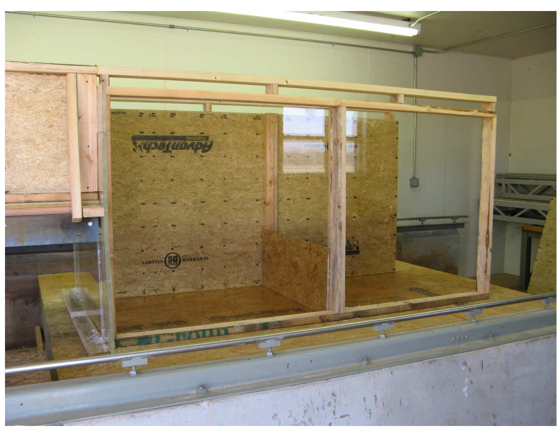


Figure 15. Completed rock box used for housing experimental materials.

Platform

The Rock Box was set on top of a platform. The platform had to be large enough to build the rock box on top of it and to allow enough area for us to walk around and observe what is happening within rock box. The platform also had to be strong enough to support the weight of the sand and rocks. In order to accomplish these tasks, the platform was built with two layers of 2x12 boards set at 90 degrees from one another. The dimensions of the platform are 10 feet wide, 2 feet high, and 10 feet long. Figure 16 shows a view of the completed platform. The drawing for the platform can be seen in Appendix B.

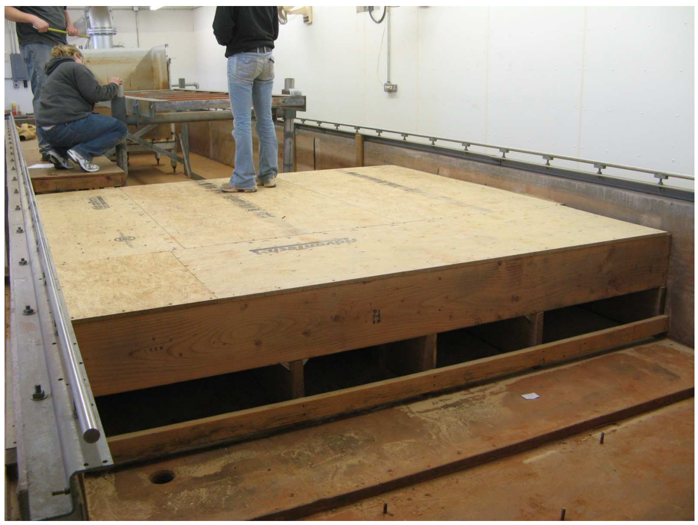


Figure 16. Completed platform.

Experimental Design

TDLP Inc. prepared a proposed experimental design plan for which to test the reactions and stability of all test materials. Steps involved in the experimental design of the project included calibration of the flume, establishing experimental set-up, and creating a procedure for testing of the experimental materials in the flume.

Calibration of the Flume

The initial step in flume calibration was to set up measuring equipment, in order to guarantee levelness of the point gage.

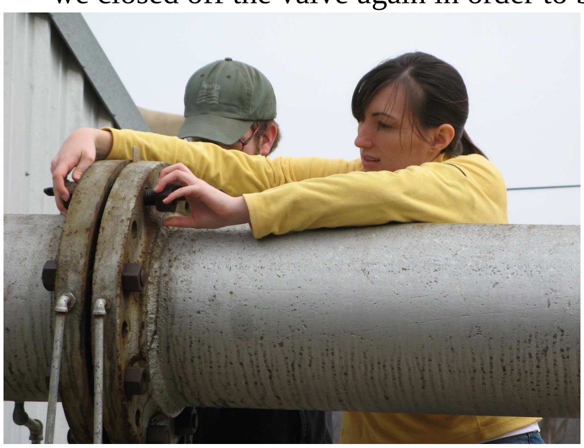
Figure 17. Railing being installed. Bolts were used to level railing.

In order to make sure that the point gage was within a thousandth on a foot, we first had to make sure that the railing that the point gage was on was level through out the length of our testing area, which was both upstream and downstream of the floodwall, as in Figure 17. A carpenter's level was initially used to make the railing as accurate as possible. The carpenter's level measured within 1/16 of an foot. The next step in leveling the point gage railings was to use surveying equipment for a larger degree of accuracy. Actual surveying of the point gage railing is shown in Figure 18. With aid of surveying equipment, the point gage was leveled within a thousandth of a foot tolerance.

Figure 18. Surveying equipment being used to ensure levelness of point gage within 1/1000 of a foot.

The next step in calibration was to run water using all orifice plates. Orifice plates used ranged from a 1.5" diameter orifice plate up to an 8" diameter plate. In order to calibrate all orifice plates to the flume, plates had to be switched in and out of the orifice plate slot and pipes had to be primed. Figure 19 shows the removal of orifice plates between calibration trials. The following explains the procedure of priming the manometers:

1. After the orifice plate was put into place, the main valve could be turned and water could then travel toward the lab. All valves along the way were opened in order to expel any air that was in the line.
2. Lines were opened in order to insure that the air in the line did not cause pressure differences that would then in turn cause errors in the manometer readings. As the water traveled thru the pipe all air was expelled.
3. After all open values had water flowing out of them with no air being expelled, the values were closed, and priming of the manometers could be completed.
4. An air tank with 60 psi was used to push air into the manometer. The valves from the air tank were turned on and the air pushed the water down, so that the meniscus from the air was at the zero point on the manometer. The manometer and air tank are shown in Figure 20.
5. Once air was pushed into manometer tubes it was essential to make sure that the meniscus was equal on each side.
6. After the manometer stabilized, we were able to open the main valve to allow water into our storage basin. Once the basin and the flume were completely full of water, we closed off the valve again in order to begin our testing.



(a)

(b)

Figure 19. (a) Orifice plate being changed, bolts had to be removed first to allow plate to slide out. (b) Orifice plate being removed, pry bar was used to help slide orifice plate in and out.

Figure 20. Manometer and air tank.

A point gauge as seen in Figure 21 was used to measure the head on the flow of water relative to the top of the floodwall at our zero location five feet upstream in order to determine critical depth. Flow was increased in increments of ten inch manometer differential. Once values were taken for each flow, the orifice plates were changed and the entire process was completed for each orifice plate.

Figure 21. Point gauge at zero location, when flow was stabilized.

After all the flow measurements were taken the data was used to create a calibration curve. Figure 22 shows the calculated calibration curve from data collected. This calibration is valid for the sharp crested weir used in the model flume. The calibration curve was used during testing in order to prevent manometer error. This calibration returns a flow rate for each head measured at station 49 in the flume.

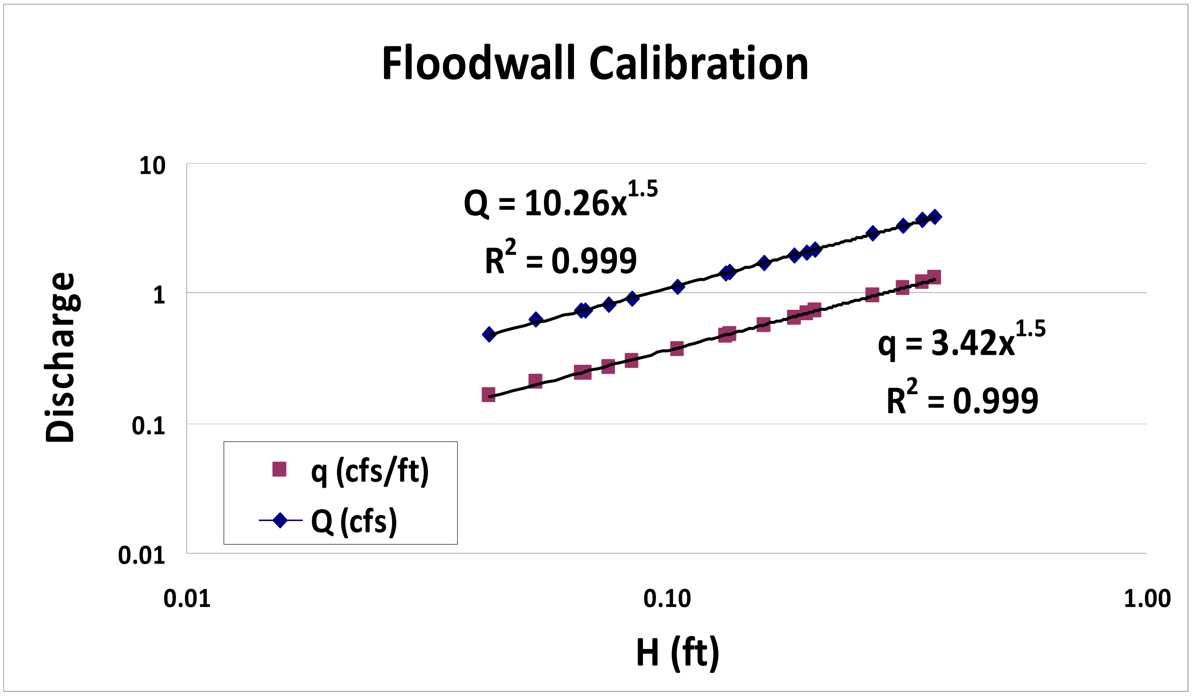


Figure 22. Calibration curves for q and Q over the model floodwall.

Experimental Set-up

The main goal of this design problem was to determine the minimum rip rap size which would create a stable bed, at the same time preventing scour for a broad range of storm events. In order to test this range, TDLP Inc. chose two drop heights (2' and 0.5') to focus on and four rip rap sizes (0.05', 0.11', 0.17', and 0.29'). Sand was used in order to raise bed depth to change the drop height with out altering the height of the flume, while geo fabric was used to prevent the sand from being washed away. Sand, geofabric, and one rip rap size of the four were placed inside the experimental container for each drop height. For each rip rap size, a depth of twice the diameter of the rip rap ($2D_{50}$) was allowed with the sand and geofabric underneath. The thickness of the riprap was held constant with respect to the riprap size, this was done by using a bed depth of 2 D_{50}. In order to ensure the levels of each material, 2 x 4's were screwed inside the container walls such that the top of the 2 x 4's were equal to the elevation of the top of the sand. Figure 23 illustrates this set-up. Once sand was filled to this level, geofabric was placed over the sand and stapled into the 2 x 4's attached to the container walls. A depth of $2D_{50}$ for each rip rap was placed on top of the geofabric to make a total depth up to the desired drop height.

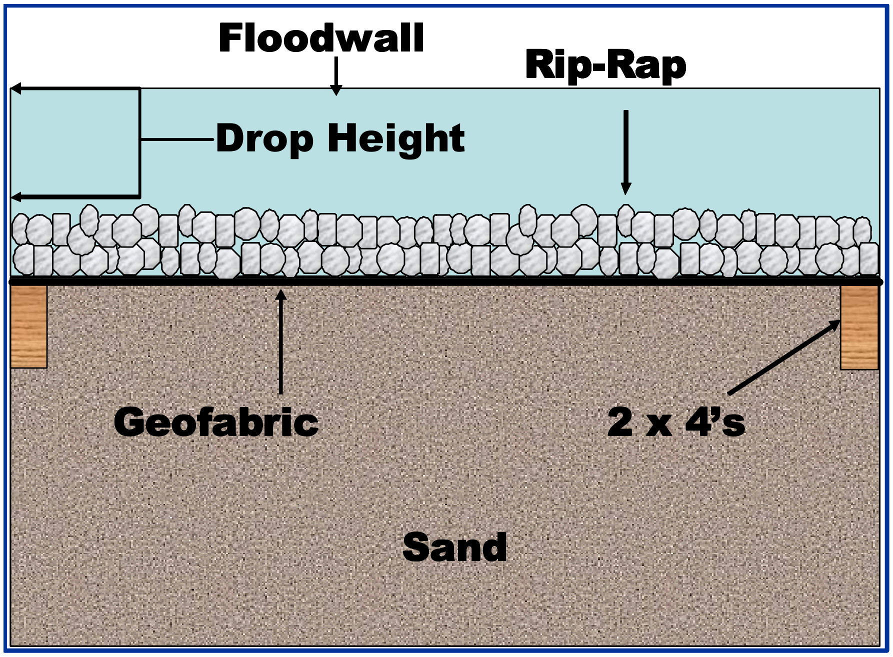


Figure 23. Set-up for sand, geofabric, and rip rap placement.

Testing Procedure

After calibrations were finished and set-up for the experimental container was completed, testing of different materials began. The following procedure was performed for each variation of drop heights and rip rap sizes:

1. Initiate discharge at a level that does not disrupt the rip rap (i.e. rip rap is stable).
2. Read and record point gage water elevation at station 49 and record discharge based on the head in the reservoir. This can be done using the equation for Q (cfs) from the calibration curve in Figure 18. Record the centerline water surface profile. Add notes indicating observations of rip rap movement. Run each flow setting a minimum of ten minutes for stable rip rap and fifteen minutes for minor movement of rip rap to failure. This was the time the group chose to allow enough time to document all changes in the bed conditions.

3. Increase flow in increments of nominal critical depth. Repeat step 2. End test run when geofabric has been exposed to the impinging jet.
4. Once this series of tests has been completed, turn off flow and record scour information through photographs and measurements.
5. Repeat steps 1-3 of the experimental set-up and steps 1-7 of the testing procedures until all rip rap sizes have been tested for the desired drop heights.
6. Once all rip rap sizes have been tested for the desired drop height, repeat the entire procedure for the next drop height.
7. Conduct steps 1-6 on a third drop height (1’) for verification of data.

For this procedure, flow and critical depth were determined for all data measured. Manometer readings and centerline water surface profiles were taken for each run unless a water surface profile for that specific flow rate and drop height had already been recorded. These profiles were taken across the entire range of flows to help specify the required rip rap placement downstream of the floodwall. After testing was completed, flow and critical depth considered stable, minor movement, and unstable (failure) beds for each drop height and rip rap size were graphed and analyzed from collected data, as can be seen in the results section.

All point gage measurement to determine the head upstream of the floodwall were taken at station 49. Station 49 is a location approximately 5’ upstream of the downstream edge of the floodwall. During step 4 of this procedure, rip rap movement was recorded quantitatively, through measurements before and after testing of placement of rip rap, and qualitatively, by taking a series of photographs for visual documentation of movement. These techniques gave TDLP Inc. a visual and analytical representation of rip rap movement and scour evolution.

Failure was defined by penetration depth of scour and displacement of rip rap. For any diameter of rip rap, scour was not allowed to penetrate a depth of $2D_{50}$ which would expose the geofabric underneath. If this occurred, it was concluded that soil underneath the bed would be disturbed in a real world situation.

Results and Discussion

Determination of Bed Scour

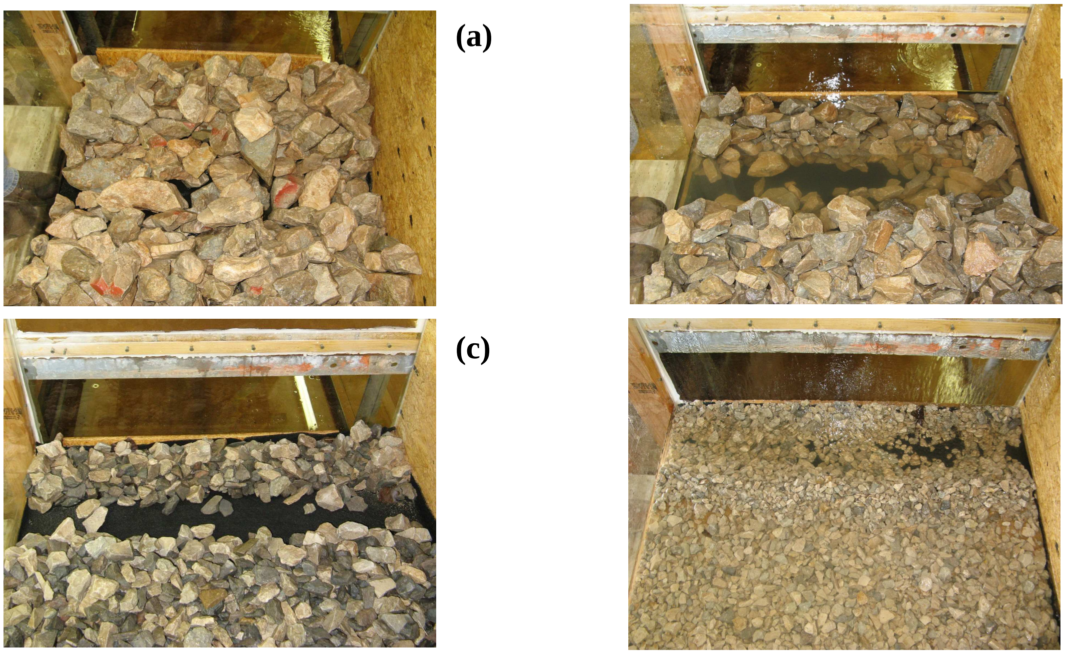
The first parameter being tested for during this project was bed scour. Determination of bed scour was taken from visual observations during testing. Actual observations can be found in Appendix C under the experimental testing data sheets section. Table 1 highlights values for flow rate and critical depth at the failure point for each variation of drop heights and rip rap diameter. For those variations that did not fail, maximum flow rate and critical depth are recorded. It can be noted from the table that data for the verification drop height of 1 ft falls in between the 2 ft and 0.5 ft drop heights. This was hypothesized to occur before testing began. The increase in flow rate required for failure can be accredited to decreasing energy of the impinging jet as drop height decreased.

Table 1. Failure/maximum flow data for all variations of drop height and rip rap diameter.

Drop Height (ft)	D50 (ft)	Failure	Flow Rate (cfs)	Critical Depth (ft)
2	0.29	YES	2.63	0.29
	0.17	YES	1.45	0.19
	0.11	YES	0.65	0.11
	0.05	YES	0.18	0.05
1	0.29	NO	3.86	0.37
	0.17	YES	2.24	0.26
	0.11	YES	0.65	0.11
	0.05	YES	0.16	0.045
0.5	0.29	NO	4.51	0.41
	0.17	NO	3.77	0.37
	0.11	YES	2.10	0.25
	0.05	YES	0.31	0.07

Tests showed that all rip rap diameters failed at a drop height of 2 ft and maximum flow of 2.63 cfs. At a drop height of 1 ft, all rip rap diameters failed with the exception of 0.29 ft. The maximum flow for failure of all smaller diameters was 2.24 ft. In conjunction with the 2 and 1 ft drop heights, maximum flow for failure at the 0.5 ft drop height occurred at 2.10 ft.

The following figures show qualitatively the effects of the impinging jet on bed scour. Figure 24 shows scour bed for all rip rap diameters at a 2 ft drop height. In Figure 24(a), exposure of geofabric is less evident than other rip rap diameters. This is due to larger pore spaces in this D_{50} having the tendency to confuse exposure points with excessive pore space.



(a) **(b)** **(c)** **(d)**

Figure 24. Qualitative data from scour tests at a 2 ft drop height for (a) D_{50} = 0.29 ft, (b) D_{50} = 0.17 ft, (c) D_{50} = 0.11 ft, and (d) D_{50} = 0.05 ft.

Figure 25 illustrates scour imprints for beds experiencing failure and final rip rap placement for beds not experiencing failure.

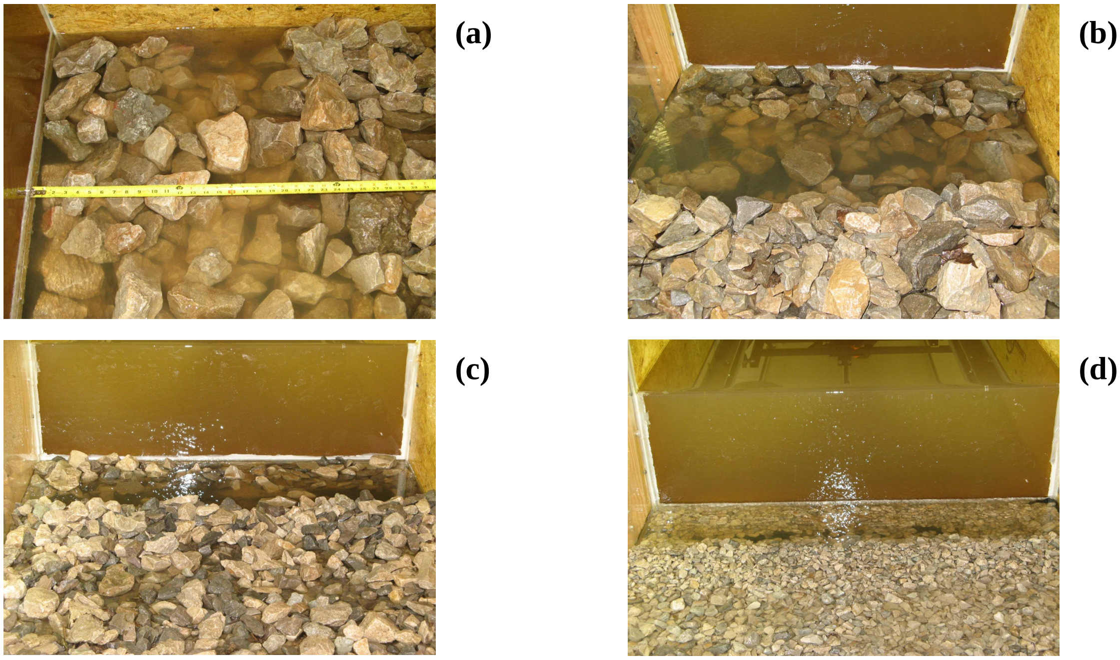


Figure 25. Qualitative data from scour tests at a 1 ft drop height for (a) D_{50} = 0.29 ft, (b) D_{50} = 0.17 ft, (c) D_{50} = 0.11 ft, and (d) D_{50} = 0.05 ft.

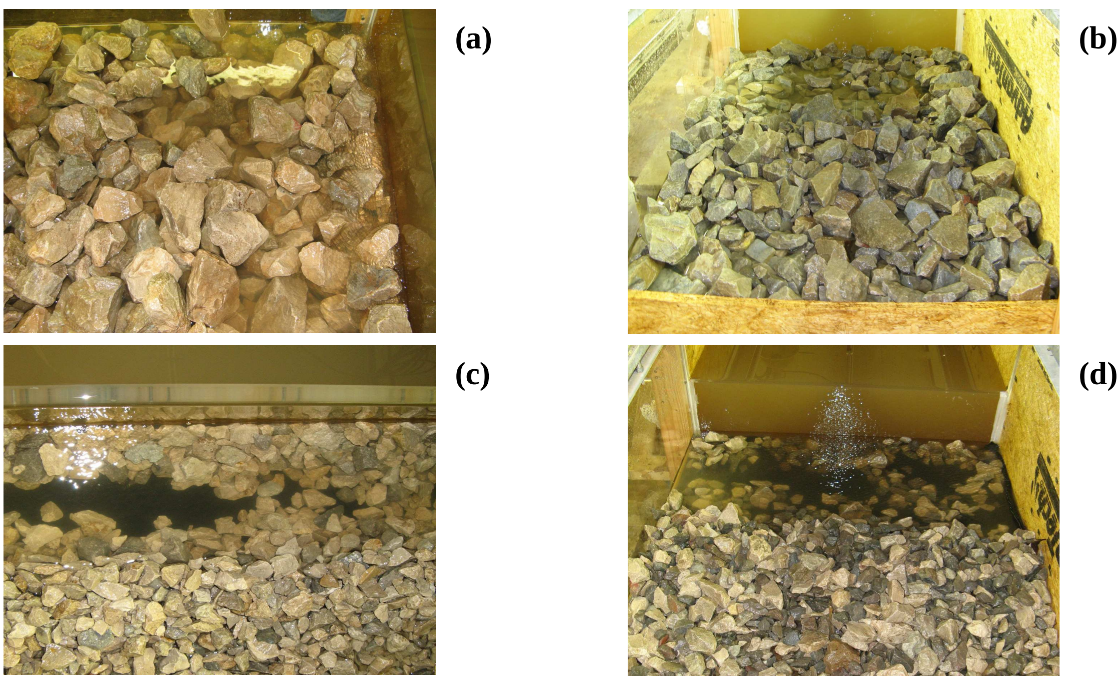


Figure 26. Qualitative data from scour tests at a 0.5 ft drop height for (a) D_{50} = 0.29 ft, (b) D_{50} = 0.17 ft, (c) D_{50} = 0.11 ft, and (d) D_{50} = 0.05 ft.

Figure 26 shows final placement of rip rap after failure/maximum flow for all rip rap diameters at a 0.5 ft drop height. During testing and after failure was reached, data from the tests shown in Figures 24-26 were used to determine recommendations for engineering design. The first step in this process was to analyze the data according to movement group. Figure 26 shows a performance chart for critical depth of overtopping flow versus rip rap diameter. All runs of all tests are represented in this graph.

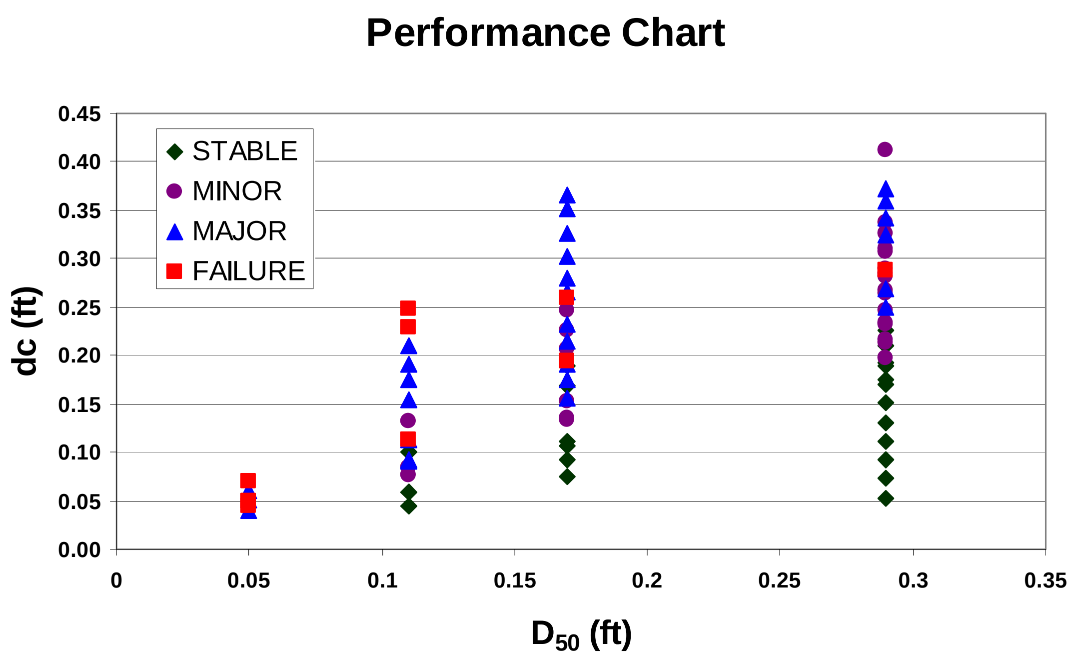


Figure 27. Performance chart for critical depth versus rip rap diameter. Variables are placed in one of four movement categories: stable, minor movement, major movement, or failure.

Unfortunately, the separation of movement categories is not well represented with this type of axis format. In order for the engineer to use this data to correctly make design decisions, movement categories must be clearly separated and defined. Figure 28 gives a more detailed view of the data in a form that is clearly comprehensible for design purposes. In this figure, data is normalized by dividing axis values by critical depth. This figure is applicable for floodwall heights to critical depth ratios up to 40 and D_{50} to critical depth ratios up to 2.0. This figure also illustrates TDLP Inc.'s best professional judgment of the separation line between acceptable design and design failure. This line was strategically placed above points representing major movement of the rip rap bed. This placement is appropriate due to the definition of major movement described earlier. According to Figure 28, any flow rate and corresponding critical depth which causes displacement of 1 D_{50} of the total bed depth or more will be categorized as design failure. Minor movement data points were placed in the acceptable design category due to the fact that minor movement only constituted displacement of a small minority of the upper layer of D_{50}.

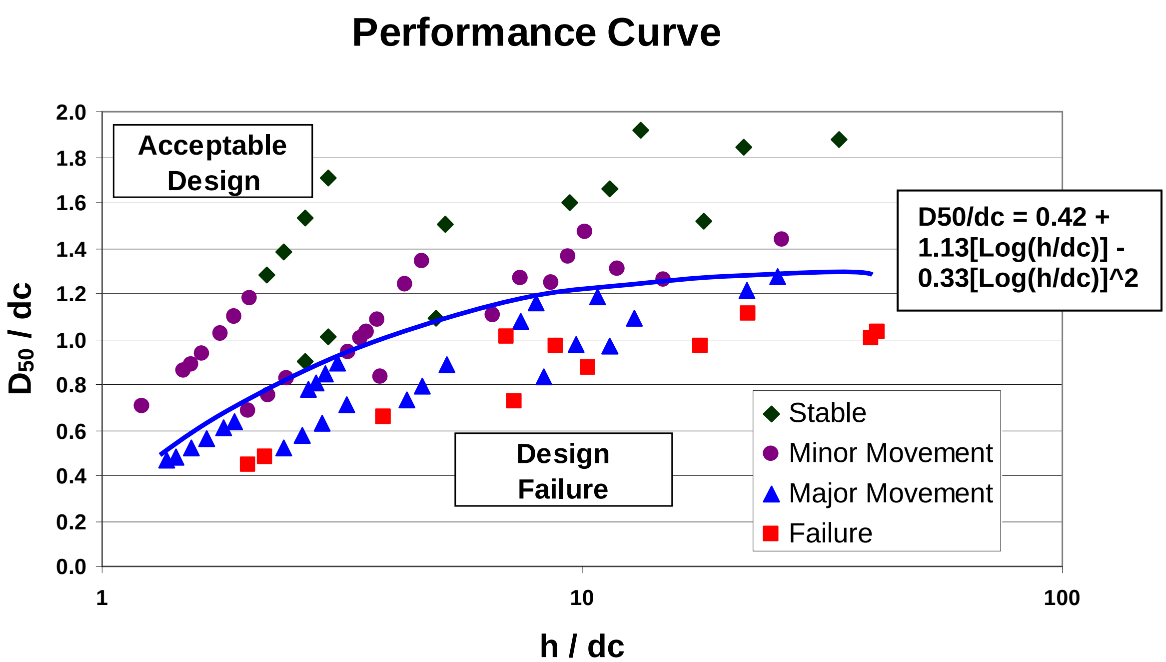


Figure 28. Performance curve for sizing rip rap downstream of a floodwall with given parameters.

Determination of Bed Placement

Although the major objective of this study was to determine sizing of rip rap downstream of overtopped floodwalls in order to prevent scour, another issue which will be faced in the field is the placement of the rip rap bed. This bed must be placed in a position as to cover ground affected by an impinging jet. It must also adhere to economic consideration and not cover more ground than needed for protection.

Water surface profiles (as seen in Figure 29) were used to determine impinging jet impact locations. This data was taken for every flow rate at every drop height in order to create a complete database from which to analyze impact location.

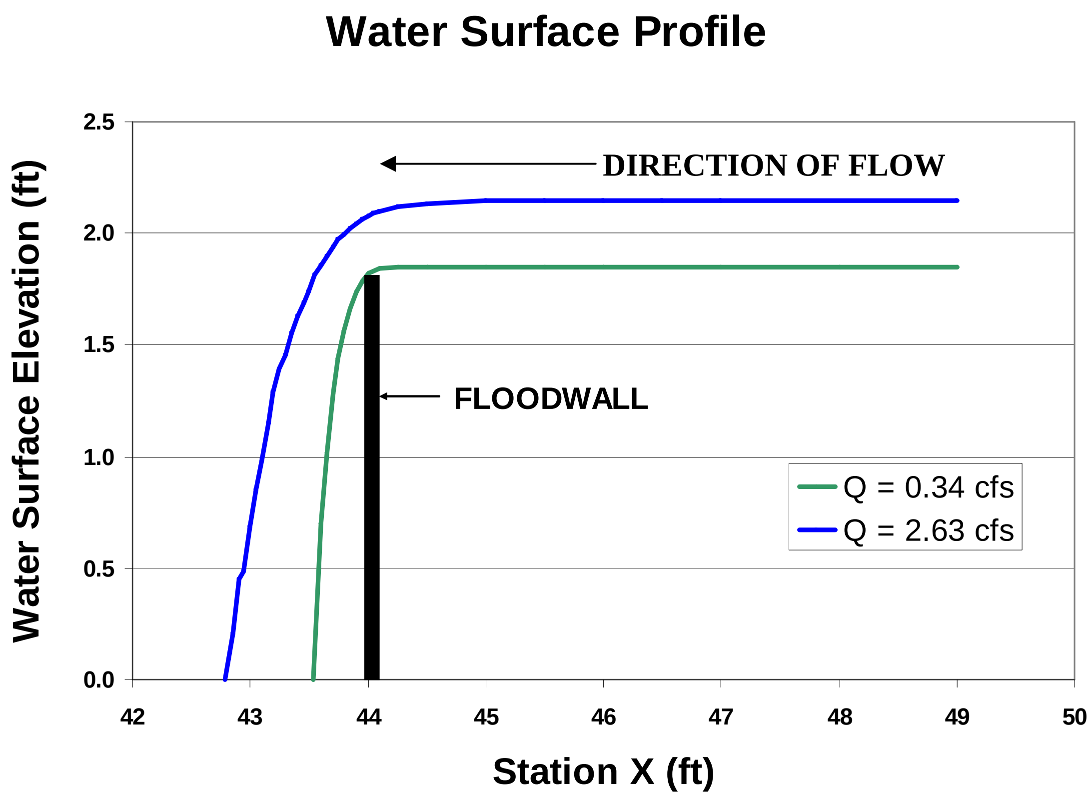


Figure 29. Typical water surface profiles for various flow rates.

Figure 30 was derived from the water surface profile information obtained. Once again, values are normalized by critical depth to apply to a broad range of drop height and critical depth variations.

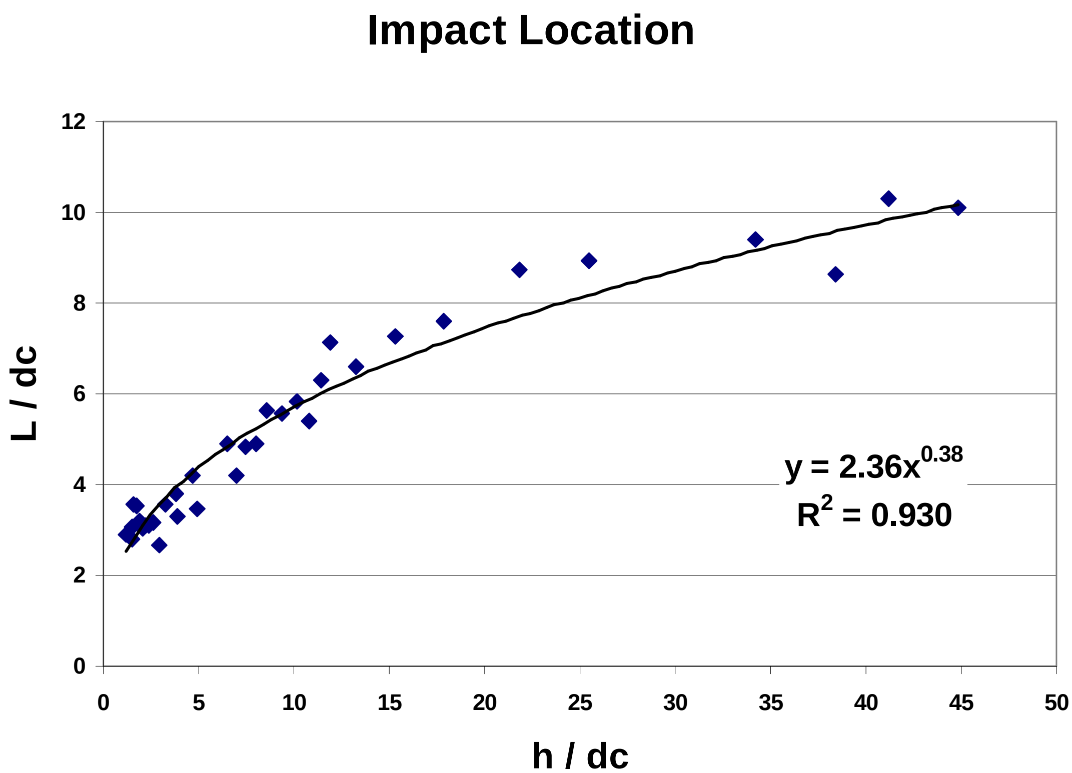


Figure 30. Location of impinging jet impact as measured downstream of floodwall.

Recommended rip rap placement downstream of the floodwall to the point of impact can be derived from Figure 30. Although this data is crucial to determining where scour is most likely to occur, other parameters must also be taken into consideration when preparation of the rip rap bed. The other major parameter is total length of bed needed to ensure stability. From the floodwall calculations for this type of application, Rice and Kadavy (1991) suggested that total length of bed be five times the critical depth of overtopping flow. From observations taken directly from testing, displacement was seen to occur in the range of 5-10 times the critical depth. From the observations along with taking calculations of bed length into consideration, it is recommended that the rip rap bed be a length of 10*dc from the base of the floodwall as a conservative measure.

Example Application

The data collected from this project and the results from that data are directly applicable to real world situations. The following in an example problem indicating how an engineer would use this development to:

1. Determine size of rip rap to specify for a project
2. Determine dimensions and limits of rip rap placement (i.e. thickness, length, location, etc.)

The first step in application of this design is to collect known data from the application site. For this example, it is known that a certain municipality has a 10 ft tall floodwall and wants to apply scour protection that will withstand a 25 year storm event. It is known to the engineer that a 25 year storm event in the region of question produces a 1 ft critical depth of overtopping waters. This data can be directly applied to the performance chart shown below in order to obtain the optimal rip rap diameter for the site in question (h/dc = 10ft / 1ft = 10).

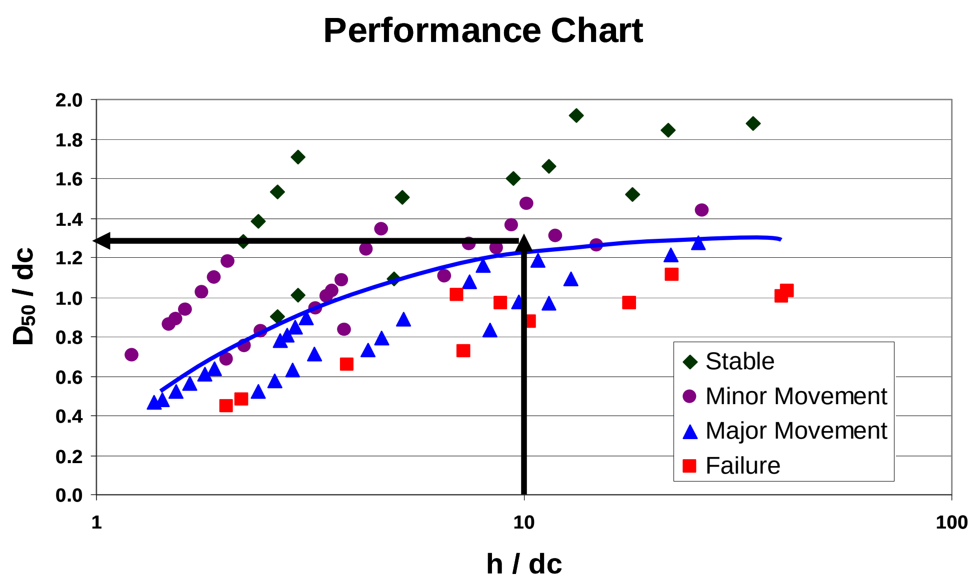


Figure 31. Performance Chart showing point of stability at a critical depth of 1ft and a drop height of 10 ft.

This gives a desired D_{50}/dc of approximately 1.3. Given a dc of 1ft, the design D_{50} for this application will be equal to 1.3 ft. The next step in engineering design would be to determine the dimensions and limits of rip rap placement. It was determined earlier in this project that thickness of the bed should equal 2* D_{50}, giving a total thickness of 2.6 ft. Impact location can be determined from the Impact Location chart shown below. For h/dc = 10, impact location L/dc will be equal to 5.7 giving a length downstream of the floodwall equal to 5.7 ft.

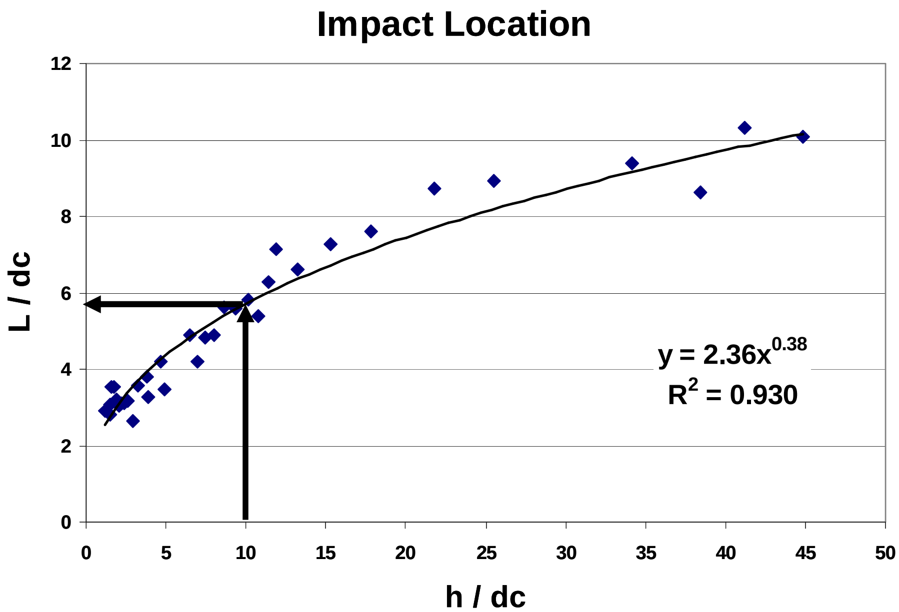


Figure 32. Impact location of flow over 10ft drop height at a critical depth of 1ft.

Now that scour location is known, the engineer must determine a total length of the rip rap bed in order to ensure stability. Using the recommended 10*dc, the engineer would know to make the length of the bed downstream of the floodwall approximately 10 ft.

Costs

Final costs for this project are shown in Table 2. Costs were based on three structures; a 10 ft x 10 ft x 2 ft platform, a 16 ft x 3 ft flume, and a 8 ft x 3 ft rock box. All materials for this project were bought at Stillwater Building Center with exception of 3 in. screws for the flume which were bought at Lowe's.

This cost analysis does not include essential materials needed for the project such as rip rap of varying diameters, geofabric, and Plexiglas used in construction of the rock box. These materials were donated to the team from sponsors at the HERU laboratory. In practical engineering design application to real world floodwalls, cost analysis would be modified.

Cost of application would be limited to buying rip rap according to parameters defined in Figure 27, cost of geofabric, and labor due to installation and design.

Table 2. Cost analysis of materials bought during the duration of the project.

Platform				
Piece	Description	Qty	$ ea.	Total
2 X 12 X10	Douglas Fir	14	10.42	145.88
2 X 4 X10	Douglas Fir	4	2.96	11.84
4 X 8 X 3/4	T&G AdvanTech Flooring	4	23.45	93.80
Wood Screws	3"	4	2.60	10.40
Wood Screws	2"	4	2.60	10.40
Flume				
Piece	Description	Qty	$ ea.	Total
Sealant	Caulking	11	2.69	29.59
2 X 4 X10	Douglas Fir	30	2.96	88.80
4 X 8 X 3/4	T&G AdvanTech Flooring	5	23.45	117.25
Rock Box				
Piece	Description	Qty	$ ea.	Total
2 X 4 X10	Douglas Fir	4	2.96	11.84
4 X 8 X 3/4	T&G AdvanTech Flooring	2	23.45	46.90
Wood Screws	3"	2	2.60	5.20
Sealant	Caulking	8	2.89	23.12
Drill Bits	1/8”	2	2.00	4.00
Totals				
Misc. & Taxes	$47.55			
Platform	$272.32			
Flume	$235.64			
Rockbox	$91.06			
Overall Total	$646.57			

Conclusions

TDLP Inc. was asked to develop a system of sizing riprap for floodwall scour prevention. After spending several months investigating current literature, market products, and patents a firm understanding of what was needed was established. A method of testing our riprap was developed and dimensions for the flume design and experimental setup were determined. The design was critiqued and problems were corrected and after several weeks of designing and planning a finished product was constructed. With use of the flume and calibration curves developed, flows used to fail the rip rap at our three drop heights were monitored.

From the data and the observations we determined that a distinction could be drawn between acceptable design of rip rap bed and design failure of rip rap bed. This analysis yielded several beneficial components of riprap installation. For example, the graphs show engineers which rip rap should be used in certain flow conditions. The trend line through the chart shows which rip rap fail at which flows and the higher the point is above the line would establish the factor of safety. When viewing the flume profiles the impact point of the impinging flow can be seen. Knowing this information enables engineers to place riprap away from the wall at a distance that will protect the entire grounds surface. The information provided is a practical outline that could be used to help better determine erosion control installation methods.

With further study and testing, this initial outline could be developed in to a more detailed guide book or manual for riprap installation. TDLP Inc. hopes that initiating this early study of riprap sizing versus flow will allow for more testing and development of future models. The improvement of floodwall erosion control structures will prove to be financially and environmentally beneficial to areas on the downstream side of floodwalls. This could lead to a reduction in insurance costs for home and business owners, as well as the general protection of valuable crops. Time would also be saved by eliminating long term cleanup efforts that result after floodwall failure. Overall, TDLP Inc was satisfied with the results and data collected and believe this project could be used in the field for effective engineering design analysis.

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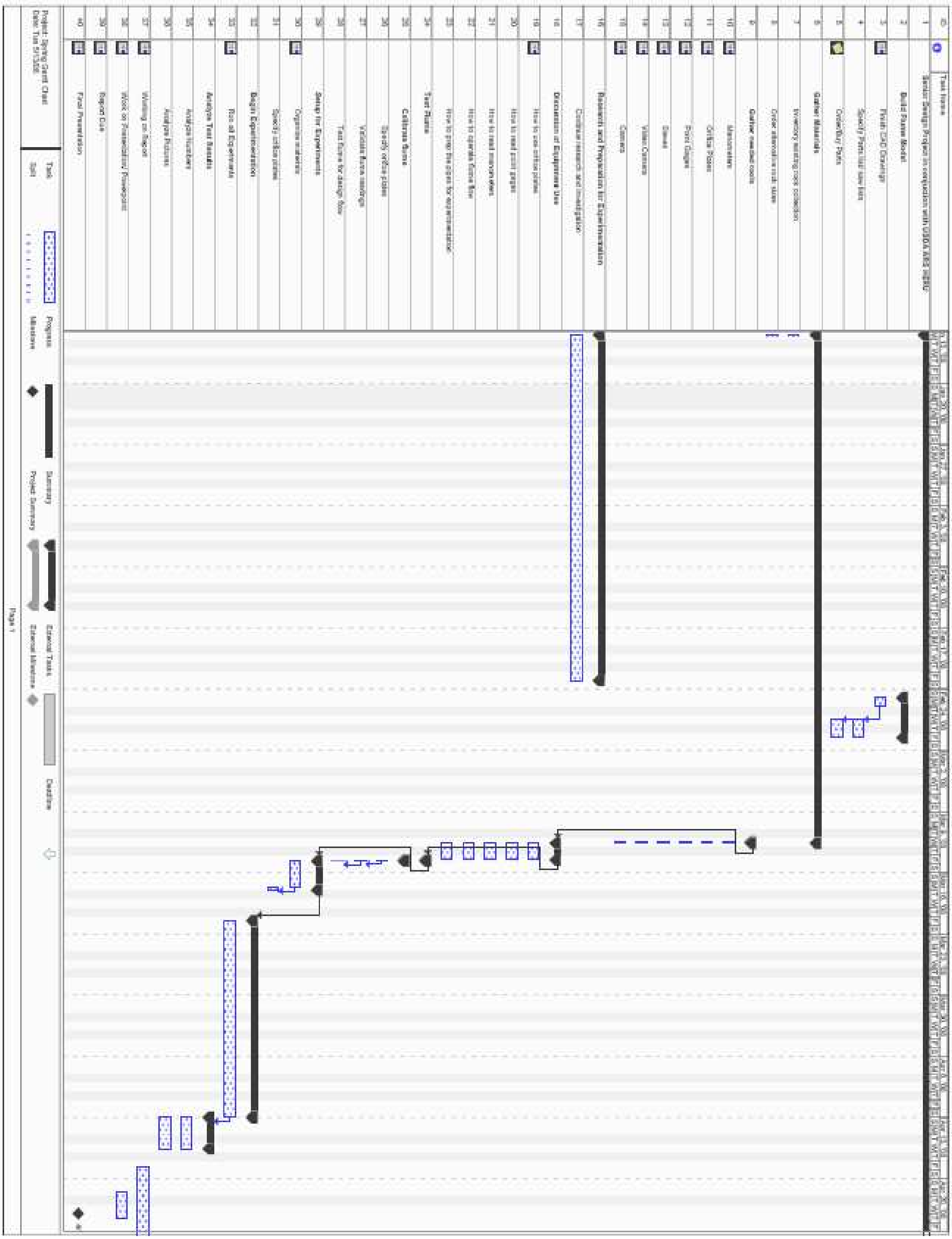
Appendix A

Gantt Chart

Task List

Summary List

Gantt Chart



Task List

TDLP, Inc.			
Task List for Weekly Activities during the Fall and Spring Semesters			
Task Name	**Description**	**Team Member(s)**	**Date**
Meeting with Dr. Hanson	Discuss progress on flume scaling equations. Get approval to start construction	Monica, Kevin, Sarah, Jason	Monday November 19
Check flume room	Look to see what supplies we need, and also talk to Dr. Hanson to see what supplies he recommends.	Monica, Kevin, Sarah, Jason	Monday November 19
Working on Gantt Chart	Start putting together the chart for the rest of the year and next semester	Monica, Sarah	Tuesday November 20
Price Checking	Visit Lowes to see some costs of potential materials	Monica, Kevin, Sarah, Jason	Tuesday November 20
Gantt Chart	Lay out schedule for this semester and the next	Sarah, Monica	Tuesday November 27
Cost Estimations	Look at materials for flume and experiments, and plan an initial budget	Jason, Kevin	Thursday November 29
Design Flume	Determine dimensions in order to make better budget calculations	All	Thursday November 29
Start Presentation	Begin the power point for our final presentation	All	Thursday November 29
Experimental Design	Begin thinking of how our experiment will be laid out for next semester in order to present it to our sponsor next Wednesday	All	Thursday November 29
Edit Fall Report	Correct grammatical errors and make some changes	All	Friday November 30
Finish Fall Report	Add parts and do grammar check	All	Monday December 3
Print off Fall Report	Have 4-6 copies printed off and bond	All	Tuesday December 4

Finish Fall Presentation	Put all parts together	All	Tuesday December 4
Practice Fall Presentation	Get together to practice the presentation	All	Tuesday December 4
Work on CAD Drawings	Work on CAD drawings for the flume and platform box	All	Monday January 14
Begin research at Lab	Begin researching journals and publications at hydraulics lab	All	Tuesday January 15
Specify parts list / saw lists	Make parts list from CAD drawings and specify tools needed such as saws	All	Wednesday January 16
Order / buy parts	Order parts for flume and platform	Jason	Wednesday January 16
Inventory existing rock collection	Meet at Hydraulics Lab to inventory existing rock library	Monica, Sarah	Friday January 18
Order alternative rock sizes	Put in orders for any alternative rock sizes not included in existing rock library	Kevin	Friday January 18
Send completed CAD drawings and parts list of platform to Hydraulics Lab and Dr. Weckler for approval	Send completed CAD drawings for review and approval before beginning anything else. Also send drawings to fire protection students. The group will wait for the OK before moving on to the next step	Kevin, Jason	Wednesday January 23
Buy parts for platform	When plans are approved we will begin buying parts from the parts list and take them out to the lab to begin construction	All	Friday January 25
Begin Construction of platform	This may depend on times available at the lab for Kem to assist us	All	Friday January 25
Begin CAD drawings of flume and experimental setup channel	Move on to finalizing our construction plans for the flume and the channel at the end of the flume where all the experimental materials will be held.	All	Saturday January 26
Continue research and investigation	Continue research into ideas and concepts	All	Weeklong Jan. 28 - Feb. 1

Buy parts for flume platform	Purchase all necessary materials for building the flume platform	All	Monday January 28
Complete building of flume platform	Schedule time with the hydraulics lab to construct flume platform	All	Wednesday January 30
Work on CAD drawing of flume	Move on to finalizing our construction plans for the flume and the channel at the end of the flume where all the experimental materials will be held.	Jason, Kevin	Friday February 1
Work on Cad drawings for Flume	Work on flume drawings in Cad make Manufacturable drawings	All	Wednesday February 6
Develop parts list	Once drawing is establish figure materials need to meet design requirements	All	Wednesday February 6
Possibly Purchase Materials	If we get drawings completed we will be able to purchase the materials needed.	All	Friday February 8
Make corrections to Flume CAD drawings	Make additional corrections to flume CAD drawing according to corrections provided by Dr. Hanson and the Hydraulics Laboratory	Jason, Kevin, Sarah	Sunday February 10
Purchase flume materials	make purchases of flume materials according to corrected CAD drawings from Stillwater Building Center	All	Monday February 11
Begin construction of flume	begin constructing flume at Hydraulics Laboratory	All	Monday February 11
Work on CAD drawings of rock box	Work on and complete CAD drawings of rock box to hold experimental materials	Jason, Kevin	Weeklong February 18-22
Meet with Safety person	Talk about designs and discuss issues involved with safety	Jason, Kevin, Monica	Wednesday February 20
Buy heater for laboratory	Buy a heater for work on cold days and buy any other materials needed to complete the flume	all	Wednesday February 20

Finish flume	Work on completing the construction of the flume at the hydraulics laboratory	all	Friday February 22
Meeting with Dr. Hanson	Set up a time to talk about progress with Dr. Hanson	Monica	Friday February 22
Buy additional materials	Buy needed materials to finish flume from Lowes	All	Monday February 25
Finish flume	Finish construction on the flume. Prime it for sealant and check all seals.	All	Monday February 25
Finish CAD drawings of rock box	Work on and complete CAD drawings for the experimental containment box. Ensure all materials are correct and dimensions are to size	Jason, Kevin	Tuesday February 26
Make parts list for rock box	From CAD drawing, make a detailed parts list	Jason, Kevin	Wednesday February 27
Give rock box CAD drawings to hydraulics lab for approval	Email or give hardcopy of rock box CAD drawing to Dr. Hanson and Kem Kadavy for approval and changes	All	Wednesday February 27
Make any changes to CAD drawings for rock box	Make appropriate changes to CAD drawing of rock box based on suggestions from hydraulics lab	All	Thursday February 28
Buy Parts and begin construction on rock box	Buy needed materials for rock box and begin construction	All	Friday February 29
Buy materials for rock box	Buy all materials for rock box from existing parts list	All	Monday March 3
Confirm with Dr. Hanson that plexi glass is at Hydraulics Lab	Make a call to the Hydraulics lab to confirm materials in their possession	Monica	Monday March 3
Build rock box	Construct rock box according to CAD drawings	All	Wednesday March 5
Apply extra coating of sealant to flume	Apply an extra coat of sealant to the part of the flume that will be coming in contact with water	Sarah	Wednesday March 5

Revise Gantt chart and project schedule	look over project schedule and revise according to position currently on project	All	Friday March 6
Finish constructing rock box	Make corrections suggested by staff at Hydraulics laboratory. Finish all details of construction.	All	Wednesday March 12
Gather needed materials	All experimental materials needed for this experiment are at the laboratory, but need to be brought to the laboratory we are working out of.	All	Wednesday March 12
Gather tools	Gather any other tools which are not currently at the lab, such as point gages, correct size orifice plates, and sieves.	Kevin, Jason	Wednesday March 12
Discussion of equipment use	Discuss proper equipment use with Dr. Hanson and Kem prior to experimentation. Equipment needing discussion includes use of orifice plates, reading manometers and point gages, operating the flow to the flume from the pipes, and prepping the pipes for experimentation.	All	Friday March 14
Calibrate flume	This includes testing the flume for design flow and validating flume readings.	All	Friday March 14
Complete flume	Complete all construction details on the flume and rock box. Add railing for point gage readings. Ensure setup is waterproof	All	Monday March 24
Discussion of equipment	Discuss proper use of equipment with Dr. Hanson prior to experimentation	All	Wednesday March 26
Calibrate flume	Run water in the flume and calibrate different flows with corresponding orifice plates	All	Wednesday March 26

Setup for experimentation	Bring in all materials needed for experimentation including sand, rip rap, point gages, instrumentation.	All	Wednesday March 26
Begin experimentation	Begin the first steps of our experimentation	All	Friday March 28
Get approval for experimental approach	Send experimental approach details to Dr. Hanson for approval	Monica	Monday March 31
Work on final report and web page	Work more on the final report including updating information about flume and experimental procedure. Work on updating web page to be closer to final webpage output.	All	Weeklong March 31 - April 4
Setup for experimentation	Bring in all materials needed for experimentation including sand, rip rap, point gages, instrumentation.	All	Wednesday April 2
Begin experimentation	Begin the first steps of our experimentation	All	Wednesday April 2
Work on rough draft of final report	Complete as much of the final report as we can to turn in on Friday. Parts that are known to be missing will be results and conclusion	All	Weeklong April 7 - 11
Testing	Continue testing of experimental materials.	All	Monday, Wednesday, Friday, Saturday
Analyze data	Analyze data from water surface profiles and failure data	Monica	Saturday April 8
Complete analysis of data	Analyze data and put into tables and graphs that are easily understandable.	Monica	Monday April 14
Send data to Hydraulics Lab	Send completed data to Hydraulics Lab for review	Monica	Tuesday April 15
Discuss data with Hydraulics Lab	Discuss analysis with Hydraulics Lab and take any suggestions for change.	All	Wednesday April 16

Work on final report	Complete unfinished parts of final report. Add updated Gantt chart and task list.	All	Weeklong April 14 - 18
Work on webpage	Work to update and complete webpage with respect to pictures and data. Final report will be posted when finished.	All	Weeklong April 14 - 18
Work on presentation	Define roles for presentation and work to complete assigned task	All	Weeklong April 14 - 18

Summary List

TDLP, INC.			
Summary List of Weekly Activities during the Fall and Spring Semesters			
Task Name	**Description**	**Team Member(s)**	**When**
Meeting with Dr. Hanson for question and answer period	Asked questions and received instruction. Things that were discussed: Flume building; Equations and Calculations; Additional research needed. Information provided: Deliverables were given and the statement of work was provided. We were informed that we needed to develop a scale model size before we could go through cleanup and destruction of flume.	Kevin, Monica, Jason	Friday November 9
Calculate critical depth for small scale floodwall model	Worked together as a group on Friday, November 16th to complete this task. Was easier than we assumed it would be after we found the correct equations.	Sarah, Kevin Monica	Friday November 16
Research ASCE articles	Found a few articles online about floodwall design	Jason	Friday November 16
Research NRCS articles and standards	Did not find much, found more from Dr. Fox from the Army Corps of Engineers	Jason, Kevin	Friday November 16
Clean out flume room	Dr. Hanson gave the group permission to not worry about this task, that he would have his men clean it out so we could focus on our calculation.	All	Friday November 16
Meeting with Dr. Hanson	discussed final expectations, course of action, completed material, fall report and presentation	All	Monday November 19

Check flume room	found exact dimensions and materials that would be needed	All	Monday November 19
Worked on Gantt Chart	Start putting together the chart for the rest of the year and next semester	Monica, Sarah	Tuesday November 20
Price Checking	Visit Lowes to see some costs of potential materials	Monica, Kevin, Sarah, Jason	Tuesday November 20
Gantt Chart	Outlined the Gant Chart - Need to put in times	Monica, Sarah	Tuesday November 27
Cost Estimations	Went to Lowes to look at materials and make cost estimations	Kevin, Jason	Thursday November 29
Design Flume	Work on initial Flume Design	Jason, Kevin	Thursday November 29
Edit Fall Report	Went back and made corrections	Monica	Friday November 30
Start Presentation	Designed slide background	Sarah, Monica	Saturday December 1
Experimental Design	Worked on the design of the experiment: how we will test and what we will test for.	all	Saturday December 1
Work on CAD Drawings	Began work on the CAD drawing for the platform of our experimental flume. This will begin construction next week so total drawing and parts list will be completed over the weekend.	All	Monday January 14
Began research at Lab	Began researching journals and publications at hydraulics lab, Henderson's book was found most informative	All	Tuesday January 15
Specify parts list / saw lists	Will make very specific parts list from CAD drawings and specify tools needed such as saws over the weekend	All	Wednesday January 16

Order / buy parts	Began ordering parts for flume platform such as wood and nails from Lowes	Jason	Wednesday January 16
Inventory existing rock collection	Met at Hydraulics lab on Thursday and was given complete inventory of rock collection	Monica, Sarah	Friday January 18
Order alternative rock sizes	Will not need to do this step, all rock sizes needed are present at the lab	Kevin	Friday January 18
Sent completed CAD drawings and parts list of platform to Hydraulics Lab and Dr. Weckler for approval	Dr. Weckler was a bit concerned about the structural safety of the platform. Dr. Hanson said everything was a "go" and that we could even eliminate a few of the beams from the bottom row of the structure.	Kevin, Jason	Wednesday January 23
Buy parts for platform	Will buy part either Friday after classes if everyone can meet, or Saturday morning/afternoon. Then proceed to take parts to Lab.	All	Friday January 25
Begin Construction of platform	Since weather will be a bit warmer over the weekend, construction has been put off until Saturday or Monday depending on operations at the lab	All	Friday January 25
Begin CAD drawings of flume and experimental setup channel	The team met to begin and complete a rough draft of plans for the flume. This will be sent to the lab and Dr. Weckler for approval.	All	Sunday January 27
Buy parts for flume platform	Purchased all necessary materials for building the flume platform. Purchasing was split between two days because of plan changes after the first day of construction.	All	Monday January 28
Complete building of flume platform	Completed the flume platform Wednesday afternoon. We were given approval of our construction by Dr. Hanson and Kem.	All	Wednesday January 30
Work on CAD drawing of flume	Move on to finalizing our construction plans for the flume and the channel at the end of the flume where all the experimental materials will be held. This will be done over the weekend.	Jason, Kevin	Friday February 1

Flume Design	Worked on flume design using AutoCAD	All	Monday February 4
Dr. Hansen flume review	Drawings were reviewed by Dr. Hansen and we made the suggested changes	All	Wednesday February 6
Figured materials list	Figured materials list and cost analysis for flume	All	Wednesday February 6
Called JR Freeman Company	Called an plexiglass supplier and got cost specs and shipping dates for plexiglass	All	Friday February 8
Meeting with group to develop next Monday's Plan	Plan on purchasing supplies Monday	All	Friday February 8
Made corrections to Flume CAD drawings	Made additional corrections to flume CAD drawing according to corrections provided by Dr. Hanson and the Hydraulics Laboratory	Jason, Kevin, Sarah	Sunday February 10
Purchased flume materials	made purchases of flume materials according to corrected CAD drawings from Stillwater Building Center	All	Monday February 11
Give purchase receipt to Jana Moore	Gave receipt from Stillwater Building Center to Jana Moore for the senior design records	Monica	Monday February 11
Began construction of flume	Began constructing flume at Hydraulics Laboratory. Weather Monday was too cold to stay in the building very long, so construction was held up until Wednesday. Finished about half of the project that day. Will continue and finish construction next Monday	All	Monday February 11
Worked on CAD drawings of rock box	Worked on an are very close to completing CAD drawings of rock box to hold experimental materials	Jason, Kevin	Weeklong February 18-22
Met with Safety person	Talked about designs and discussed issues involved with safety. We plan to meet with him again next week to go out to the lab and show what we have done.	Jason, Kevin, Monica	Wednesday February 20

Worked on flume	Worked on the construction of the flume at the hydraulics laboratory. We are very close to completing and will be done by next week.	Jason, Kevin, Monica	Wednesday February 20
Met with Dr. Hanson	Talked with Dr. Hanson about progress and the next steps of experimentation.	Monica	Friday February 22
Buy additional materials	The team met at Lowes to buy additional caulking for the flume and sealant.	All	Monday February 25
Finish flume	Finished construction of flume walls and wall supports	All	Monday February 25
Seal Flume	Used water sealant of flume walls and platform	Sarah, Monica	Tuesday February 26
Met with Safety people	Met at the Hydraulic Lab with our safety team to show them construction and clarify any issues	All	Wednesday February 27
Met with Dr. Hanson	Had a short meeting with Dr. Hanson and Kem Kadavy to get suggestions for rock box	Jason, Kevin	Wednesday February 27
Finished CAD drawings of rock box	Worked on and completed CAD drawings for the experimental containment box.	Jason, Kevin	Thursday February 28
Gave rock box CAD drawings to hydraulics lab for approval	Emailed copy of rock box CAD drawing to Dr. Hanson and Kem Kadavy for approval and changes	All	Thursday February 28
Made parts list for rock box	From CAD drawing, made a detailed parts list	All	Friday February 29
Bought materials for rock box	Bought all materials for rock box from existing parts list from Stillwater Building Center	All	Monday March 3
Confirmed with Dr. Hanson that plexiglass is at Hydraulics Lab	Talked with Kem out at the lab to confirm that they had plexiglass for us to use when building the rock box	All	Monday March 3
Build rock box	Began construction on the rock box. Will need to complete small details next week.	All	Wednesday March 5
Revise Gantt chart and project schedule	Look over project schedule and revise according to position currently on project. This will be completed over the weekend.	All	Friday March 6

Finished constructing rock box	Make corrections suggested by staff at Hydraulics laboratory. Finish all details of construction.	All	Wednesday March 12
Finished constructing rock box	Added braces to rock box.	All	Wednesday March 12
Discussion of equipment use	Discuss proper equipment use with Dr. Hanson and Kem prior to experimentation. Equipment needing discussion includes use of orifice plates, reading manometers and point gages, operating the flow to the flume from the pipes, and prepping the pipes for experimentation.	All	Friday March 14
Mounting Railing	Discussed mounting angle iron railing for point gauge.	All	Friday March 14
Sealant	Put another coat of sealant on flume and platform.	Sarah and Monica	Friday March 14
Sand	Got a bobcat scoop of sand placed next to testing building and began to place sand into rock box	Sarah and Jason	Friday March 14
Vertical bracing	Got angle iron for vertical bracing of flume. Cut to length and attached to flume.	Sarah and Jason	Friday March 14
Completed flume	Completed all construction details on the flume and rock box. Add railing for point gage readings.	All	Monday March 24
Finished final details on flume	Went over all aspects of the flume with workers from the Hydraulic Lab to ensure it was completed properly. Also adjusted railing for point gage to ensure levelness within hundredth of a degree	All	Wednesday March 26
Discussed equipment	Discussed proper use of equipment with Dr. Hanson prior to experimentation. Went over how to start flow in the flume, how to read manometer and get flow rate from books, and how to exchange orifice plates	All	Wednesday March 26

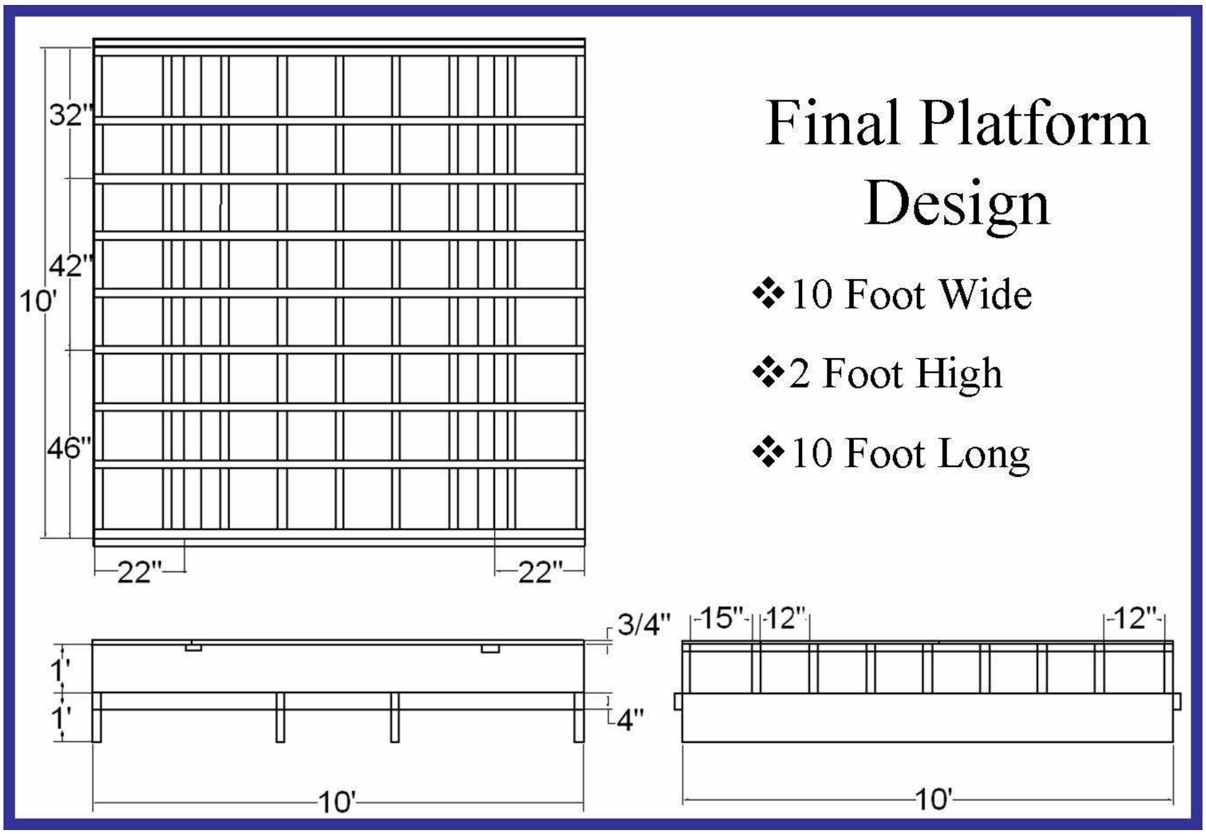
Calibrated flume	Ran water in the flume and calibrated different flows with corresponding orifice plates. Six reading per orifice plate were taken and will be used to create an equation to calculate critical depth.	All	Wednesday March 26 and Friday March 28
Begin working on draft of final report	Edit Fall Report and add additional information from this semester.	All	Weekend March 29-30
Approval of experimental approach	Send experimental approach details to Dr. Hanson for approval	All	Monday March 31
Analyze calibration data	Analyzed all the calibration data and fit that data to curves that will be used for experimental data	Monica	Monday March 31
Approval of calibration data	Discussed analysis of calibration data back and forth with Dr. Hanson for verification and accuracy	All	Monday March 31
Worked on final report	Worked more on the final report including updating information about flume and experimental procedure. Plan on working on updating web page to be closer to final webpage output over the weekend.	All	Weeklong March 31 - April 4
Setup for experimentation	Brought in all materials needed for initial experimentation. This included sand, 0.29 ft diameter rip rap, geofabric, and all instruments needed.	All	Wednesday April 2
Began experimentation	Began the first steps of our experimentation with a drop height of 2 ft and a rip rap diameter of 0.29 ft.	All	Wednesday April 2
Continue experimentation	Will continue experimentation according to experimental design	All	Friday April 4 and Weekend
Complete rough draft of final report	Completed as much of the final report as possible. Parts missing are results and conclusion along with flume calibration notes.	All	Weeklong April 7 - 11

Tested Materials	Continued testing of experimental materials. Should be completed on Saturday.	All	Monday, Wednesday, Friday, Saturday
Analyzed data	Analyzed existing data from water surface profiles and failure data. Will be completed when testing is completed.	Monica	Saturday April 8
Completed analysis of data	Analyzed data and put into tables and graphs that are easily understandable.	Monica	Monday April 14
Sent data to Hydraulics Lab	Sent completed data to Hydraulics Lab for review	Monica	Tuesday April 15
Discussed data with Hydraulics Lab	Discussed analysis with Hydraulics Lab and take any suggestions for change. Made changes according to suggestions.	All	Wednesday April 16
Worked on final report	Completed unfinished parts of final report. Added updated Gantt chart and task list.	All	Weeklong April 14 - 18
Worked on webpage	Worked to update and complete webpage with respect to pictures and data. Final report will be posted when finished.	All	Weeklong April 14 - 18
Worked on presentation	Defined roles for presentation and worked to complete assigned task	All	Weeklong April 14 - 18

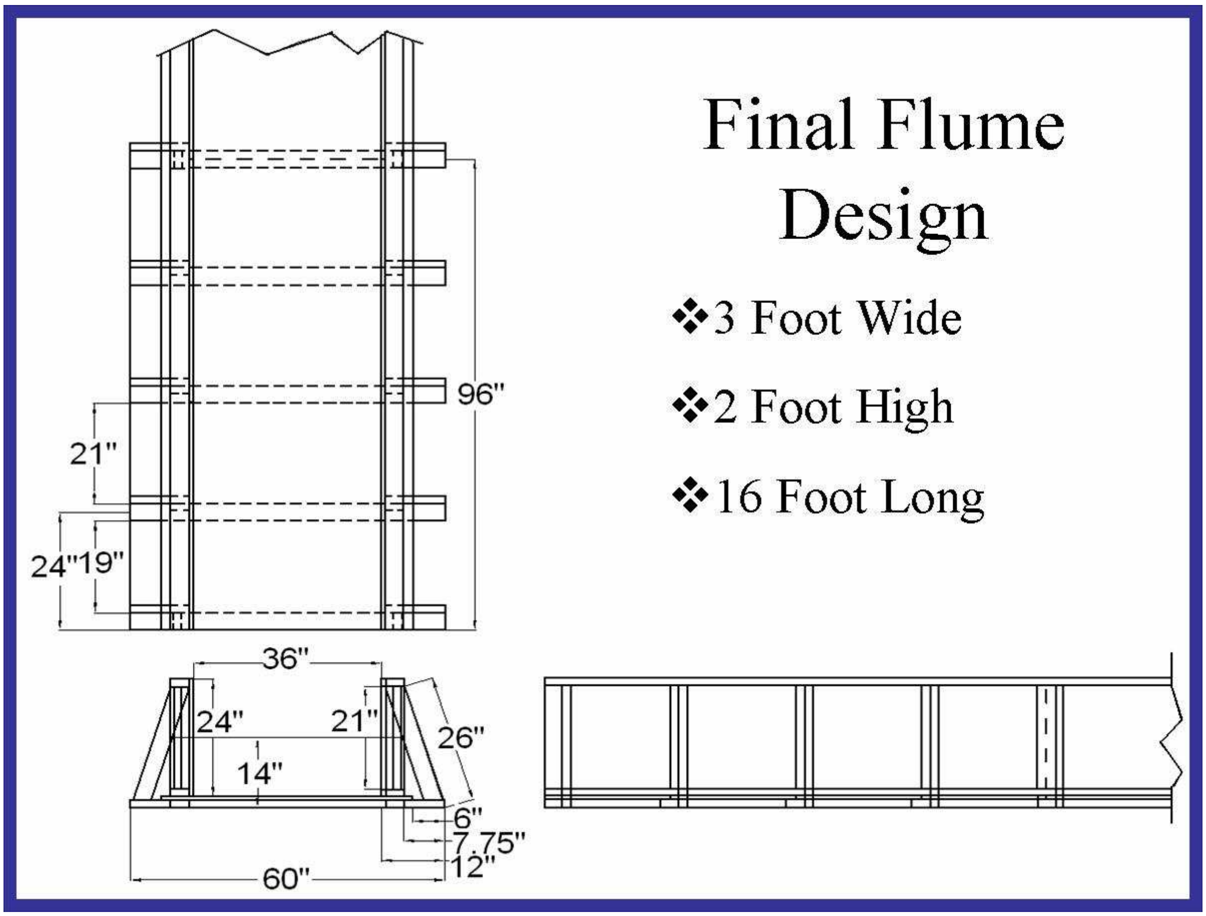
Appendix B

Design Drawings

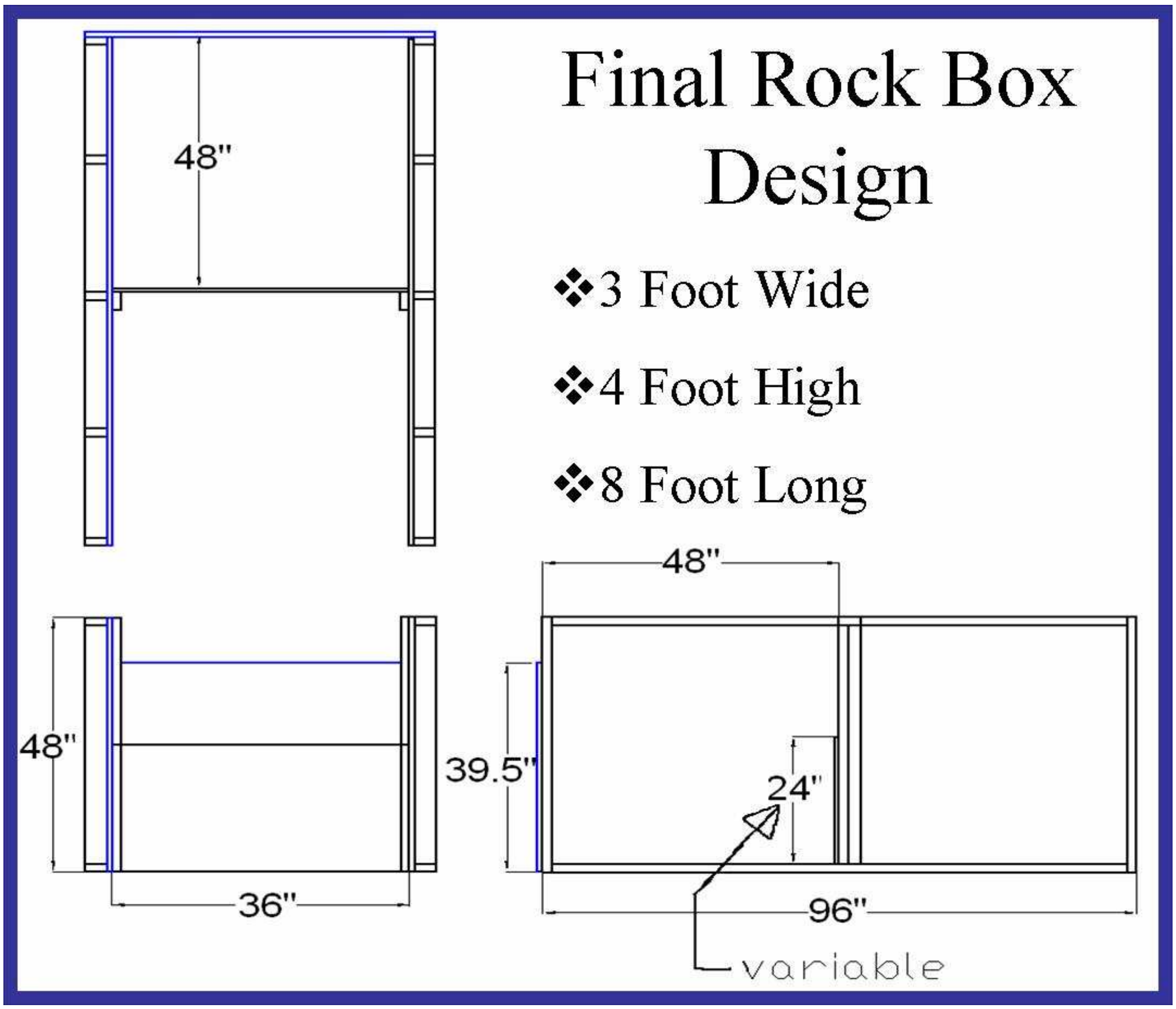
Platform


Final Platform Design
❖10 Foot Wide
❖2 Foot High
❖10 Foot Long
32"
42"
10'
46"
22"
22"
3/4"
1'
1'
4"
10'
15"
12"
12"
10'

Flume


Final Flume Design
❖3 Foot Wide
❖2 Foot High
❖16 Foot Long
96"
21"
24"
19"
36"
24"
21"
26"
14"
6"
7.75"
12"
60"

Rock Box


Final Rock Box Design
❖3 Foot Wide
❖4 Foot High
❖8 Foot Long
48"
48"
36"
48"
39.5"
24"
96"
variable

Appendix C

Calibration Data Sheets

Experimental Testing Data Sheets

Water Surface Profile Data Sheets

Calibration Data Sheets

	Run	Left	Right	Differential	Flow Q (cfs)	Average Flow Qave (cfs)	Point Gage	Critical Depth	h (ft)	h^1.5	q (cfs/ft)
1.500 in Orifice	1A	5.6	0.8	6.4	0.04359	0.043425	1.778	0.0388	0.031	0.005	0.014475
	1B	5.6	0.7	6.3	0.04326						
	2A	9.6	5.3	14.9	0.06550	0.06550	1.787	0.0511	0.040	0.008	0.021833
	2B	9.6	5.3	14.9	0.06550						
	3A	14.4	11.2	25.6	0.08585	0.08577	1.793	0.0611	0.046	0.010	0.02859
	3B	14.4	11.1	25.5	0.08569						
	4A	17.8	15.3	33.1	0.09762	0.09762	1.796	0.0666	0.049	0.011	0.03254
	4B	17.8	15.3	33.1	0.09762						
	5A	22.5	21.0	43.5	0.1119	0.1117	1.800	0.0729	0.053	0.012	0.037233
	5B	22.3	20.9	43.2	0.1115						
	6A	28.9	29.1	58.0	0.1292	0.12915	1.804	0.0803	0.057	0.014	0.04305
	6B	28.8	29.1	57.9	0.1291						
2.500 in Orifice	1A	3.7	2.7	6.4	0.1188	0.1188	1.811	0.0760	0.064	0.016	0.0396
	1B	4.3	2.1	6.4	0.1188						
	2A	9.1	17.3	26.4	0.1903	0.1903	1.818	0.1040	0.071	0.019	0.063433
	2B	9.1	17.3	26.4	0.1903						
	3A	14.0	13.1	27.1	0.2447	0.24425	1.829	0.1228	0.082	0.023	0.081417
	3B	13.9	13.0	26.9	0.2438						
	4A	18.6	18.7	37.3	0.2871	0.2871	1.837	0.1368	0.090	0.027	0.0957
	4B	18.6	18.7	37.3	0.2871						
	5A	23.2	24.5	47.7	0.3247	0.3245	1.843	0.1484	0.096	0.030	0.108167
	5B	23.2	24.4	47.6	0.3243						
	6A	27.6	29.7	57.3	0.3559	0.35555	1.849	0.1578	0.102	0.033	0.118517
	6B	27.5	29.6	57.1	0.3552						
4.000 in Orifice	1A	4.1	2.5	6.6	0.3084	0.3084	1.841	0.1435	0.094	0.029	0.1028
	1B	4.3	2.3	6.6	0.3084						
	2A	8.6	7.5	16.1	0.4845	0.48450	1.869	0.1939	0.122	0.043	0.1615
	2B	8.7	7.4	16.1	0.4845						
	3A	13.5	13.2	26.7	0.6254	0.6230	1.889	0.2293	0.142	0.054	0.207667
	3B	13.3	13.0	26.3	0.6206						
	4A	17.7	18.7	36.4	0.7310	0.7300	1.913	0.2548	0.166	0.068	0.243333
	4B	17.8	18.5	36.3	0.7290						
	5A	21.6	23.3	44.9	0.8124	0.8124	1.926	0.2737	0.179	0.076	0.2708
	5B	21.7	23.2	44.9	0.8124						
	6A	26.7	29.3	56.0	0.9079	0.90790	1.940	0.2947	0.193	0.085	0.302633
	6B	26.5	29.5	56.0	0.9079						

	Run	Left	Right	Differential	Flow Q (cfs)	Average Flow Qave (cfs)	Point Gage	Critical Depth	h (ft)	h^1.5	q (cfs/ft)
6.000 in Orifice	1A	4.7	1.9	6.6	0.7391	0.73635	1.911	0.2563	0.164	0.066	0.24545
	1B	4.9	1.6	6.5	0.7336						
	2A	8.7	6.7	15.4	1.119	1.11900	1.970	0.3388	0.223	0.105	0.373
	2B	8.9	6.5	15.4	1.119						
	3A	13.3	12.3	25.6	1.436	1.4405	2.011	0.4009	0.264	0.136	0.480167
	3B	13.5	12.4	25.9	1.445						
	4A	18.0	18.4	36.4	1.709	1.6995	2.042	0.4476	0.295	0.160	0.5665
	4B	17.7	17.9	35.6	1.69						
	5A	22.7	24.5	47.2	1.943	1.944	2.072	0.4896	0.325	0.185	0.648
	5B	22.8	24.5	47.3	1.945						
	6A	25.7	28.6	54.3	2.083	2.07350	2.085	0.5111	0.338	0.197	0.691167
	6B	25.3	28.0	53.3	2.064						
8.000 in Orifice	1A	5.2	1.3	6.5	1.413	1.418	2.007	0.3967	0.260	0.133	0.472667
	1B	5.4	1.2	6.6	1.423						
	2A	9.0	7.0	16.0	2.200	2.18650	2.094	0.5295	0.347	0.204	0.728833
	2B	9.1	6.5	15.6	2.173						
	3A	13.7	14.0	27.7	2.886	2.886	2.164	0.6372	0.417	0.269	0.962
	3B	13.9	13.8	27.7	2.886						
	4A	17.5	19.3	36.8	3.322	3.3155	2.206	0.6989	0.459	0.311	1.105167
	4B	17.5	19.0	36.5	3.309						
	5A	20.8	24.3	45.1	3.675	3.677	2.236	0.7488	0.489	0.342	1.225667
	5B	21.0	24.2	45.2	3.679						
	6A	28.0	23.0	51.0	3.906	3.91350	2.256	0.7806	0.509	0.363	1.3045
	6B	28.2	23.2	51.4	3.921						

Experimental Testing Data Sheets

Test #	1	Drop height, ft	2		
Recorder	Jason	rock size, mm	89		
Date	4/2/2008	pt gage crest rd, ft	x= 49	y= centerline	z= 1.747

calibration curve: $Q = CH^{3/2}$ C = 10.26

run #	time start/end	sta. 49 pt gage rd, ft	head on crest H, ft	flume discharge Q, cfs	comments: stable/shift/scour
1	2:52	1.820	0.073	0.202	no movement / stable
	3:12	1.820	0.073	0.202	
2	3:19	1.850	0.103	0.339	no movement / stable
	3:29	1.849	0.102	0.334	
3	3:32	1.876	0.129	0.475	no movement / stable
	3:45	1.875	0.128	0.470	
4	3:51	1.904	0.157	0.638	no movement / stable
	4:02	1.904	0.157	0.638	
5	12:08	1.930	0.183	0.803	stable with one rock swaying /
	12:18	1.930	0.183	0.803	swaying rock stabilized by end time
6	12:22	1.959	0.212	1.002	stable with one rock swaying /
	12:37	1.959	0.212	1.002	swaying rock stabilized by end time
7	12:43	1.992	0.245	1.244	stable with one rock swaying /
	12:58	1.992	0.245	1.244	swaying rock stabilized by end time
8	1:02	2.024	0.277	1.496	a few rocks swaying /
	1:18	2.023	0.276	1.488	swaying rocks stabilized by end time
9	1:24	2.046	0.299	1.677	a few rocks swaying /
	1:34	2.046	0.299	1.677	swaying rocks stabilized by end time
10	1:40	2.073	0.326	1.910	more movement than previous /
	1:50	2.073	0.326	1.910	multiple rocks swaying
11	1:57	2.097	0.350	2.124	shift of at least 1 D_{50} / movement along entire line /
	2:12	2.097	0.350	2.124	three rocks next to plexiglass showed the shift
12	2:17	2.124	0.377	2.375	large shift / bed movement /
	2:32	2.124	0.377	2.375	rocks swaying up to 3ft from floodwall /
					scour hole 4 D_{50} width with lots of movement
13	2:38	2.150	0.403	2.625	more movement than previous
	2:52	2.150	0.403	2.625	multiple rocks swaying

Run #	Average Q (cfs)	q (cfs/ft)	dc (ft)	h/dc	D_{50}/dc
1	0.202	0.067	0.052	38.40	5.57
2	0.337	0.112	0.073	27.35	3.97
3	0.473	0.158	0.092	21.81	3.16
4	0.638	0.213	0.112	17.85	2.59
5	0.803	0.268	0.131	15.32	2.22
6	1.002	0.334	0.151	13.22	1.92
7	1.244	0.415	0.175	11.44	1.66
8	1.492	0.497	0.197	10.14	1.47
9	1.677	0.559	0.213	9.37	1.36
10	1.910	0.637	0.233	8.60	1.25
11	2.124	0.708	0.250	8.01	1.16
12	2.375	0.792	0.269	7.44	1.08
13	2.625	0.875	0.288	6.96	1.01

Test #	2	Drop height, ft	2	
Recorder	Jason	rock size, mm	52	
Date	4/5/2008	pt gage crest rd, ft	x= 49	y= centerline	z= 1.747

calibration curve: $Q = CH^{3/2}$ C = 10.26

run #	time start/end	sta. 49 pt gage rd, ft	head on crest H, ft	flume discharge Q, cfs	comments: stable/shift/scour
1	8:00	1.851	0.104	0.344	no movement / stable
	8:10	1.851	0.104	0.344	
2	8:12	1.876	0.129	0.475	no movement / stable
	8:25	1.876	0.129	0.475	
3	8:26	1.904	0.157	0.638	no movement / stable
	8:36	1.904	0.157	0.638	
4	8:38	1.936	0.189	0.843	minor movement of 1 D_{50} in view of window
	8:48	1.936	0.189	0.843	
5	8:50	1.965	0.218	1.044	minor movement / 2 D_{50} moved 0.5 ft downstream / increased uplift line
	9:05	1.965	0.218	1.044	
6	9:07	1.992	0.245	1.244	movement began in bottom D_{50} of bed / displacement of upper D_{50} under jet
	9:22	1.992	0.245	1.244	
7	9:25	2.019	0.272	1.455	instability to a depth of 1 D_{50} / shift of several rocks / failure within first 3 minutes / scour extended full 2 D_{50} depth across 80% of length
	9:40	2.019	0.272	1.455	

Run #	Average Q (cfs)	q (cfs/ft)	dc (ft)	h/dc	D_{50}/dc
1	0.344	0.115	0.074	26.95	2.29
2	0.475	0.158	0.092	21.73	1.85
3	0.638	0.213	0.112	17.85	1.52
4	0.843	0.281	0.135	14.83	1.26
5	1.044	0.348	0.156	12.86	1.09
6	1.244	0.415	0.175	11.44	0.97
7	1.455	0.485	0.194	10.31	0.88

Test #	3		Drop height, ft	2		
Recorder	Jason		rock size, mm	33		
Date	4/5/2008		pt gage crest rd, ft	x= 49	y= centerline	z= 1.747

			calibration curve: $Q = CH^{3/2}$	C = 10.26	
run #	time start/end	sta. 49 pt gage rd, ft	head on crest H, ft	flume discharge Q, cfs	comments: stable/shift/scour
1	10:43	1.810	0.063	0.162	stable / no movement
	10:56	1.809	0.062	0.158	
2	10:57	1.829	0.082	0.241	1 visible rock swaying / stable overall /
	11:10	1.829	0.082	0.241	no movement
3	11:11	1.855	0.108	0.364	minor movement initially / settled quickly /
		1.854	0.107	0.359	
4	11:21	1.874	0.127	0.464	movement downstream and upstream of jet /
	11:33	1.874	0.127	0.464	scour bed 1 D50 deep
5	11:35	1.906	0.159	0.650	displacement of 1 D50 depth at jet /
	11:50	1.906	0.159	0.650	visible failure at 11:40 / complete failure at 11:43

Run #	Average Q (cfs)	q (cfs/ft)	dc (ft)	h/dc	D_{50}/dc
1	0.160	0.053	0.045	44.85	2.47
2	0.241	0.080	0.059	34.18	1.88
3	0.362	0.121	0.077	26.07	1.43
4	0.464	0.155	0.091	22.07	1.21
5	0.650	0.217	0.113	17.63	0.97

Test #	4		Drop height, ft	2		
Recorder	Jason		rock size, mm	15.3		
Date	4/5/2008		pt gage crest rd, ft	x= 49	y= centerline	z= 1.747

			calibration curve: $Q = CH^{3/2}$	C = 10.26	
run #	time start/end	sta. 49 pt gage rd, ft	head on crest H, ft	flume discharge Q, cfs	comments: stable/shift/scour
1	3:11	1.815	0.068	0.182	Instant failure
	3:13	1.815	0.068	0.182	scour entire length
2	3:20	1.817	0.070	0.190	instant movement
	3:35	1.817	0.070	0.190	failure within first 5 minutes

Run #	Average Q (cfs)	q (cfs/ft)	dc (ft)	h/dc	D_{50}/dc
1	0.182	0.061	0.049	41.22	1.03
2	0.190	0.063	0.050	40.04	1.00

Test #	5	Drop height, ft	0.5		
Recorder	Jason / Kevin	rock size, mm	89		
Date	4/9/2008	pt gage crest rd, ft	x= 49	y= centerline	z= 1.747

			calibration curve: $Q = CH^{3/2}$		C = 10.26
run #	time start/end	sta. 49 pt gage rd, ft	head on crest H, ft	flume discharge Q, cfs	comments: stable/shift/scour
1	12:29	1.985	0.238	1.191	stable / no movement
	12:44	1.984	0.237	1.184	
2	12:49	2.013	0.266	1.408	minor movement of 1-2 rocks
	1:04	2.011	0.264	1.392	
3	1:09	2.040	0.293	1.627	minor movement of 1-2 rocks
	1:24	2.041	0.294	1.636	
4	1:30	2.064	0.317	1.831	minor movement of 1-2 rocks
	1:46	2.064	0.317	1.831	
5	1:52	2.092	0.345	2.079	minor movement
	2:07	2.092	0.345	2.079	
6	2:10	2.118	0.371	2.319	displacement towards downstream of 1 rock
	2:25	2.118	0.371	2.319	
7	2:30	2.145	0.398	2.576	bottom D50 swaying along with top D50
	2:45	2.145	0.398	2.576	
8	2:51	2.180	0.433	2.923	no air space / slight shift of top D50
	3:06	2.182	0.435	2.944	
9	3:15	2.203	0.456	3.159	Visible movement up to 20" downstream of wall
	3:30	2.204	0.457	3.170	
10	3:35	2.220	0.473	3.338	visible movement
	3:50	2.220	0.473	3.338	
11	3:55	2.325	0.578	4.509	visible movement
	4:10	2.325	0.578	4.509	

Run #	Average Q (cfs)	q (cfs/ft)	dc (ft)	h/dc	D_{50}/dc
1	1.188	0.396	0.169	2.95	1.71
2	1.400	0.467	0.189	2.64	1.53
3	1.631	0.544	0.209	2.39	1.38
4	1.831	0.610	0.226	2.21	1.28
5	2.079	0.693	0.246	2.03	1.18
6	2.319	0.773	0.265	1.89	1.10
7	2.576	0.859	0.284	1.76	1.02
8	2.933	0.978	0.310	1.61	0.94
9	3.165	1.055	0.326	1.54	0.89
10	3.338	1.113	0.337	1.48	0.86
11	4.509	1.503	0.412	1.21	0.70

Test #	6	Drop height, ft	0.5		
Recorder	Jason	rock size, mm	52		
Date	4/10/2008	pt gage crest rd, ft	x= 49	y= centerline	z= 1.747

calibration curve: $Q = CH^{3/2}$ C = 10.26

run #	time start/end	sta. 49 pt gage rd, ft	head on crest H, ft	flume discharge Q, cfs	comments: stable/shift/scour
1	9:15	1.983	0.236	1.176	initial movement until rocks settled into place /
	9:30	1.983	0.236	1.176	stable after initial water impact
2	9:32	2.014	0.267	1.416	minor movement of one rock /
	9:47	2.010	0.263	1.384	stable for the majority
3	9:48	2.036	0.289	1.594	2 rocks in visible area moving /
	10:03	2.036	0.289	1.594	2 rocks displaced downstream
4	10:07	2.063	0.316	1.823	minor movement
	10:22	2.064	0.317	1.831	
5	10:26	2.093	0.346	2.088	minor movement of 3 rocks in visible area
	10:41	2.094	0.347	2.097	
6	10:43	2.119	0.372	2.328	minor movement of rocks in visible area /
	10:58	2.119	0.372	2.328	shift of 4 rocks downstream (at 19" from wall)
7	11:01	2.139	0.392	2.518	displacement of 1 rock from 13" to 22" downstream of
	11:16	2.139	0.392	2.518	wall / minor movement of several rocks in visible area /
					bottom of bed stable
8	11:19	2.171	0.424	2.833	ridge shifted after 3 minutes / rocks at 21-22" begin
	11:34	2.171	0.424	2.833	to move and crest is pushed farther out
9	11:35	2.204	0.457	3.170	rocks on crest shifting and moving to a more stable
	11:50	2.202	0.455	3.149	structure / bottom still stable
10	11:53	2.239	0.492	3.541	minor movement beginning in bottom D50
	12:08	2.240	0.493	3.552	
11	12:10	2.260	0.513	3.770	minor movement beginning in bottom D50
	12:25	2.260	0.513	3.770	

Run #	Average Q (cfs)	q (cfs/ft)	dc (ft)	h/dc	D_{50}/dc
1	1.176	0.392	0.168	2.97	1.01
2	1.400	0.467	0.189	2.64	0.90
3	1.594	0.531	0.206	2.42	0.82
4	1.827	0.609	0.226	2.21	0.75
5	2.093	0.698	0.247	2.02	0.69
6	2.328	0.776	0.265	1.88	0.64
7	2.518	0.839	0.280	1.79	0.61
8	2.833	0.944	0.303	1.65	0.56
9	3.159	1.053	0.325	1.54	0.52
10	3.546	1.182	0.351	1.42	0.48
11	3.770	1.257	0.366	1.37	0.46

Test #	7	Drop height, ft	0.5	
Recorder	Sarah	rock size, mm	33	
Date	4/10/2008	pt gage crest rd, ft	x= 49	y= centerline	z= 1.747

run #	time start/end	sta. 49 pt gage rd, ft	head on crest H, ft	flume discharge Q, cfs	comments: stable/shift/scour
			calibration curve: $Q = CH^{3/2}$		C = 10.26
1	2:38	1.887	0.140	0.537	steady / no movement
	2:48	1.890	0.143	0.555	
2	2:53	1.932	0.185	0.816	slight movement of 2 rocks in visible area
	3:03	1.931	0.184	0.810	
3	3:08	1.963	0.216	1.030	whole layer of D50 shifted downstream / beginning of scour / crest forming / distinct crest formed after 10 minutes
	3:23	1.963	0.216	1.030	
4	3:24	1.991	0.244	1.237	minor movement
	3:40	1.992	0.245	1.244	
5	3:43	2.015	0.268	1.423	crest leveled off / bottom D50 beginning to move
	4:00	2.014	0.267	1.416	
6	4:02	2.041	0.294	1.636	bottom D50 movement / rocks pushed off back
	4:18	2.041	0.294	1.636	
7	4:20	2.067	0.320	1.857	bottom D50 starting to have lift / small failure point at 4:39 into time
	4:35	2.068	0.321	1.866	
8	4:37	2.094	0.347	2.097	failure point 5 D50 into width / crest stacked up at 5 D50
	4:52	2.094	0.347	2.097	

Run #	Average Q (cfs)	q (cfs/ft)	dc (ft)	h/dc	D_{50}/dc
1	0.546	0.182	0.10	4.95	1.089495
2	0.813	0.271	0.13	3.80	0.835597
3	1.030	0.343	0.15	3.24	0.71374
4	1.240	0.413	0.17	2.87	0.630543
5	1.419	0.473	0.19	2.62	0.576328
6	1.636	0.545	0.21	2.38	0.524381
7	1.862	0.621	0.23	2.19	0.481023
8	2.097	0.699	0.25	2.02	0.444288

Test #	8	Drop height, ft	0.5		
Recorder	Sarah	rock size, mm	15.3		
Date	4/10/2008	pt gage crest rd, ft	x= 49	y= centerline	z= 1.747

			calibration curve: $Q = CH^{3/2}$		C = 10.26
run #	time start/end	sta. 49 pt gage rd, ft	head on crest H, ft	flume discharge Q, cfs	comments: stable/shift/scour
1	5:55	1.819	0.072	0.198	displacement of rocks /
	6:10	1.819	0.072	0.198	ridge forming
2	6:15	1.831	0.084	0.250	displacement of rocks /
	6:30	1.831	0.084	0.250	ridge growing
3	6:31	1.844	0.097	0.310	failure in middle / scour hole 3 D50 in width
	6:46	1.844	0.097	0.310	

Run #	Average Q (cfs)	q (cfs/ft)	dc (ft)	h/dc	D_{50}/dc
1	0.198	0.066	0.051	9.73	0.97
2	0.250	0.083	0.060	8.34	0.83
3	0.310	0.103	0.069	7.22	0.72

Test #	9	Drop height, ft	1		
Recorder	Kevin	rock size, mm	15.3		
Date	4/11/2008	pt gage crest rd, ft	x= 49	y= centerline	z= 1.747

			calibration curve: $Q = CH^{3/2}$		C = 10.26
run #	time start/end	sta. 49 pt gage rd, ft	head on crest H, ft	flume discharge Q, cfs	comments: stable/shift/scour
1	2:03	1.802	0.055	0.132	top layer of D50 moved within 2 minutes /
	2:18	1.802	0.055	0.132	bottom D50 beginning to have lift
2	2:19	1.810	0.063	0.162	Failure reaced within 2 minutes
	2:35	1.810	0.063	0.162	

Run #	Average Q (cfs)	q (cfs/ft)	dc (ft)	h/dc	D_{50}/dc
1	0.132	0.044	0.039	25.48	1.27
2	0.162	0.054	0.045	22.25	1.11

Test #	10	Drop height, ft	1		
Recorder	Kevin	rock size, mm	33		
Date	4/12/2008	pt gage crest rd, ft	x= 49	y= centerline	z= 1.747

run #	time start/end	sta. 49 pt gage rd, ft	head on crest H, ft	flume discharge Q, cfs	comments: stable/shift/scour
			calibration curve: $Q = CH^{3/2}$		C = 10.26
1	8:10	1.865	0.118	0.416	minor movement
	8:25	1.865	0.118	0.416	
2	8:33	1.877	0.130	0.481	displacement of upper D50
	8:38	1.877	0.130	0.481	
3	8:39	1.906	0.159	0.650	failure after 5 minutes
	8:47	1.906	0.159	0.650	

Run #	Average Q (cfs)	q (cfs/ft)	dc (ft)	h/dc	D_{50}/dc
1	0.416	0.139	0.084	11.877	1.307
2	0.481	0.160	0.093	10.781	1.186
3	0.650	0.217	0.113	8.815	0.970

Test #	11	Drop height, ft	1		
Recorder	Kevin	rock size, mm	52		
Date	4/12/2008	pt gage crest rd, ft	x= 49	y= centerline	z= 1.747

run #	time start/end	sta. 49 pt gage rd, ft	head on crest H, ft	flume discharge Q, cfs	comments: stable/shift/scour
			calibration curve: $Q = CH^{3/2}$		C = 10.26
1	9:27	1.896	0.149	0.590	no movement / stable
	9:42	1.896	0.149	0.590	
2	9:43	1.935	0.188	0.836	minor movement / a few rocks moving
	9:58	1.935	0.188	0.836	
3	10:00	1.962	0.215	1.023	minor movement downstream of overtop
	10:15	1.962	0.215	1.023	
4	10:17	2.015	0.268	1.423	minor movement in scour zone
	10:32	2.015	0.268	1.423	
5	10:33	2.048	0.301	1.694	minor movement in scour zone
	10:48	2.048	0.301	1.694	
6	10:50	2.073	0.326	1.910	minor movement in scour zone
	11:05	2.073	0.326	1.910	
7	11:06	2.109	0.362	2.235	failure after 4 minutes
	11:21	2.110	0.363	2.244	

Run #	Average Q (cfs)	q (cfs/ft)	dc (ft)	h/dc	D_{50}/dc
1	0.590	0.197	0.106	9.41	1.60
2	0.836	0.279	0.134	7.45	1.27
3	1.023	0.341	0.153	6.52	1.11
4	1.423	0.474	0.191	5.230	0.889
5	1.694	0.565	0.215	4.656	0.792
6	1.910	0.637	0.233	4.299	0.731
7	2.239	0.746	0.259	3.866	0.657

Test #	12	Drop height, ft	2		
Recorder	Kevin	rock size, mm	89		
Date	4/12/2008	pt gage crest rd, ft	x= 49	y= centerline	z= 1.747

calibration curve: $Q = CH^{3/2}$ C = 10.26

run #	time start/end	sta. 49 pt gage rd, ft	head on crest H, ft	flume discharge Q, cfs	comments: stable/shift/scour
1	12:05	2.017	0.270	1.439	shifted to stable
	12:20	2.017	0.270	1.439	
2	12:21	2.049	0.302	1.703	minor movement to stable
	12:36	2.050	0.303	1.711	
3	12:38	2.074	0.327	1.919	minor movement through entire depth of bed at jet
	12:51	2.074	0.327	1.919	
4	12:55	2.121	0.374	2.347	minor movement through entire depth of bed at jet
	1:10	2.121	0.374	2.347	
5	1:14	2.140	0.393	2.528	minor movement has let to stabilization
	1:29	2.141	0.394	2.537	
6	1:32	2.153	0.406	2.654	minor movement through entire depth of bed at jet / displacement of top D50 downstream
	1:47	2.153	0.406	2.654	
7	1:50	2.177	0.430	2.893	movement of rocks up to 28" downstream of wall
	2:15	2.177	0.430	2.893	
8	2:17	2.201	0.454	3.139	minor movement of rocks 28-30" downstream / 1 D50 scour
	2:32	2.201	0.454	3.139	
9	2:35	2.227	0.480	3.412	minor movement
	2:50	2.227	0.480	3.412	
10	2:53	2.251	0.504	3.671	bottom D50 stabilized / minor movement of upper D50
	3:08	2.251	0.504	3.671	
11	3:11	2.266	0.519	3.836	minor movement
	3:27	2.270	0.523	3.881	

Run #	Average Q (cfs)	q (cfs/ft)	dc (ft)	h/dc	D_{50}/dc
1	1.439	0.480	0.193	5.191	1.505
2	1.707	0.569	0.216	4.633	1.344
3	1.919	0.640	0.233	4.286	1.243
4	2.347	0.782	0.267	3.747	1.087
5	2.533	0.844	0.281	3.562	1.033
6	2.654	0.885	0.290	3.452	1.001
7	2.893	0.964	0.307	3.259	0.945
8	3.139	1.046	0.324	3.087	0.895
9	3.412	1.137	0.342	2.920	0.847
10	3.671	1.224	0.360	2.781	0.806
11	3.858	1.286	0.372	2.690	0.780

Water Surface Profile Data Sheets

Run #	1	pnt gage crest reading, ft	1.747
Test #	1		
Date #	4/2/2008		
Recorder	Kevin Chancey		

Time	Station (x)	Station (y)	Water Surface Elevation (z)	Comments
2:52	49.00	Centerline	1.820	
	48.00	"	1.820	
	47.00	"	1.819	
	46.50	"	1.819	
	46.00	"	1.818	
	45.50	"	1.817	
	45.00	"	1.817	
	44.50	"	1.817	
	44.25	"	1.817	
	44.15	"	1.816	
	44.10	"	1.814	
	44.05	"	1.809	
	44.00	"	1.794	
	43.95	"	1.757	
	43.90	"	1.697	
	43.85	"	1.593	
	43.80	"	1.461	
	43.75	"	1.295	
	43.65	"	0.784	
	43.58	"	0.206	
3:12	43.55	"	0.000	IMPACT POINT

Run #	2	pnt gage crest reading, ft	1.747
Test #	1		
Date #	4/2/2008		
Recorder	Kevin Chancey		

Time	Station (x)	Station (y)	Water Surface Elevation (z)	Comments
3:20	49.00	Centerline	1.850	
	48.00	"	1.850	
	47.00	"	1.849	
	46.00	"	1.848	
	45.50	"	1.848	
	45.00	"	1.847	
	44.50	"	1.847	
	44.25	"	1.846	
	44.10	"	1.840	
	44.00	"	1.818	
	43.95	"	1.787	
	43.90	"	1.739	
	43.85	"	1.659	
	43.80	"	1.567	
	43.75	"	1.437	
	43.70	"	1.278	
	43.65	"	1.019	
	43.60	"	0.701	
3:27	43.54	"	0.000	IMPACT POINT

Run #	3
Test #	1
Date #	4/2/2008
Recorder	Kevin Chancey

pnt gage crest reading, ft 1.747

Time	Station (x)	Station (y)	Water Surface Elevation (z)	Comments
3:32	49.00	Centerline	1.875	
	48.00	"	1.875	
	47.00	"	1.874	
	46.50	"	1.874	
	46.00	"	1.874	
	45.50	"	1.873	
	45.00	"	1.873	
	44.50	"	1.872	
	44.25	"	1.870	
	44.10	"	1.861	
	44.05	"	1.853	
	44.00	"	1.837	
	43.95	"	1.810	
	43.90	"	1.769	
	43.85	"	1.709	
	43.80	"	1.633	
	43.75	"	1.547	
	43.70	"	1.458	
	43.65	"	1.330	
	43.60	"	1.205	
	43.55	"	1.062	
	43.50	"	0.904	
	43.45	"	0.753	
	43.40	"	0.589	
	43.35	"	0.417	
	43.30	"	0.268	
	43.25	"	0.052	
3:43	43.20	"	0.000	IMPACT POINT

Run #	4
Test #	1
Date #	4/2/2008
Recorder	Kevin Chancey

pnt gage crest reading, ft 1.747

Time	Station (x)	Station (y)	Water Surface Elevation (z)	Comments
3:50	49.00	Centerline	1.904	
	47.00	"	1.903	
	46.50	"	1.903	
	46.00	"	1.902	
	45.50	"	1.901	
	45.00	"	1.900	
	44.50	"	1.900	
	44.25	"	1.898	
	44.10	"	1.887	
	44.05	"	1.879	
	44.00	"	1.863	
	43.95	"	1.842	
	43.90	"	1.814	
	43.85	"	1.764	
	43.80	"	1.706	
	43.75	"	1.638	
	43.70	"	1.560	
	43.65	"	1.463	
	43.60	"	1.362	
	43.55	"	1.235	
	43.50	"	1.090	
	43.45	"	0.943	
	43.40	"	0.781	
	43.35	"	0.619	
	43.30	"	0.490	
	43.25	"	0.271	
	43.20	"	0.046	
4:01	43.15	"	0.000	IMPACT POINT

Run #	5	pnt gage crest reading, ft	1.747
Test #	1		
Date #	4/4/2008		
Recorder	Kevin Chancey		

Time	Station (x)	Station (y)	Water Surface Elevation (z)	Comments
12:08	49.00	Centerline	1.930	
	47.00	"	1.930	
	46.50	"	1.929	
	46.00	"	1.928	
	45.50	"	1.928	
	45.00	"	1.928	
	44.50	"	1.926	
	44.25	"	1.922	
	44.10	"	1.912	
	44.05	"	1.903	
	44.00	"	1.887	
	43.95	"	1.870	
	43.90	"	1.837	
	43.85	"	1.803	
	43.80	"	1.755	
	43.75	"	1.699	
	43.70	"	1.631	
	43.65	"	1.545	
	43.60	"	1.462	
	43.55	"	1.370	
	43.50	"	1.256	
	43.45	"	1.125	
	43.40	"	1.000	
	43.35	"	0.834	
	43.30	"	0.702	
	43.25	"	0.528	
	43.20	"	0.359	
	43.15	"	0.115	
	43.10	"	0.000	
12:18	43.05	"	0.000	IMPACT POINT

Run #	6	pnt gage crest reading, ft	1.747
Test #	1		
Date #	4/4/2008		
Recorder	Kevin Chancey		

Time	Station (x)	Station (y)	Water Surface Elevation (z)	Comments
12:25	49.00	Centerline	1.959	
	47.00	"	1.959	
	46.50	"	1.958	
	46.00	"	1.958	
	45.50	"	1.957	
	45.00	"	1.956	
	44.50	"	1.955	
	44.25	"	1.950	
	44.10	"	1.936	
	44.05	"	1.927	
	44.00	"	1.914	
	43.95	"	1.898	
	43.90	"	1.872	
	43.85	"	1.838	
	43.80	"	1.800	
	43.75	"	1.743	
	43.70	"	1.687	
	43.65	"	1.627	
	43.60	"	1.543	
	43.55	"	1.450	
	43.50	"	1.368	
	43.45	"	1.252	
	43.40	"	1.136	
	43.35	"	0.995	
	43.30	"	0.880	
	43.25	"	0.738	
	43.20	"	0.588	
	43.15	"	0.390	
	43.10	"	0.210	
	43.05	"	0.038	
12:35	43.00	"	0.000	IMPACT POINT

Run #	7
Test #	1
Date #	4/4/2008
Recorder	Kevin Chancey

pnt gage crest reading, ft 1.747

Time	Station (x)	Station (y)	Water Surface Elevation (z)	Comments
12:43	49.00	Centerline	1.992	
	47.00	"	1.992	
	46.50	"	1.992	
	46.00	"	1.991	
	45.50	"	1.990	
	45.00	"	1.989	
	44.50	"	1.986	
	44.25	"	1.980	
	44.10	"	1.962	
	44.05	"	1.956	
	44.00	"	1.942	
	43.95	"	1.952	
	43.90	"	1.903	
	43.85	"	1.873	
	43.80	"	1.834	
	43.75	"	1.787	
	43.70	"	1.746	
	43.65	"	1.685	
	43.60	"	1.621	
	43.55	"	1.545	
	43.50	"	1.459	
	43.45	"	1.358	
	43.40	"	1.267	
	43.35	"	1.134	
	43.30	"	1.044	
	43.25	"	0.903	
	43.20	"	0.774	
	43.15	"	0.611	
	43.10	"	0.495	
	43.05	"	0.264	
	43.00	"	0.116	
	42.95	"	0.000	
12:52	42.90	"	0.000	IMPACT POINT

Run #	8
Test #	1
Date #	4/4/2008
Recorder	Kevin Chancey

pnt gage crest reading, ft 1.747

Time	Station (x)	Station (y)	Water Surface Elevation (z)	Comments
1:04	49.00	Centerline	2.024	
	47.00	"	2.024	
	46.50	"	2.023	
	46.00	"	2.022	
	45.50	"	2.021	
	45.00	"	2.020	
	44.50	"	2.016	
	44.25	"	2.008	
	44.10	"	1.993	
	44.05	"	1.982	
	44.00	"	1.967	
	43.95	"	1.950	
	43.90	"	1.933	
	43.85	"	1.905	
	43.80	"	1.873	
	43.75	"	1.830	
	43.70	"	1.790	
	43.65	"	1.729	
	43.60	"	1.679	
	43.55	"	1.599	
	43.50	"	1.525	
	43.45	"	1.440	
	43.40	"	1.359	
	43.35	"	1.244	
	43.30	"	1.145	
	43.25	"	1.031	
	43.20	"	0.875	
	43.15	"	0.725	
	43.10	"	0.599	
	43.05	"	0.475	
	43.00	"	0.220	
	42.95	"	0.056	
	42.90	"	0.000	
1:18	42.85	"	0.000	IMPACT POINT

Run #	9	pnt gage crest reading, ft	1.747
Test #	1		
Date #	4/4/2008		
Recorder	Kevin Chancey		

Time	Station (x)	Station (y)	Water Surface Elevation (z)	Comments
1:24	49.00	Centerline	2.046	
	47.00	"	2.046	
	46.50	"	2.045	
	46.00	"	2.045	
	45.50	"	2.045	
	45.00	"	2.043	
	44.50	"	2.038	
	44.25	"	2.028	
	44.10	"	2.011	
	44.05	"	2.000	
	44.00	"	1.988	
	43.95	"	1.973	
	43.90	"	1.956	
	43.85	"	1.926	
	43.80	"	1.896	
	43.75	"	1.863	
	43.70	"	1.819	
	43.65	"	1.772	
	43.60	"	1.708	
	43.55	"	1.646	
	43.50	"	1.580	
	43.45	"	1.496	
	43.40	"	1.416	
	43.35	"	1.336	
	43.30	"	1.219	
	43.25	"	1.098	
	43.20	"	0.958	
	43.15	"	0.850	
	43.10	"	0.676	
	43.05	"	0.500	
	43.00	"	0.285	
	42.95	"	0.059	
	42.90	"	0.000	
1:34	42.81	"	0.000	IMPACT POINT

Run #	10
Test #	1
Date #	4/4/2008
Recorder	Kevin Chancey

pnt gage crest reading, ft: 1.747

Time	Station (x)	Station (y)	Water Surface Elevation (z)	Comments
1:40	49.00	Centerline	2.073	
	47.00	"	2.073	
	46.50	"	2.073	
	46.00	"	2.073	
	45.50	"	2.072	
	45.00	"	2.071	
	44.50	"	2.064	
	44.25	"	2.053	
	44.10	"	2.035	
	44.05	"	2.024	
	44.00	"	2.009	
	43.95	"	1.998	
	43.90	"	1.977	
	43.85	"	1.953	
	43.80	"	1.923	
	43.75	"	1.897	
	43.70	"	1.853	
	43.65	"	1.803	
	43.60	"	1.760	
	43.55	"	1.698	
	43.50	"	1.630	
	43.45	"	1.564	
	43.40	"	1.476	
	43.35	"	1.398	
	43.30	"	1.313	
	43.25	"	1.200	
	43.20	"	1.108	
	43.15	"	0.984	
	43.10	"	0.828	
	43.05	"	0.682	
	43.00	"	0.574	
	42.95	"	0.391	
	42.90	"	0.258	
	42.85	"	0.055	
	42.80	"	0.000	
1:50	42.69	"	0.000	IMPACT POINT

Run #	11
Test #	1
Date #	4/4/2008
Recorder	Kevin Chancey

pnt gage crest reading, ft 1.747

Time	Station (x)	Station (y)	Water Surface Elevation (z)	Comments
2:00	49.00	Centerline	2.097	
	47.00	"	2.097	
	46.50	"	2.097	
	46.00	"	2.096	
	45.50	"	2.095	
	45.00	"	2.094	
	44.50	"	2.084	
	44.25	"	2.072	
	44.10	"	2.054	
	44.05	"	2.045	
	44.00	"	2.030	
	43.95	"	2.015	
	43.90	"	2.000	
	43.85	"	1.976	
	43.80	"	1.948	
	43.75	"	1.915	
	43.70	"	1.882	
	43.65	"	1.828	
	43.60	"	1.791	
	43.55	"	1.726	
	43.50	"	1.661	
	43.45	"	1.617	
	43.40	"	1.527	
	43.35	"	1.432	
	43.30	"	1.367	
	43.25	"	1.244	
	43.20	"	1.133	
	43.15	"	1.028	
	43.10	"	0.894	
	43.05	"	0.780	
	43.00	"	0.647	
	42.95	"	0.541	
	42.90	"	0.352	
	42.85	"	0.183	
2:10	42.78	"	0.000	IMPACT POINT

Run #	12
Test #	1
Date #	4/4/2008
Recorder	Kevin Chancey

pnt gage crest reading, ft 1.747

Time	Station (x)	Station (y)	Water Surface Elevation (z)	Comments
2:20	49.00	Centerline	2.124	
	47.00	"	2.124	
	46.50	"	2.124	
	46.00	"	2.124	
	45.50	"	2.122	
	45.00	"	2.118	
	44.50	"	2.110	
	44.25	"	2.096	
	44.10	"	2.079	
	44.05	"	2.069	
	44.00	"	2.053	
	43.95	"	2.043	
	43.90	"	2.024	
	43.85	"	2.000	
	43.80	"	1.971	
	43.75	"	1.950	
	43.70	"	1.906	
	43.65	"	1.866	
	43.60	"	1.818	
	43.55	"	1.769	
	43.50	"	1.712	
	43.45	"	1.641	
	43.40	"	1.554	
	43.35	"	1.505	
	43.30	"	1.417	
	43.25	"	1.342	
	43.20	"	1.240	
	43.15	"	1.116	
	43.10	"	1.014	
	43.05	"	0.890	
	43.00	"	0.728	
	42.95	"	0.519	
	42.90	"	0.410	
	42.85	"	0.145	
	42.80	"	0.025	
	42.75	"	0.000	
2:32	42.70	"	0.000	IMPACT POINT

Run #	13	pnt gage crest reading, ft	1.747
Test #	1		
Date #	4/4/2008		
Recorder	Kevin Chancey		

Time	Station (x)	Station (y)	Water Surface Elevation (z)	Comments
2:40	49.00	Centerline	2.150	
	47.00	"	2.150	
	46.50	"	2.148	
	46.00	"	2.148	
	45.50	"	2.148	
	45.00	"	2.145	
	44.50	"	2.135	
	44.25	"	2.120	
	44.10	"	2.100	
	44.05	"	2.093	
	44.00	"	2.077	
	43.95	"	2.062	
	43.90	"	2.046	
	43.85	"	2.025	
	43.80	"	1.997	
	43.75	"	1.971	
	43.70	"	1.939	
	43.65	"	1.900	
	43.60	"	1.857	
	43.55	"	1.812	
	43.50	"	1.741	
	43.45	"	1.687	
	43.40	"	1.628	
	43.35	"	1.551	
	43.30	"	1.457	
	43.25	"	1.395	
	43.20	"	1.290	
	43.15	"	1.147	
	43.10	"	0.991	
	43.05	"	0.852	
	43.00	"	0.684	
	42.95	"	0.487	
	42.90	"	0.447	
	42.85	"	0.211	
2:52	42.79	"	0.000	IMPACT POINT

Run #	1	pnt gage crest reading, ft	1.747
Test #	3		
Date #	4/5/2008		
Recorder	Sarah Edens		

Time	Station (x)	Station (y)	Water Surface Elevation (z)	Comments
10:43	49.00	Centerline	1.810	
	47.00	"	1.809	
	46.50	"	1.808	
	46.00	"	1.808	
	45.50	"	1.807	
	45.00	"	1.807	
	44.50	"	1.806	
	44.25	"	1.806	
	44.10	"	1.804	
	44.05	"	1.801	
	44.00	"	1.785	
	43.95	"	1.744	
	43.90	"	1.653	
	43.85	"	1.525	
	43.80	"	1.379	
	43.75	"	1.168	
	43.70	"	0.957	
	43.65	"	0.854	
	43.60	"	0.294	
10:55	43.55	"		Impact Point

Run #	2	pnt gage crest reading, ft	1.747
Test #	3		
Date #	4/5/2008		
Recorder	Sarah Edens		

Time	Station (x)	Station (y)	Water Surface Elevation (z)	Comments
10:57	49.00	Centerline	1.829	
	47.00	"	1.829	
	46.50	"	1.828	
	46.00	"	1.828	
	45.50	"	1.827	
	45.00	"	1.826	
	44.50	"	1.826	
	44.25	"	1.826	
	44.10	"	1.822	
	44.05	"	1.815	
	44.00	"	1.801	
	43.95	"	1.767	
	43.90	"	1.706	
	43.85	"	1.622	
	43.80	"	1.511	
	43.75	"	1.382	
	43.70	"	1.215	
	43.65	"	1.026	
	43.60	"	0.810	
	43.55	"	0.570	
	43.50	"	0.296	
11:07	43.45	"		Impact Point

Run #	1	pnt gage crest reading, ft	1.747
Test #	4		
Date #	4/5/2008		
Recorder	Monica Murie		

Time	Station (x)	Station (y)	Water Surface Elevation (z)	Comments
3:20	49.00	Centerline	1.817	
	47.00	"	1.816	
	46.50	"	1.815	
	46.00	"	1.815	
	45.50	"	1.814	
	45.00	"	1.814	
	44.50	"	1.813	
	44.25	"	1.813	
	44.10	"	1.810	
	44.05	"	1.807	
	44.00	"	1.791	
	43.95	"	1.750	
	43.90	"	1.689	
	43.85	"	1.581	
	43.80	"	1.440	
	43.75	"	1.273	
	43.70	"	1.053	
	43.65	"	0.781	
	43.60	"	0.550	
	43.55	"	0.273	
3:30	43.50		---	Impact Point

Run #	1	pnt gage crest reading, ft	1.747
Test #	5		
Date #	4/9/2008		
Recorder	Sarah Edens		

Time	Station (x)	Station (y)	Water Surface Elevation (z)	Comments
12:29	49.00	Centerline	1.985	
	47.00	"	1.985	
	46.50	"	1.982	
	46.00	"	1.982	
	45.50	"	1.982	
	45.00	"	1.982	
	44.50	"	1.981	
	44.25	"	1.972	
	44.10	"	1.956	
	44.05	"	1.946	
	44.00	"	1.930	
	43.95	"	1.915	
	43.90	"	1.889	
	43.85	"	1.855	
	43.80	"	1.805	
	43.75	"	1.746	
	43.70	"	1.686	
	43.65	"	1.587	
	43.60	"	1.468	
12:38	43.55	"	1.410	IMPACT POINT

Run #	2	pnt gage crest reading, ft	1.747
Test #	5		
Date #	4/9/2008		
Recorder	Sarah Edens		

Time	Station (x)	Station (y)	Water Surface Elevation (z)	Comments
12:49	49.00	Centerline	2.013	
	47.00	"	2.009	
	46.50	"	2.009	
	46.00	"	2.009	
	45.50	"	2.009	
	45.00	"	2.007	
	44.50	"	2.003	
	44.25	"	1.994	
	44.10	"	1.979	
	44.05	"	1.968	
	44.00	"	1.956	
	43.95	"	1.938	
	43.90	"	1.914	
	43.85	"	1.884	
	43.80	"	1.848	
	43.75	"	1.799	
	43.70	"	1.755	
	43.65	"	1.680	
	43.60	"	1.612	
	43.55	"	1.538	
	43.50	"	1.450	
	43.45	"	1.372	
1:04	43.40	"	1.300	IMPACT POINT

Run #	3	pnt gage crest reading, ft	1.747
Test #	5		
Date #	4/9/2008		
Recorder	Sarah Edens		

Time	Station (x)	Station (y)	Water Surface Elevation (z)	Comments
1:09	49.00	Centerline	2.040	
	47.00	"	2.040	
	46.50	"	2.039	
	46.00	"	2.039	
	45.50	"	2.037	
	45.00	"	2.036	
	44.50	"	2.031	
	44.25	"	2.030	
	44.10	"	2.004	
	44.05	"	1.994	
	44.00	"	1.980	
	43.95	"	1.967	
	43.90	"	1.943	
	43.85	"	1.920	
	43.80	"	1.880	
	43.75	"	1.841	
	43.70	"	1.800	
	43.65	"	1.742	
	43.60	"	1.676	
	43.55	"	1.594	
	43.50	"	1.521	
	43.45	"	1.450	
	43.40	"	1.385	
1:16	43.35	"	1.324	IMPACT POINT

Run #	4
Test #	5
Date #	4/9/2008
Recorder	Sarah Edens

pnt gage crest reading, ft 1.747

Time	Station (x)	Station (y)	Water Surface Elevation (z)	Comments
1:30	49.00	Centerline	2.064	
	47.00	"	2.064	
	46.50	"	2.063	
	46.00	"	2.062	
	45.50	"	2.060	
	45.00	"	2.057	
	44.50	"	2.051	
	44.25	"	2.040	
	44.10	"	2.023	
	44.05	"	2.011	
	44.00	"	2.002	
	43.95	"	1.987	
	43.90	"	1.966	
	43.85	"	1.940	
	43.80	"	1.908	
	43.75	"	1.868	
	43.70	"	1.827	
	43.65	"	1.776	
	43.60	"	1.705	
	43.55	"	1.648	
	43.50	"	1.580	
	43.45	"	1.508	
	43.40	"	1.442	
	43.35	"	1.380	
1:41	43.30	"	1.336	IMPACT POINT

Run #	5
Test #	5
Date #	4/9/2008
Recorder	Sarah Edens

pnt gage crest reading, ft 1.747

Time	Station (x)	Station (y)	Water Surface Elevation (z)	Comments
1:52	49.00	Centerline	2.092	
	47.00	"	2.092	
	46.50	"	2.090	
	46.00	"	2.089	
	45.50	"	2.088	
	45.00	"	2.087	
	44.50	"	2.080	
	44.25	"	2.066	
	44.10	"	2.048	
	44.05	"	2.037	
	44.00	"	2.028	
	43.95	"	2.007	
	43.90	"	1.994	
	43.85	"	1.963	
	43.80	"	1.936	
	43.75	"	1.901	
	43.70	"	1.855	
	43.65	"	1.802	
	43.60	"	1.755	
	43.55	"	1.680	
	43.50	"	1.611	
	43.45	"	1.538	
	43.40	"	1.472	
	43.35	"	1.410	
	43.30	"	1.372	
2:01	43.25	"	1.330	IMPACT POINT

Run #	6
Test #	5
Date #	4/9/2008
Recorder	Sarah Edens

pnt gage crest reading, ft 1.747

Time	Station (x)	Station (y)	Water Surface Elevation (z)	Comments
2:10	49.00	Centerline	2.112	
	47.00	"	2.118	
	46.50	"	2.116	
	46.00	"	2.116	
	45.50	"	2.115	
	45.00	"	2.111	
	44.50	"	2.105	
	44.25	"	2.087	
	44.10	"	2.070	
	44.05	"	2.060	
	44.00	"	2.047	
	43.95	"	2.030	
	43.90	"	2.008	
	43.85	"	1.989	
	43.80	"	1.961	
	43.75	"	1.922	
	43.70	"	1.891	
	43.65	"	1.835	
	43.60	"	1.781	
	43.55	"	1.728	
	43.50	"	1.667	
	43.45	"	1.589	
	43.40	"	1.528	
	43.35	"	1.466	
	43.30	"	1.420	
	43.25	"	1.382	
	43.20	"	1.346	
2:18	43.15	"	1.316	IMPACT POINT

Run #	7
Test #	5
Date #	4/9/2008
Recorder	Sarah Edens

pnt gage crest reading, ft 1.747

Time	Station (x)	Station (y)	Water Surface Elevation (z)	Comments
2:30	49.00	Centerline	2.145	
	47.00	"	2.142	
	46.50	"	2.142	
	46.00	"	2.141	
	45.50	"	2.141	
	45.00	"	2.140	
	44.50	"	2.130	
	44.25	"	2.123	
	44.10	"	2.094	
	44.05	"	2.080	
	44.00	"	2.065	
	43.95	"	2.035	
	43.90	"	2.013	
	43.85	"	1.987	
	43.80	"	1.955	
	43.75	"	1.925	
	43.70	"	1.880	
	43.65	"	1.865	
	43.60	"	1.835	
	43.55	"	1.770	
	43.50	"	1.715	
	43.45	"	1.647	
	43.40	"	1.584	
	43.35	"	1.524	
	43.30	"	1.460	
	43.25	"	1.413	
	43.20	"	1.374	
	43.15	"	1.345	
	43.10	"	1.323	
	43.05	"	1.303	
2:39	43.00	"	1.301	IMPACT POINT

Run #	8
Test #	5
Date #	4/9/2008
Recorder	Sarah Edens

pnt gage crest reading, ft 1.747

Time	Station (x)	Station (y)	Water Surface Elevation (z)	Comments
2:51	49.00	Centerline	2.180	
	47.00	"	2.181	
	46.50	"	2.182	
	46.00	"	2.183	
	45.50	"	2.180	
	45.00	"	2.173	
	44.50	"	2.158	
	44.25	"	2.140	
	44.10	"	2.130	
	44.05	"	2.120	
	44.00	"	2.105	
	43.95	"	2.087	
	43.90	"	2.067	
	43.85	"	2.044	
	43.80	"	2.037	
	43.75	"	2.010	
	43.70	"	1.967	
	43.65	"	1.921	
	43.60	"	1.873	
	43.55	"	1.811	
	43.50	"	1.779	
	43.45	"	1.711	
	43.40	"	1.653	
	43.35	"	1.578	
	43.30	"	1.538	
	43.25	"	1.479	
	43.20	"	1.428	
	43.15	"	1.394	
	43.10	"	1.359	
	43.05	"	1.339	
	43.00	"	1.327	
	42.95	"	1.315	
3:00	42.90	"	1.315	IMPACT POINT

Run #	9
Test #	5
Date #	4/9/2008
Recorder	Sarah Edens

pnt gage crest reading, ft 1.747

Time	Station (x)	Station (y)	Water Surface Elevation (z)	Comments
3:15	49.00	Centerline	2.203	
	47.00	"	2.201	
	46.50	"	2.200	
	46.00	"	2.200	
	45.50	"	2.200	
	45.00	"	2.195	
	44.50	"	2.181	
	44.25	"	2.163	
	44.10	"	2.140	
	44.05	"	2.130	
	44.00	"	2.115	
	43.95	"	2.100	
	43.90	"	2.081	
	43.85	"	2.080	
	43.80	"	2.050	
	43.75	"	2.031	
	43.70	"	2.003	
	43.65	"	1.954	
	43.60	"	1.931	
	43.55	"	1.880	
	43.50	"	1.834	
	43.45	"	1.753	
	43.40	"	1.706	
	43.35	"	1.678	
	43.30	"	1.600	
	43.25	"	1.554	
	43.20	"	1.480	
	43.15	"	1.467	
	43.10	"	1.423	
	43.05	"	1.412	
3:25	43.00	"	1.438	IMPACT POINT

Run #	10
Test #	5
Date #	4/9/2008
Recorder	Sarah Edens

pnt gage crest reading, ft 1.747

Time	Station (x)	Station (y)	Water Surface Elevation (z)	Comments
3:35	49.00	Centerline	2.220	
	47.00	"	2.219	
	46.50	"	2.219	
	46.00	"	2.219	
	45.50	"	2.219	
	45.00	"	2.215	
	44.50	"	2.202	
	44.25	"	2.179	
	44.10	"	2.150	
	44.05	"	2.145	
	44.00	"	2.130	
	43.95	"	2.113	
	43.90	"	2.091	
	43.85	"	2.073	
	43.80	"	2.049	
	43.75	"	2.035	
	43.70	"	1.995	
	43.65	"	1.950	
	43.60	"	1.907	
	43.55	"	1.858	
	43.50	"	1.810	
	43.45	"	1.757	
	43.40	"	1.685	
	43.35	"	1.635	
	43.30	"	1.587	
	43.25	"	1.522	
	43.20	"	1.481	
	43.15	"	1.434	
	43.10	"	1.400	
3:45	43.05	"	1.369	IMPACT POINT

Run #	11
Test #	5
Date #	4/9/2008
Recorder	Sarah Edens

pnt gage crest reading, ft 1.747

Time	Station (x)	Station (y)	Water Surface Elevation (z)	Comments
3:55	49.00	Centerline	2.325	
	47.00	"	2.325	
	46.50	"	2.325	
	46.00	"		POINT GAGE BLOCKED
	45.50	"	2.318	
	45.00	"	2.310	
	44.50	"	2.295	
	44.25	"	2.275	
	44.10	"	2.250	
	44.05	"	2.238	
	44.00	"	2.224	
	43.95	"	2.220	
	43.90	"	2.200	
	43.85	"	2.180	
	43.80	"	2.160	
	43.75	"	2.134	
	43.70	"	2.106	
	43.65	"	2.078	
	43.60	"	2.046	
	43.55	"	2.012	
	43.50	"	1.982	
	43.45	"	1.937	
	43.40	"	1.890	
	43.35	"	1.843	
	43.30	"	1.794	
	43.25	"	1.750	
	43.20	"	1.705	
	43.15	"	1.658	
	43.10	"	1.608	
	43.05	"	1.580	
	43.00	"	1.540	
	42.95	"	1.507	
	42.90	"	1.474	
	42.85	"	1.450	
4:06	42.80	"	0.443	IMPACT POINT

Run #	1	pnt gage crest reading, ft	1.747
Test #	7		
Date #	4/10/2008		
Recorder	JASON UNRUH		

Time	Station (x)	Station (y)	Water Surface Elevation (z)	Comments
2:38	49.00	Centerline	1.887	
	47.00	"	1.887	
	46.50	"	1.886	
	46.00	"	1.885	
	45.50	"	1.882	
	45.00	"	1.882	
	44.50	"	1.882	
	44.25	"	1.880	
	44.10	"	1.868	
	44.05	"	1.856	
	44.00	"	1.837	
	43.95	"	1.813	
	43.90	"	1.771	
	43.85	"	1.692	
	43.80	"	1.615	
	43.75	"	1.534	
	43.70	"	1.440	
2:49	43.65	"	1.417	IMPACT POINT

Run #	2	pnt gage crest reading, ft	1.747
Test #	7		
Date #	4/10/2008		
Recorder	JASON UNRUH		

Time	Station (x)	Station (y)	Water Surface Elevation (z)	Comments
2:55	49.00	Centerline	1.932	
	47.00	"	1.931	
	46.50	"	1.930	
	46.00	"	1.930	
	45.50	"	1.930	
	45.00	"	1.929	
	44.50	"	1.927	
	44.25	"	1.921	
	44.10	"	1.910	
	44.05	"	1.900	
	44.00	"	1.889	
	43.95	"	1.867	
	43.90	"	1.845	
	43.85	"	1.797	
	43.80	"	1.758	
	43.75	"	1.692	
	43.70	"	1.620	
	43.65	"	1.525	
	43.60	"	1.459	
	43.55	"	1.406	
3:03	43.50	"	---	IMPACT POINT

Run #	1	pnt gage crest reading, ft	1.747
Test #	8		
Date #	4/10/2008		
Recorder	JASON UNRUH		

Time	Station (x)	Station (y)	Water Surface Elevation (z)	Comments
5:37	49.00	Centerline	1.821	
	47.00	"	1.820	
	46.50	"	1.819	
	46.00	"	1.819	
	45.50	"	1.818	
	45.00	"	1.817	
	44.50	"	1.817	
	44.25	"	1.817	
	44.10	"	1.812	
	44.05	"	1.807	
	44.00	"	1.790	
	43.95	"	1.756	
	43.90	"	1.680	
	43.85	"	1.557	
5:43	43.80	"	---	IMPACT POINT

Run #	2	pnt gage crest reading, ft	1.747
Test #	8		
Date #	4/10/2008		
Recorder	JASON UNRUH		

Time	Station (x)	Station (y)	Water Surface Elevation (z)	Comments
6:15	49.00	Centerline	1.831	
	47.00	"	1.830	
	46.50	"	1.830	
	46.00	"	1.829	
	45.50	"	1.829	
	45.00	"	1.828	
	44.50	"	1.828	
	44.25	"	1.828	
	44.10	"	1.823	
	44.05	"	1.816	
	44.00	"	1.800	
	43.95	"	1.770	
	43.90	"	1.703	
	43.85	"	1.601	
6:30	43.80	"	---	IMPACT POINT

Run #	3
Test #	8
Date #	4/10/2008
Recorder	JASON UNRUH

pnt gage crest reading, ft 1.747

Time	Station (x)	Station (y)	Water Surface Elevation (z)	Comments
6:31	49.00	Centerline	1.844	
	47.00	"	1.844	
	46.50	"	1.843	
	46.00	"	1.843	
	45.50	"	1.842	
	45.00	"	1.841	
	44.50	"	1.841	
	44.25	"	1.840	
	44.10	"	1.835	
	44.05	"	1.828	
	44.00	"	1.811	
	43.95	"	1.781	
	43.90	"	1.722	
	43.85	"	1.650	
	43.80	"	1.523	
6:46	43.75	"	---	IMPACT POINT

Run #	1
Test #	9
Date #	4/11/2008
Recorder	MONICA MURIE

pnt gage crest reading, ft 1.747

Time	Station (x)	Station (y)	Water Surface Elevation (z)	Comments
1:53	49.00	Centerline	1.810	
	47.00	"	1.809	
	46.50	"	1.808	
	46.00	"	1.808	
	45.50	"	1.807	
	45.00	"	1.807	
	44.50	"	1.806	
	44.25	"	1.806	
	44.10	"	1.804	
	44.05	"	1.799	
	44.00	"	1.784	
	43.95	"	1.743	
	43.90	"	1.664	
	43.85	"	1.544	
	43.80	"	1.415	
	43.75	"	1.208	
	43.70	"	1.027	
1:58	43.65	"	---	IMPACT POINT

Run #	2
Test #	9
Date #	4/11/2008
Recorder	MONICA MURIE

pnt gage crest reading, ft 1.747

Time	Station (x)	Station (y)	Water Surface Elevation (z)	Comments
2:03	49.00	Centerline	1.802	
	47.00	"	1.801	
	46.50	"	1.800	
	46.00	"	1.800	
	45.50	"	1.800	
	45.00	"	1.800	
	44.50	"	1.799	
	44.25	"	1.799	
	44.10	"	1.797	
	44.05	"	1.792	
	44.00	"	1.778	
	43.95	"	1.733	
	43.90	"	1.648	
	43.85	"	1.510	
	43.80	"	1.316	
	43.75	"	1.053	
2:12	43.73	"	---	IMPACT POINT

Run #	1
Test #	10
Date #	4/12/2008
Recorder	MONICA MURIE

pnt gage crest reading, ft 1.747

Time	Station (x)	Station (y)	Water Surface Elevation (z)	Comments
8:10	49.00	Centerline	1.906	
	47.00	"	1.906	
	46.50	"	1.903	
	46.00	"	1.903	
	45.50	"	1.902	
	45.00	"	1.901	
	44.50	"	1.901	
	44.25	"	1.897	
	44.10	"	1.887	
	44.05	"	1.878	
	44.00	"	1.864	
	43.95	"	1.843	
	43.90	"	1.811	
	43.85	"	1.777	
	43.80	"	1.717	
	43.75	"	1.655	
	43.70	"	1.582	
	43.65	"	1.487	
	43.60	"	1.381	
	43.55	"	1.277	
	43.50	"	1.161	
	43.45	"	1.000	
8:18	43.40	"	---	IMPACT POINT

Run #	2
Test #	10
Date #	4/12/2008
Recorder	MONICA MURIE

pnt gage crest reading, ft 1.747

Time	Station (x)	Station (y)	Water Surface Elevation (z)	Comments
8:33	49.00	Centerline	1.877	
	47.00	"	1.877	
	46.50	"	1.876	
	46.00	"	1.875	
	45.50	"	1.874	
	45.00	"	1.873	
	44.50	"	1.873	
	44.25	"	1.870	
	44.10	"	1.862	
	44.05	"	1.852	
	44.00	"	1.836	
	43.95	"	1.808	
	43.90	"	1.759	
	43.85	"	1.713	
	43.80	"	1.636	
	43.75	"	1.548	
	43.70	"	1.445	
	43.65	"	1.336	
	43.60	"	1.188	
	43.55	"	0.989	
8:38	43.50	"	---	IMPACT POINT

Run #	3
Test #	11
Date #	4/12/2008
Recorder	MONICA MURIE

pnt gage crest reading, ft 1.747

Time	Station (x)	Station (y)	Water Surface Elevation (z)	Comments
10:00	49.00	Centerline	1.962	
	47.00	"	1.960	
	46.50	"	1.959	
	46.00	"	1.959	
	45.50	"	1.958	
	45.00	"	1.958	
	44.50	"	1.955	
	44.25	"	1.950	
	44.10	"	1.938	
	44.05	"	1.924	
	44.00	"	1.912	
	43.95	"	1.896	
	43.90	"	1.869	
	43.85	"	1.836	
	43.80	"	1.798	
	43.75	"	1.750	
	43.70	"	1.692	
	43.65	"	1.638	
	43.60	"	1.555	
	43.55	"	1.467	
	43.50	"	1.364	
	43.45	"	1.264	
	43.40	"	1.144	
	43.35	"	1.029	
	43.30	"	0.941	
10:09	43.25	"	---	IMPACT POINT

Run #	5	pnt gage crest reading, ft	1.747
Test #	11		
Date #	4/12/2008		
Recorder	MONICA MURIE		

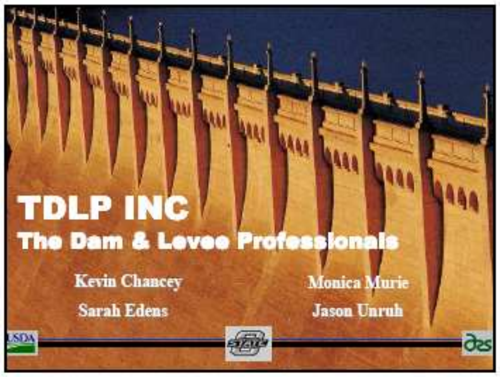
Time	Station (x)	Station (y)	Water Surface Elevation (z)	Comments
10:33	49.00	Centerline	2.048	
	47.00	"	2.046	
	46.50	"	2.046	
	46.00	"	2.045	
	45.50	"	2.043	
	45.00	"	2.040	
	44.50	"	2.034	
	44.25	"	2.025	
	44.10	"	2.008	
	44.05	"	1.997	
	44.00	"	1.987	
	43.95	"	1.971	
	43.90	"	1.948	
	43.85	"	1.923	
	43.80	"	1.895	
	43.75	"	1.855	
	43.70	"	1.813	
	43.65	"	1.770	
	43.60	"	1.705	
	43.55	"	1.647	
	43.50	"	1.584	
	43.45	"	1.512	
	43.40	"	1.428	
	43.35	"	1.338	
	43.30	"	1.251	
	43.25	"	1.146	
	43.20	"	1.041	
	43.15	"	0.970	
10:42	43.10	"	---	IMPACT POINT

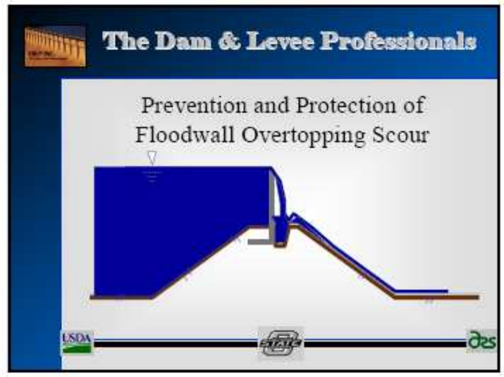
Run #	7	pnt gage crest reading, ft	1.747
Test #	11		
Date #	4/12/2008		
Recorder	MONICA MURIE		

Time	Station (x)	Station (y)	Water Surface Elevation (z)	Comments
11:06	49.00	Centerline	2.109	
	47.00	"	2.107	
	46.50	"	2.107	
	46.00	"	2.107	
	45.50	"	2.105	
	45.00	"	2.103	
	44.50	"	2.096	
	44.25	"	2.082	
	44.10	"	2.064	
	44.05	"	2.052	
	44.00	"	2.041	
	43.95	"	2.028	
	43.90	"	2.010	
	43.85	"	1.982	
	43.80	"	1.959	
	43.75	"	1.932	
	43.70	"	1.895	
	43.65	"	1.850	
	43.60	"	1.803	
	43.55	"	1.755	
	43.50	"	1.697	
	43.45	"	1.641	
	43.40	"	1.557	
	43.35	"	1.493	
	43.30	"	1.429	
	43.25	"	1.334	
	43.20	"	1.223	
11:16	43.15	"	---	IMPACT POINT

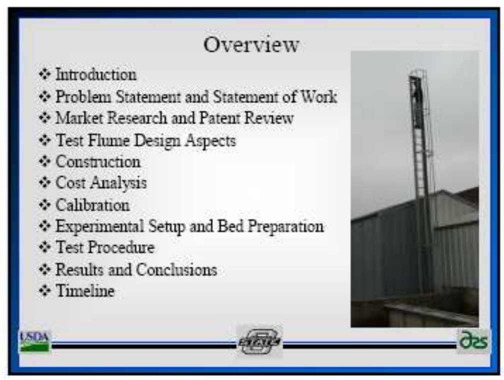
Appendix D

PowerPoint Presentation Slides


TDLP INC
The Dam & Levee Professionals
Kevin Chancey
Sarah Edens
Monica Murie
Jason Unruh


The Dam & Levee Professionals
Prevention and Protection of Floodwall Overtopping Scour


The Dam & Levee Professionals
Mission Statement
"TDLP Inc. will be the innovator of dam and levee erosion control designs that will meet and exceed our customers needs to provide them with the safety and security we all deserve.
TDLP Inc. will go above and beyond industry standards to provide protection of property and quality of life by designing and maintaining top notch erosion protection structures."

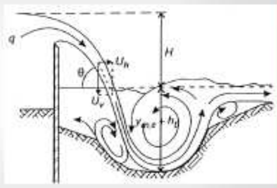

Overview
Introduction
Problem Statement and Statement of Work
Market Research and Patent Review
Test Flume Design Aspects
Construction
Cost Analysis
Calibration
Experimental Setup and Bed Preparation
Test Procedure
Results and Conclusions
Timeline


Sponsor
USDA-ARS HERU
Established in 1940
Located on 100 acres adjoining Lake Carl Blackwell
Innovator in vegetated channel design concepts


Background
Flood wall scour
The process of erosion caused by flood wall overtop.
Water overtops the floodwall
Concrete floodwall
Steel sheetpile
Water spilling over the wall erodes soil at the base and causes the wall to fail.

Problem Statement

- What is the Problem?
  - Overtopping
  - Impinging Flow
  - Scour and Erosion
  - Destabilization
  - Lack of current design standards
- What can be done to prevent this?



USDA — OSU — BAE

Introduction

- Floodwall Scour can cause instability in the wall and cause failure.

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The Dam & Levee Professionals

Statement of Work

Work to be Done

- develop a generalized approach with consideration of an optimal ground application
- decrease scour from water overtopping floodwalls
- increase ground stability
- protect the integrity of existing floodwalls
- remain within economic constraints

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The Dam & Levee Professionals

Statement of Work (cont.)

In order to accomplish all of the tasks….

- investigate the specific issues
- generate design concepts
- build a floodwall prototype
- determine experimental procedures
- model these concepts
- present findings for evaluation

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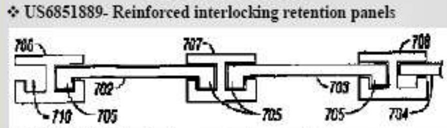
Market Research

- **A-Jacks® by Armortec ™**
- **Kiciman Gabion Baskets**

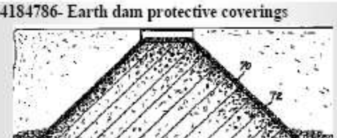
USDA — OSU — BAE

Patent Research

- **US6851889- Reinforced interlocking retention panels**



- **US4184786- Earth dam protective coverings**



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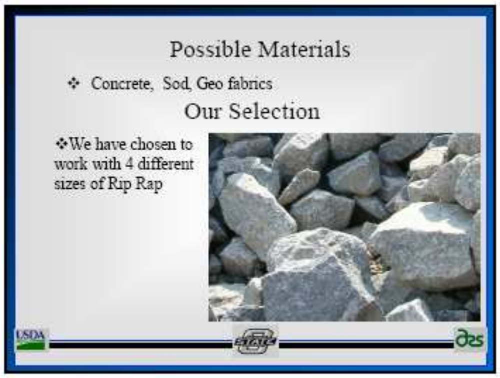
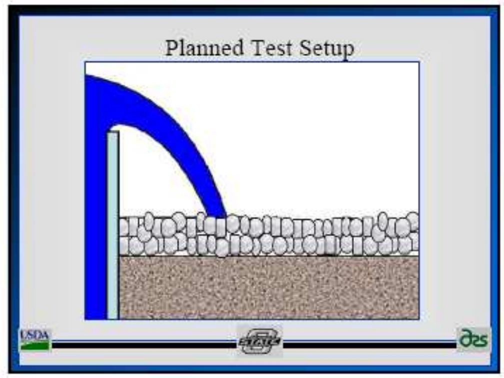
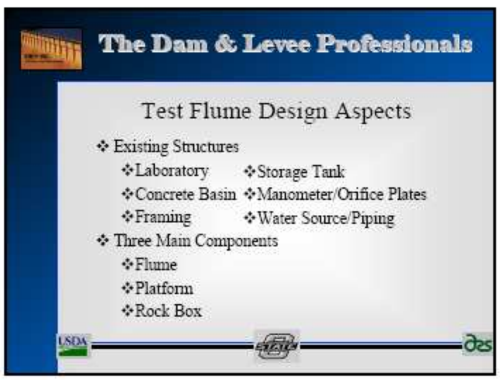

Possible Materials
❖ Concrete, Sod, Geo fabrics
Our Selection
❖We have chosen to work with 4 different sizes of Rip Rap
USDA


Planned Test Setup
USDA

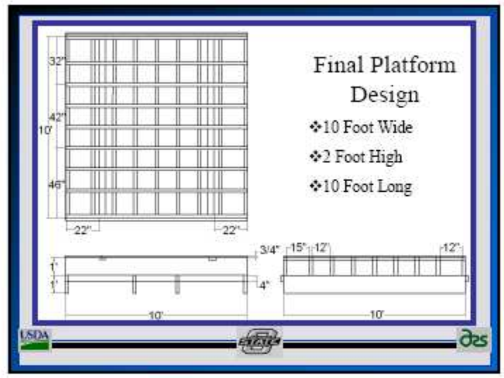

The Dam & Levee Professionals
Test Flume Design Aspects
❖ Existing Structures
❖Laboratory
❖Storage Tank
❖Concrete Basin
❖Manometer/Orifice Plates
❖Framing
❖Water Source/Piping
❖ Three Main Components
❖Flume
❖Platform
❖Rock Box
USDA


Test Flume Design Aspects
Laboratory
USDA

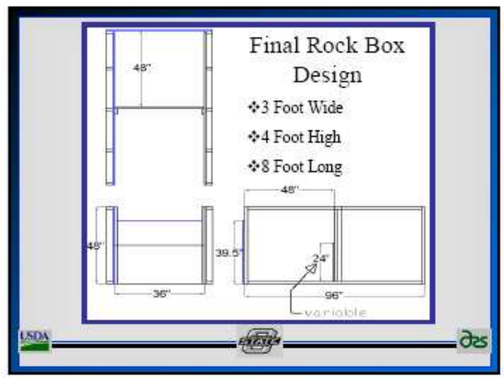

Flume Design Aspects
Water Source/Piping
USDA


Flume Design Aspects
Manometer / Orifice Plates
USDA


Flume Design Aspects
Concrete Basin and Framing


Final Platform Design
❖10 Foot Wide
❖2 Foot High
❖10 Foot Long


Final Flume Design
❖3 Foot Wide
❖2 Foot High
❖16 Foot Long


Final Rock Box Design
❖3 Foot Wide
❖4 Foot High
❖8 Foot Long


Platform Construction


Flume Construction

Rockbox Construction

Proposed Cost

Materials	Qty	$ ea.	Total
4' x 8' x 3/4"	11	$21.44	$235.84
2" x 4" x 10'	21	$2.85	$59.85
2" x 6" x 8'	6	$3.84	$23.04
Plexiglass	1	$173.71	$173.71
Wood Screws (1 lb Box)	2	$6.97	$13.94
Wood Sealer (1 Gallon)	1	$20.00	$20.00
Silicon Caulking	5	$3.00	$15.00
Paint Roller Kit	1	$13.00	$13.00
	Grand Total		$554.38

Actual Cost

Materials	Qty	$ ea.	Total
2" x 12" x 10'	14	$10.42	$145.88
2" x 4" x 10'	38	$2.96	$112.48
4' x 8' x 3/4"	11	$23.45	$257.95
3" Wood Screws (1 lb)	6	$3.86	$23.16
2" Wood Screws (1 lb)	4	$3.86	$15.44
Silicon Caulking	19	$2.69	$51.11
Wood Sealer (1 gal)	1	$12.88	$12.88
Miscellaneous			$47.55
	Grand Total		$666.45

List of Common Terms

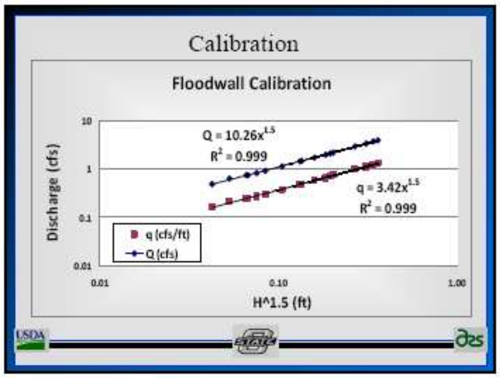
- Critical Depth (d_c) - Depth of water flowing directly above weir
- Drop Height (h) – Height from top of rip rap surface to top of weir
- Flow Rate (Q) – Rate of fluid flow
- Head (H) – Total height of water from ground level
- Length to Impact (L) – Distance from floodwall to impact point
- Rip Rap Nominal Diameter (D_{50}) – Average diameter of a set of rip rap

Calibration

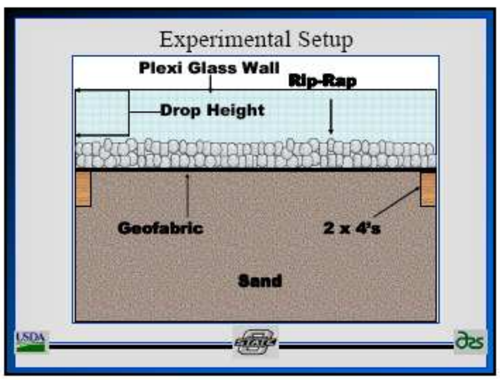
- Establish level railing
- Point Gauge Carriage was in place

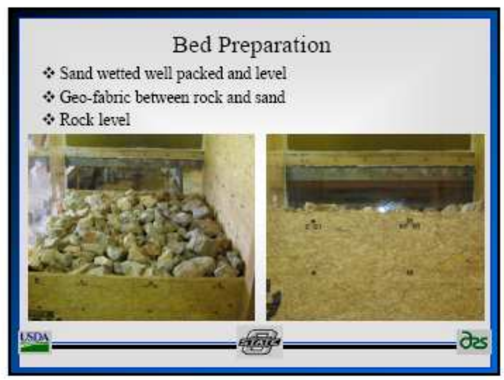
Calibration

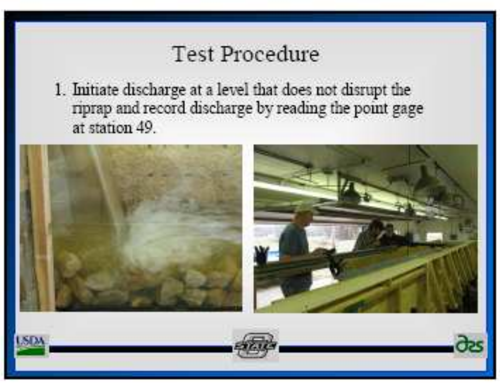
- Point Gauge readings were taken 5 ft upstream from the flood fall in order to read the head
- Manometer readings taken at each flow.

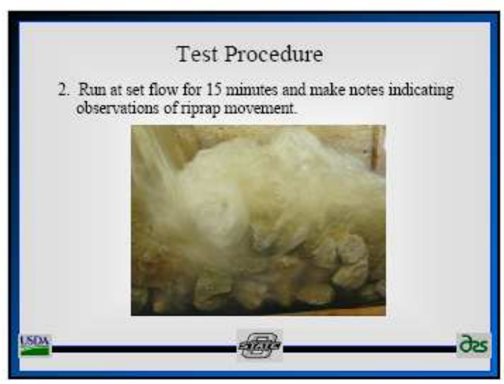


Calibration
Floodwall Calibration
Discharge (cfs)
H^1.5 (ft)
Q = 10.26x^1.5
R^2 = 0.999
q = 3.42x^1.5
R^2 = 0.999
q (cfs/ft)
Q (cfs)
10
1
0.1
0.01
0.01
0.10
1.00
USDA


Experimental Setup
Rock Size Selection
D50 - 0.05 ft
D50 - 0.11 ft
D50 - 0.17 ft
D50 - 0.29 ft
USDA


Experimental Setup
Plexi Glass Wall
Rip-Rap
Drop Height
Geofabric
2 x 4's
Sand
USDA


Bed Preparation
❖ Sand wetted well packed and level
❖ Geo-fabric between rock and sand
❖ Rock level
USDA


Test Procedure
1. Initiate discharge at a level that does not disrupt the riprap and record discharge by reading the point gage at station 49.
USDA


Test Procedure
2. Run at set flow for 15 minutes and make notes indicating observations of riprap movement.
USDA

Example Data Collection Sheet

Test #	3		Drop height, ft	2	
Recorder	Jason		rock size, mm	33	
Date	4/5/2008		pt gage crest rd, ft	x= 49	y= cente / z= 1.747
			calibration curve: Q = CH[illegible]		C = 10.26
run #	time start/end	sta. 49 pt gage rd, ft	head on crest H, ft	flume discharge Q, cfs	comments: stable/shift/scour
1	10:43	1.810	0.063	0.162	stable / no movement
	10:58	1.809	0.062	0.158	
2	11:00	1.829	0.082	0.241	1 visible rock swaying / stable overall /
	11:15	1.829	0.082	0.241	no movement
3	11:18	1.855	0.108	0.364	minor movement initially / settled quickly /
	11:33	1.854	0.107	0.359	
4	11:35	1.874	0.127	0.464	movement downstream and upstream of jet /
	11:50	1.874	0.127	0.464	scour bed 1 D50 deep
5	11:54	1.906	0.159	0.650	displacement of 1 D50 depth at jet /
	12:09	1.906	0.159	0.650	visible failure at 11:40 / complete failure at 11:43

Test Procedure

3. Increase flow of water in increments proportional to the nominal dc. Repeat step 2 for each flow increase until geofabric is exposed.

Test Procedure

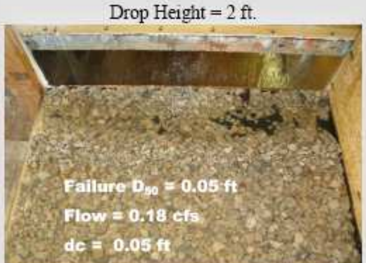
4. Once geofabric is exposed, turn off flow, and record scour.

Test Procedure

5. Repeat steps 1-3 of test set-up and 1-4 of test procedure until all rock sizes have been tested for the desired drop height.
6. Repeat the entire procedure for next drop height.
7. Conduct steps 1-6 on the third drop height (1') for verification data.

Test Results

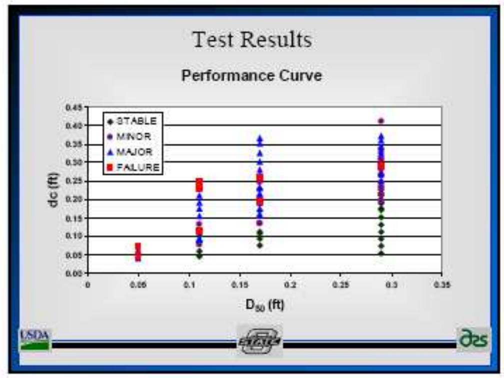
Drop Height = 2 ft.

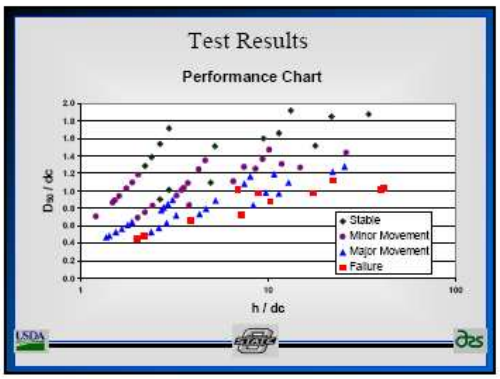


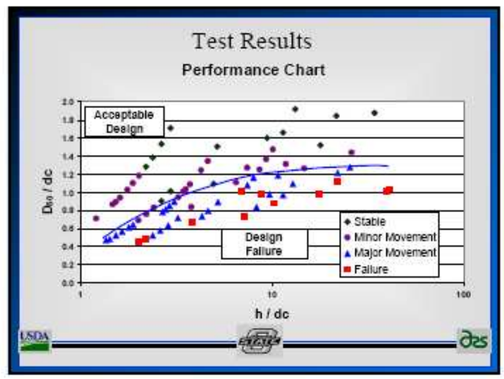
Test Results

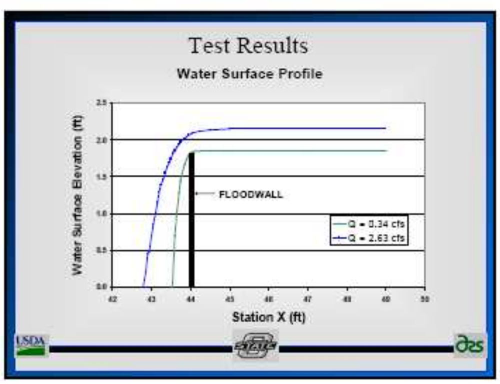
Drop Height = 0.5 ft.

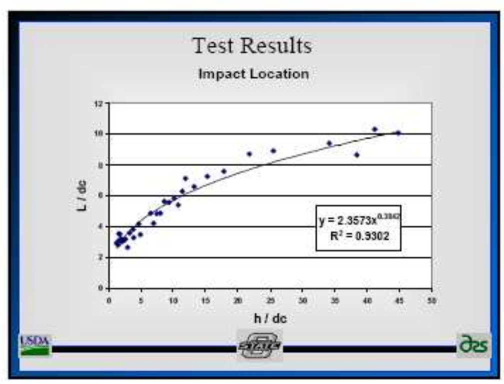

Test Results
Drop Height = 1 ft
No Failure D50 = 0.29 ft
Flow = 3.86 cfs
dc = 0.37 ft

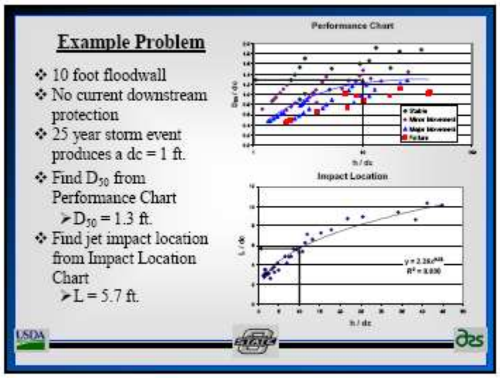

Test Results
Performance Curve
STABLE
MINOR
MAJOR
FAILURE
dc (ft)
D50 (ft)

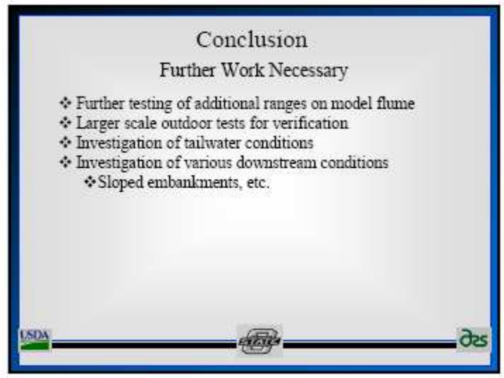

Test Results
Performance Chart
Stable
Minor Movement
Major Movement
Failure
D50 / dc
h / dc

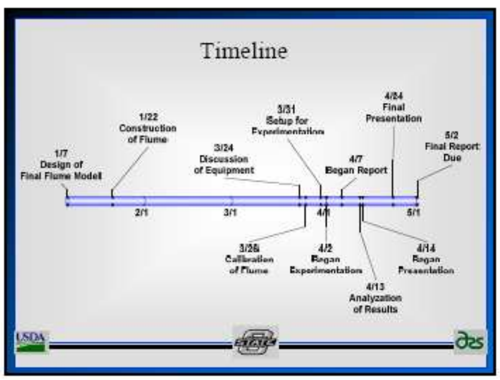

Test Results
Performance Chart
Acceptable Design
Design Failure
Stable
Minor Movement
Major Movement
Failure
D50 / dc
h / dc

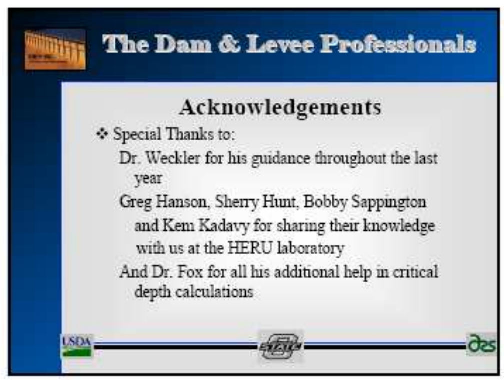

Test Results
Water Surface Profile
FLOODWALL
Q = 0.34 cfs
Q = 2.63 cfs
Water Surface Elevation (ft)
Station X (ft)


Test Results
Impact Location
y = 2.3573x^0.3842
R² = 0.9302
L / dc
h / dc


Example Problem
❖ 10 foot floodwall
❖ No current downstream protection
❖ 25 year storm event produces a dc = 1 ft.
❖ Find D50 from Performance Chart
➢D50 = 1.3 ft.
❖ Find jet impact location from Impact Location Chart
➢L = 5.7 ft.
Performance Chart
Stable
Minor Movement
Major Movement
Failure
h / dc
Impact Location
L / dc
h / dc
USDA


Conclusion
Further Work Necessary
❖ Further testing of additional ranges on model flume
❖ Larger scale outdoor tests for verification
❖ Investigation of tailwater conditions
❖ Investigation of various downstream conditions
❖Sloped embankments, etc.
USDA


Timeline
1/7
Design of
Final Flume Model
1/22
Construction
of Flume
3/24
Discussion
of Equipment
3/31
Setup for
Experimentation
4/7
Began Report
4/24
Final
Presentation
5/2
Final Report
Due
2/1
3/1
4/1
5/1
3/26
Calibration
of Flume
4/2
Began
Experimentation
4/13
Analyzation
of Results
4/14
Began
Presentation
USDA


The Dam & Levee Professionals
Acknowledgements
❖ Special Thanks to:
Dr. Weckler for his guidance throughout the last year
Greg Hanson, Sherry Hunt, Bobby Sappington and Kem Kadavy for sharing their knowledge with us at the HERU laboratory
And Dr. Fox for all his additional help in critical depth calculations
USDA


Questions?
USDA

TDLP INC

The Dam & Levee Professionals

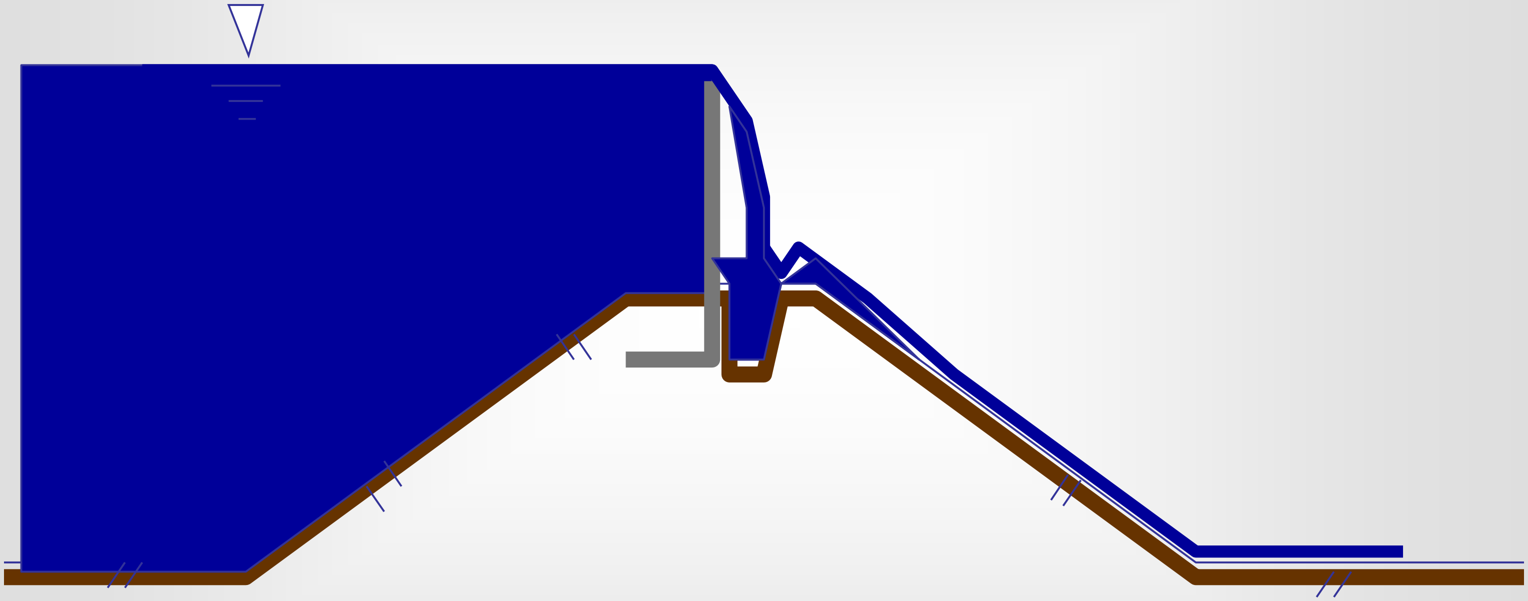
Kevin Chancey

Sarah Edens

Monica Murie

Jason Unruh

Prevention and Protection of Floodwall Overtopping Scour



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Overview

- ❖ Introduction
- ❖ Problem Statement and Statement of Work
- ❖ Market Research and Patent Review
- ❖ Test Flume Design Aspects
- ❖ Construction
- ❖ Cost Analysis
- ❖ Calibration
- ❖ Experimental Setup and Bed Preparation
- ❖ Test Procedure
- ❖ Results and Conclusions
- ❖ Timeline

Sponsor

- USDA-ARS HERU
  - Established in 1940
  - Located on 100 acres adjoining Lake Carl Blackwell
  - Innovator in vegetated channel design concepts

Background

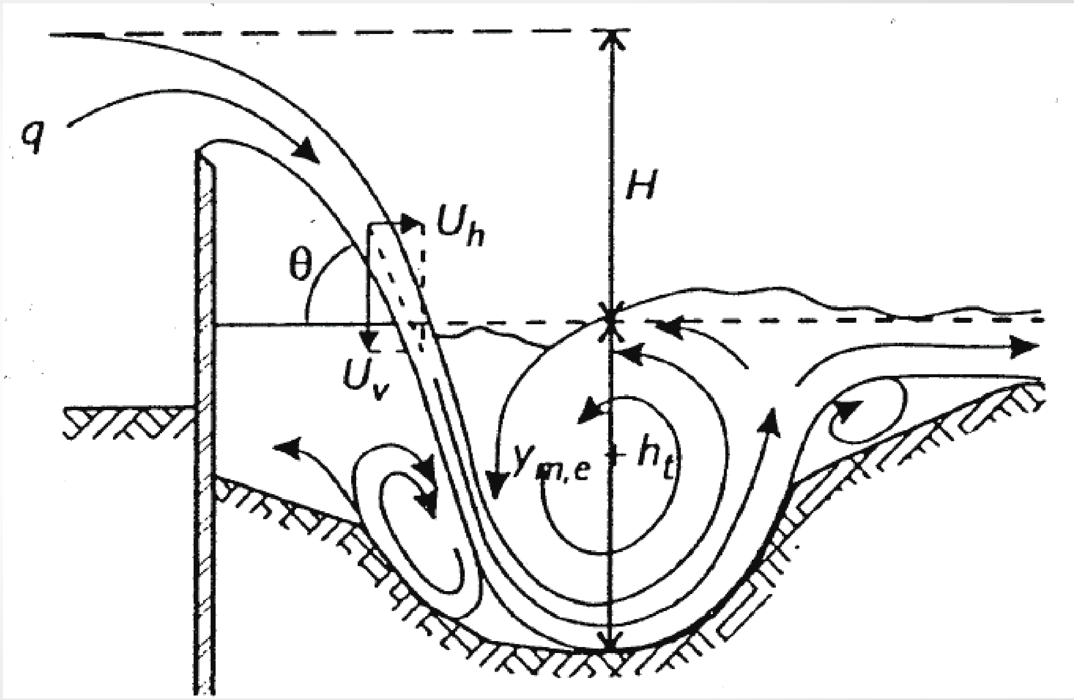
- ❖ Flood wall scour
  - ❖ The process of erosion caused by flood wall overtop.

http://hsgac.senate.gov/_files/Katrina/Preliminary_Report.pdf

USDA OKLAHOMA STATE UNIVERSITY ARS

Problem Statement

- What is the Problem?
  - Overtopping
  - Impinging Flow
  - Scour and Erosion
  - Destabilization
  - Lack of current design standards
- What can be done to prevent this?



Introduction

- Floodwall Scour can cause instability in the wall and cause failure.

Statement of Work

Work to be Done

- develop a generalized approach with consideration of an optimal ground application
- decrease scour from water overtopping floodwalls
- increase ground stability
- protect the integrity of existing floodwalls
- remain within economic constraints

Statement of Work (cont.)

In order to accomplish all of the tasks….

- investigate the specific issues
- generate design concepts
- build a floodwall prototype
- determine experimental procedures
- model these concepts
- present findings for evaluation

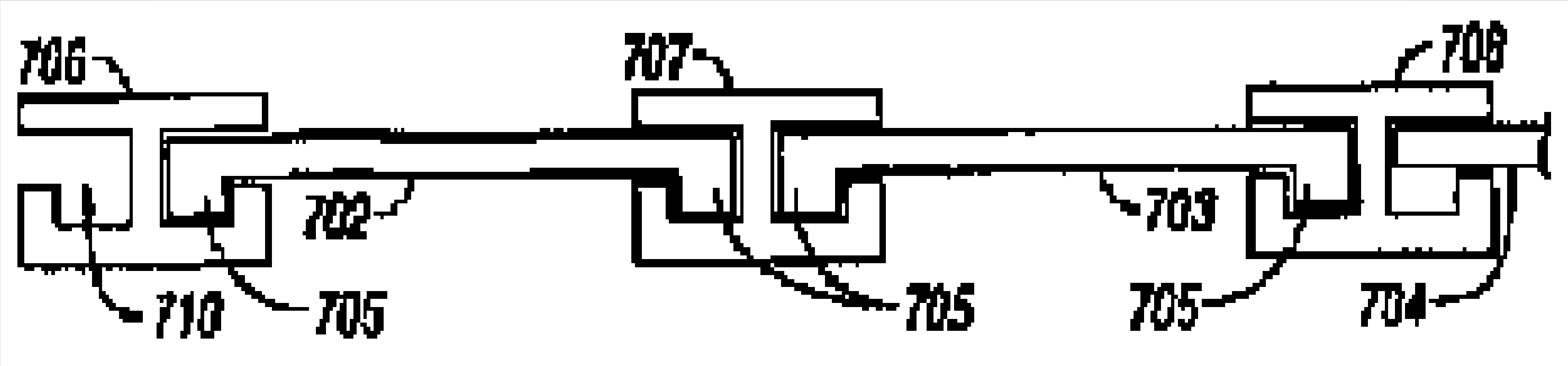
Market Research

- ❖ **A-Jacks® by Armortec ™**

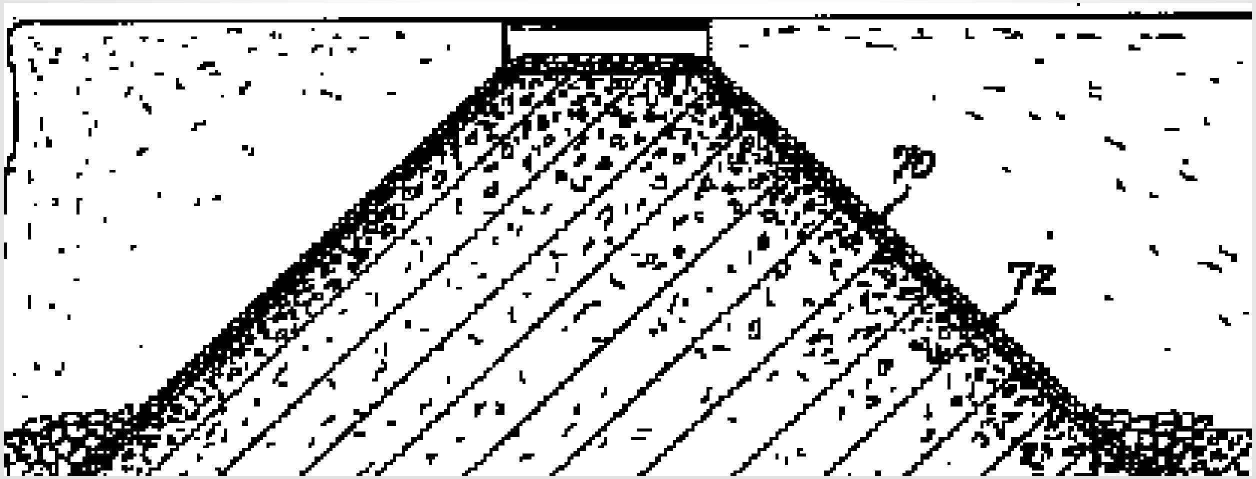
- ❖ **Kiciman Gabion Baskets**

Patent Research

- US6851889- Reinforced interlocking retention panels



- US4184786- Earth dam protective coverings

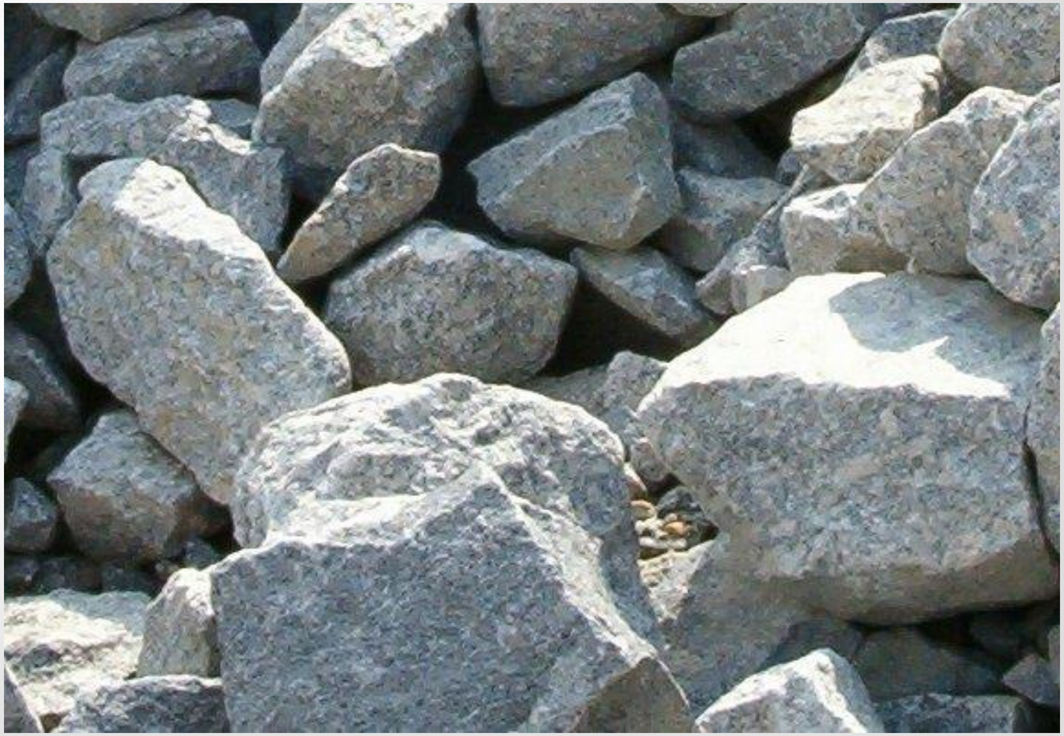


Possible Materials

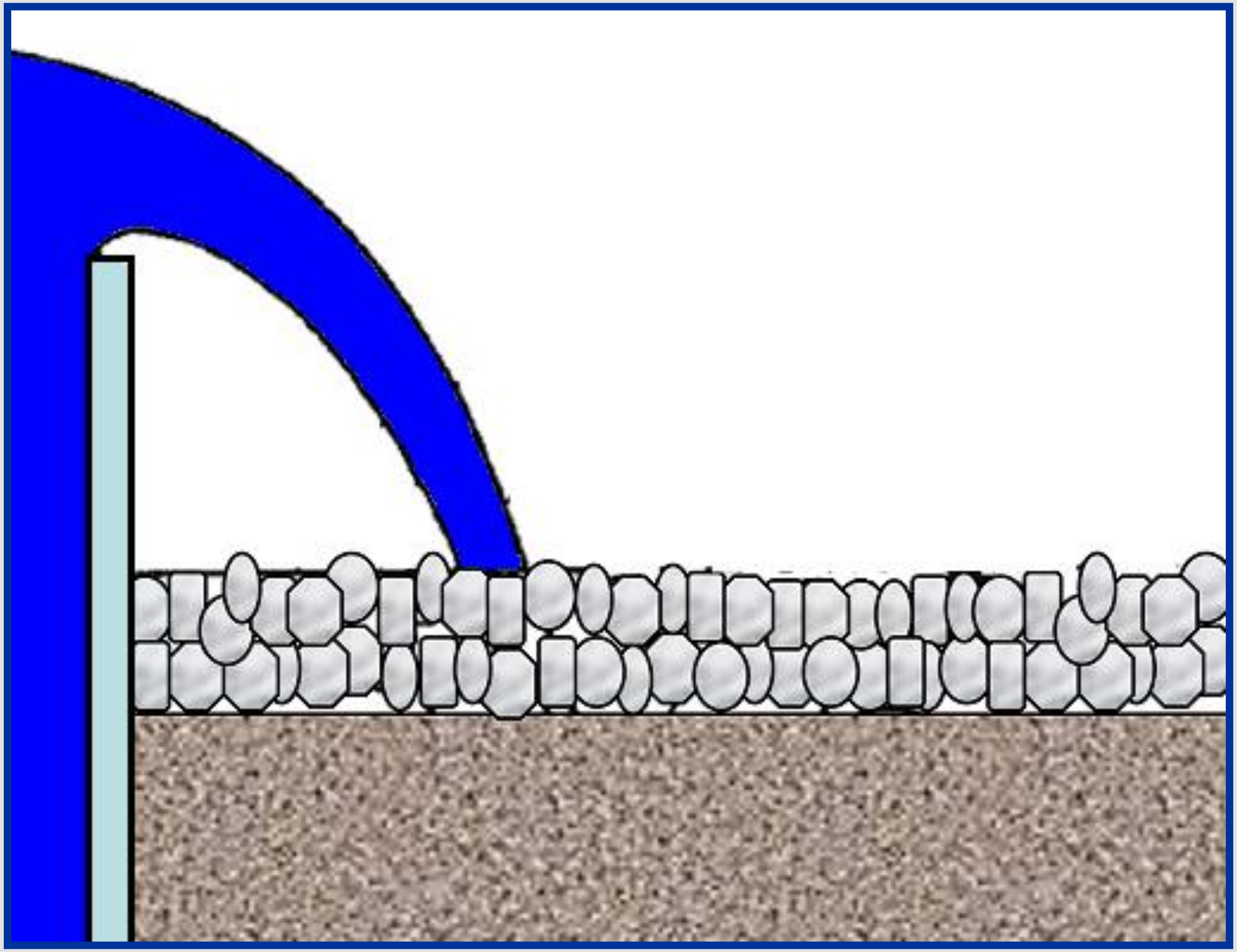
- ❖ Concrete, Sod, Geo fabrics

Our Selection

❖We have chosen to work with 4 different sizes of Rip Rap



Planned Test Setup



Test Flume Design Aspects

- Existing Structures
  - Laboratory
  - Concrete Basin
  - Framing
  - Storage Tank
  - Manometer/Orifice Plates
  - Water Source/Piping
- Three Main Components
  - Flume
  - Platform
  - Rock Box

Test Flume Design Aspects

Laboratory

Flume Design Aspects

Water Source/Piping

Flume Design Aspects

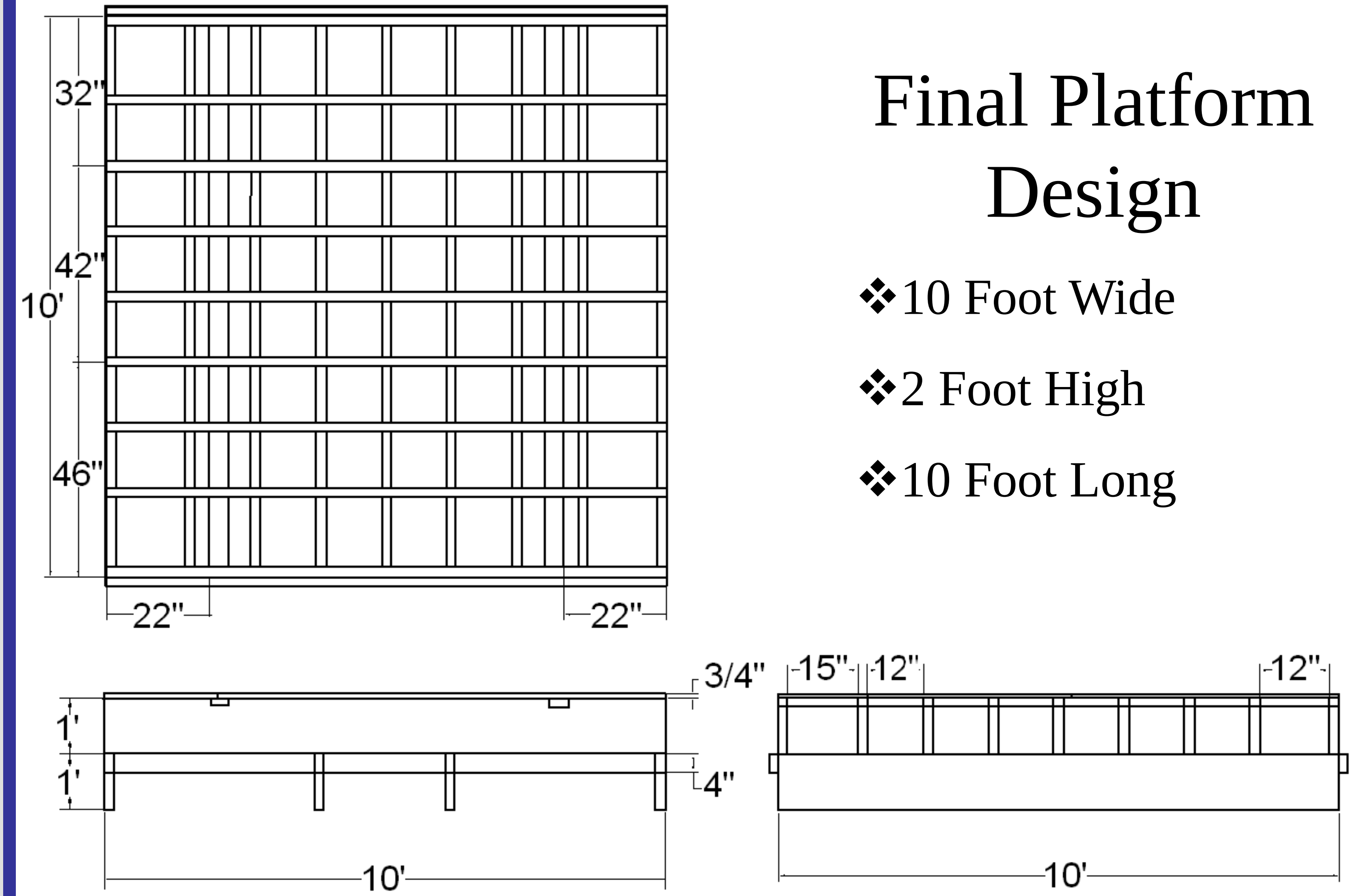
Manometer / Orifice Plates

Flume Design Aspects

Concrete Basin and Framing

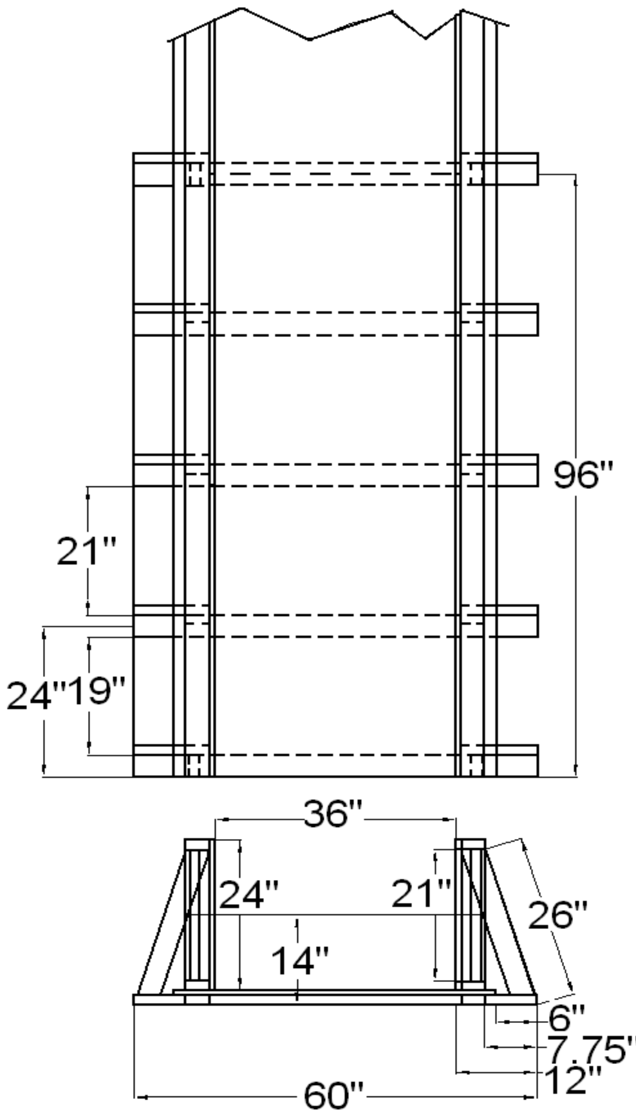
Final Platform Design

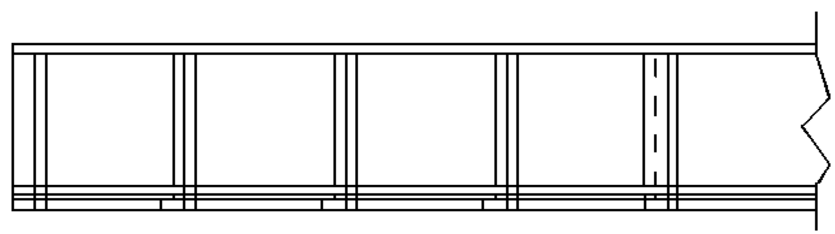
- ❖10 Foot Wide
- ❖2 Foot High
- ❖10 Foot Long



Final Flume Design

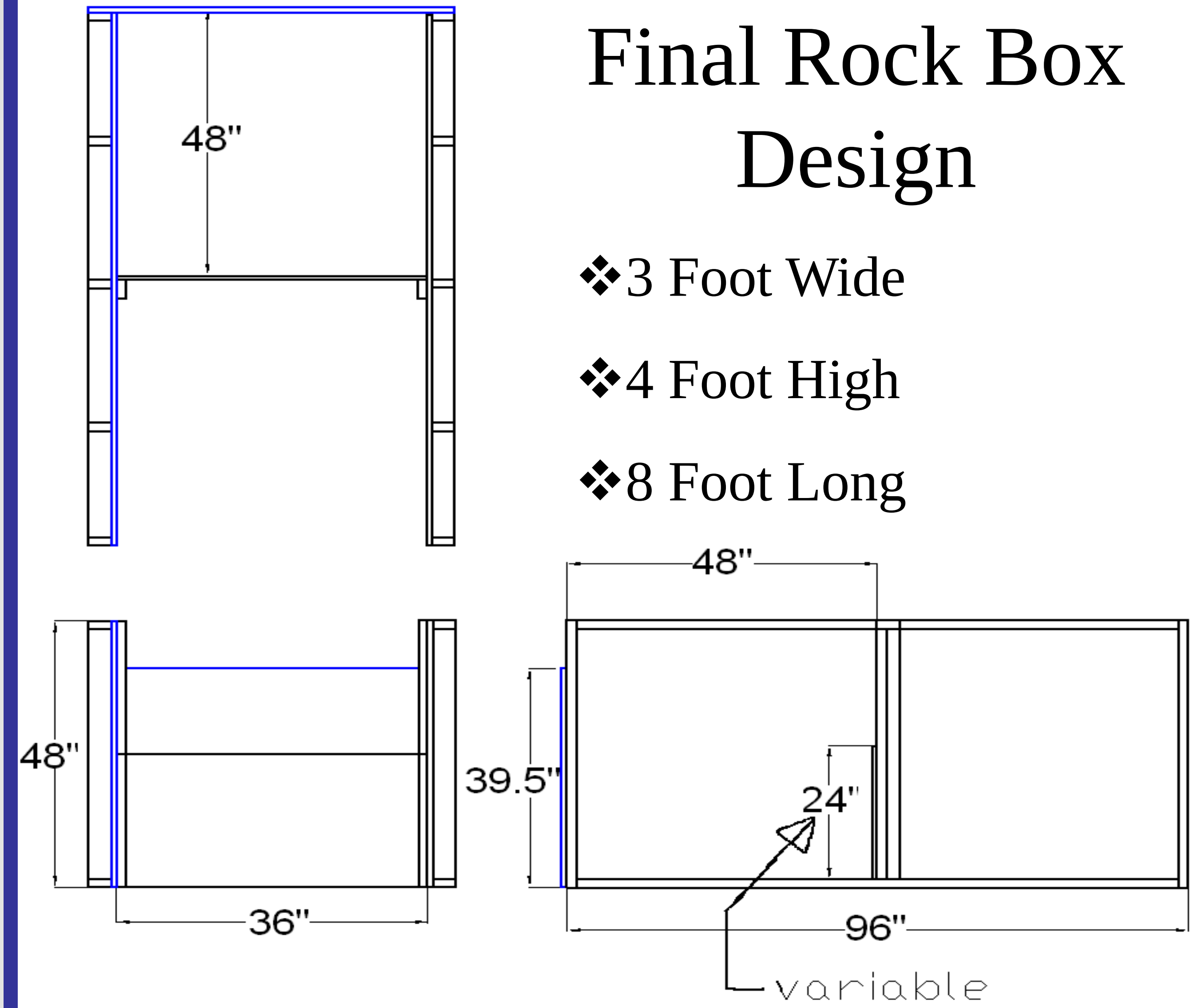
- 3 Foot Wide
- 2 Foot High
- 16 Foot Long



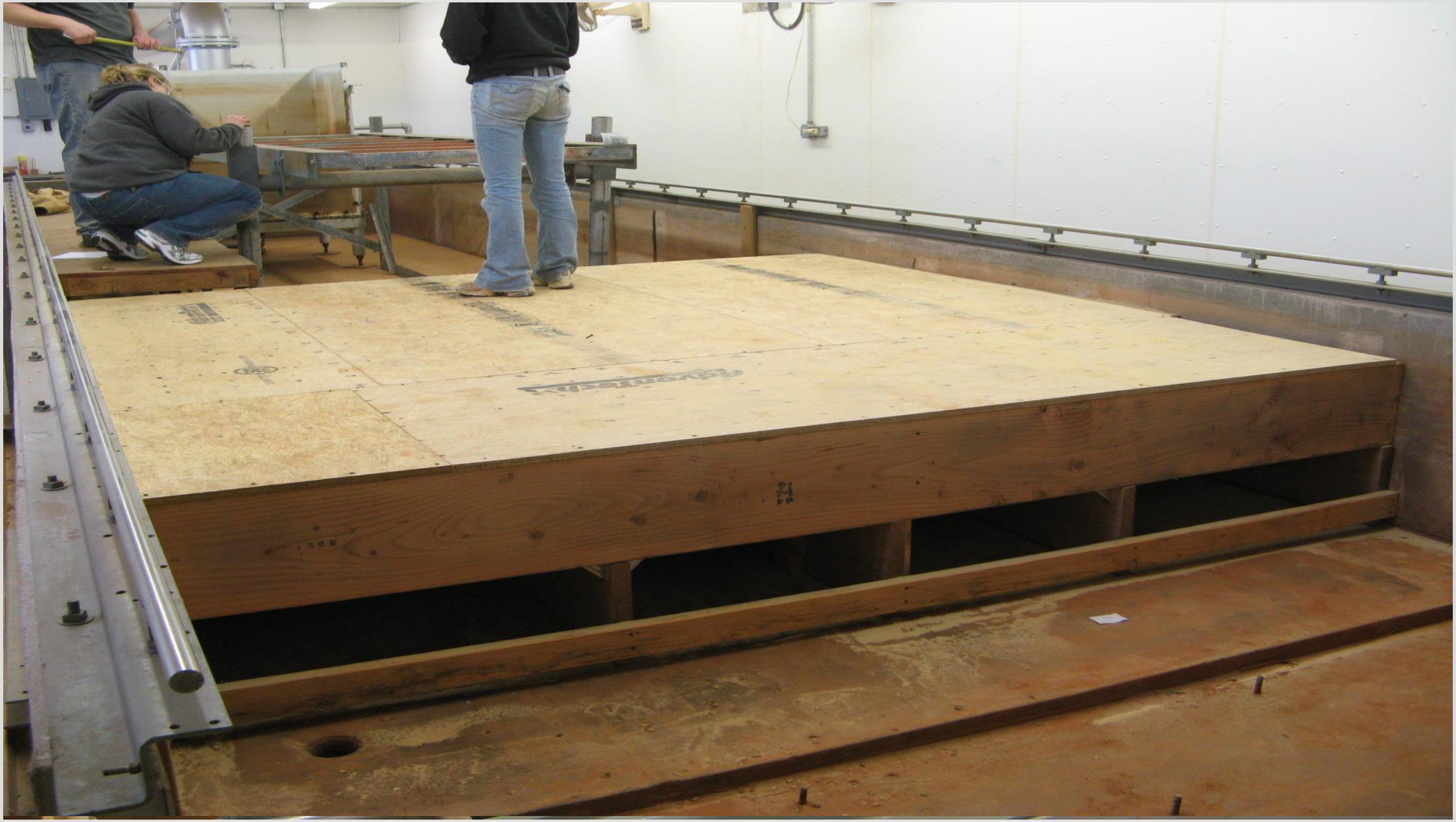


Final Rock Box Design

- 3 Foot Wide
- 4 Foot High
- 8 Foot Long

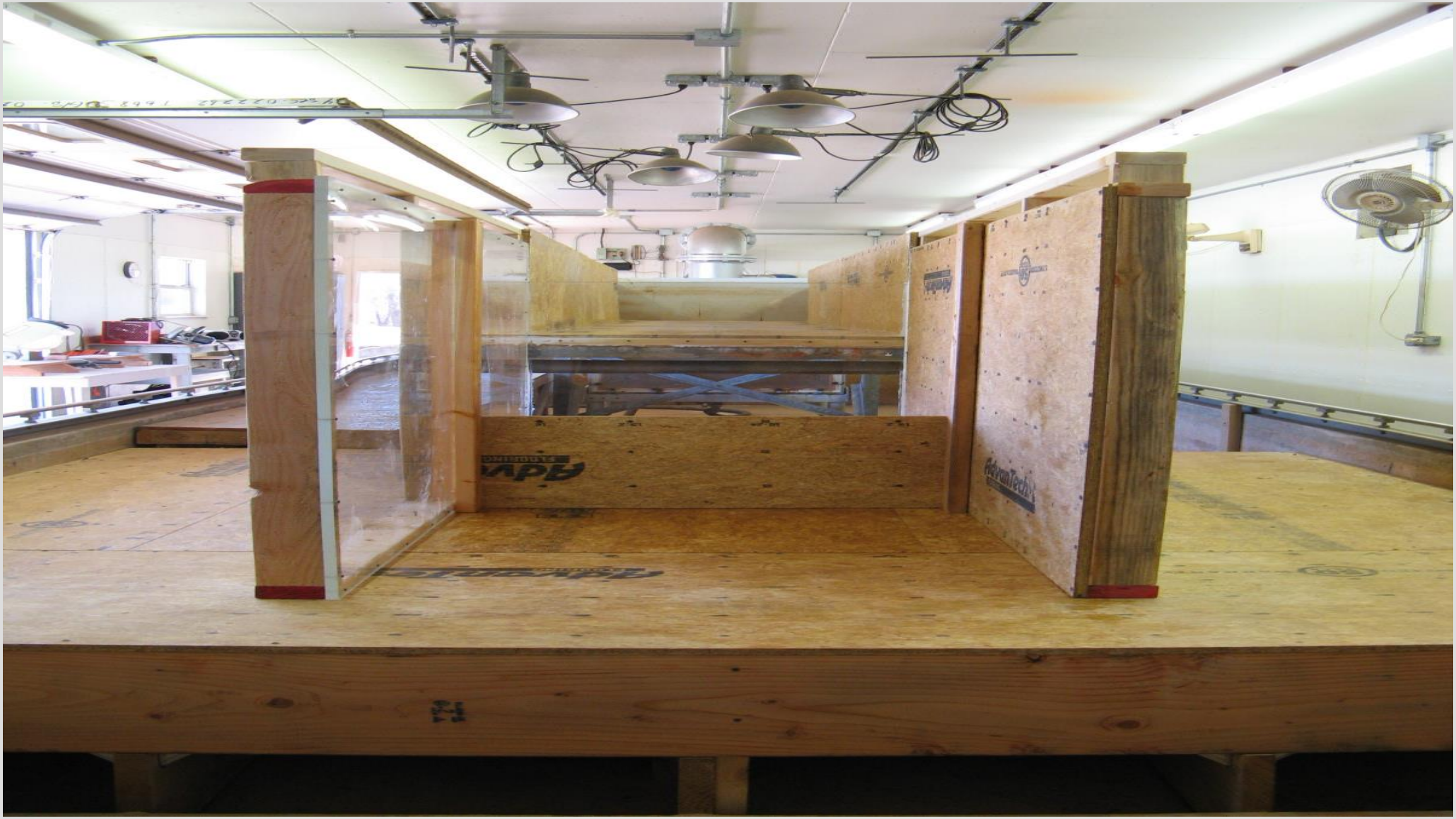


Platform Construction



Flume Construction

Rockbox Construction



Proposed Cost

Materials	Qty	$ ea.	Total
4' x 8' x 3/4"	11	$21.44	$235.84
2" x 4" x 10'	21	$2.85	$59.85
2" x 6" x 8'	6	$3.84	$23.04
Plexiglass	1	$173.71	$173.71
Wood Screws (1 lb Box)	2	$6.97	$13.94
Wood Sealer (1 Gallon)	1	$20.00	$20.00
Silicon Caulking	5	$3.00	$15.00
Paint Roller Kit	1	$13.00	$13.00
	Grand Total		$554.38

Actual Cost

Materials	Qty	$ ea.	Total
2” x 12” x 10’	14	$10.42	$145.88
2” x 4” x 10’	38	$2.96	$112.48
4’ x 8’ x 3/4”	11	$23.45	$257.95
3" Wood Screws (1 lb)	6	$3.86	$23.16
2" Wood Screws (1 lb)	4	$3.86	$15.44
Silicon Caulking	19	$2.69	$51.11
Wood Sealer (1 gal)	1	$12.88	$12.88
Miscellaneous			$47.55
	Grand Total		$666.45

List of Common Terms

- Critical Depth (d_c) - Depth of water flowing directly above weir
- Drop Height (h) – Height from top of rip rap surface to top of weir
- Flow Rate (Q) – Rate of fluid flow
- Head (H) – Total height of water from ground level
- Length to Impact (L) – Distance from floodwall to impact point
- Rip Rap Nominal Diameter (D_{50}) – Average diameter of a set of rip rap

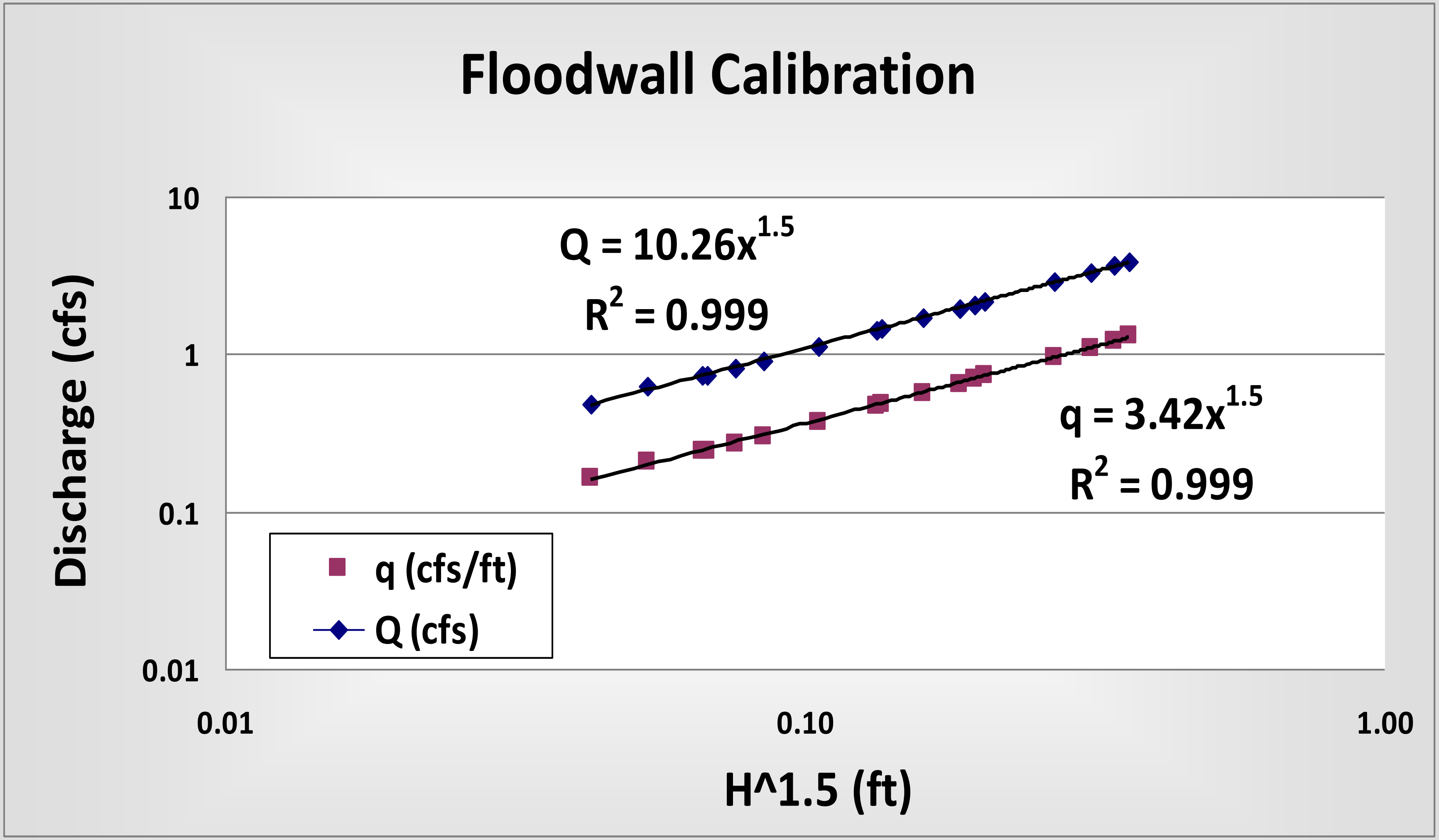
Calibration

- Establish level railing
- Point Gauge Carriage was in place

Calibration

- Point Gauge readings were taken 5 ft upstream from the flood fall in order to read the head
- Manometer readings taken at each flow.

Calibration

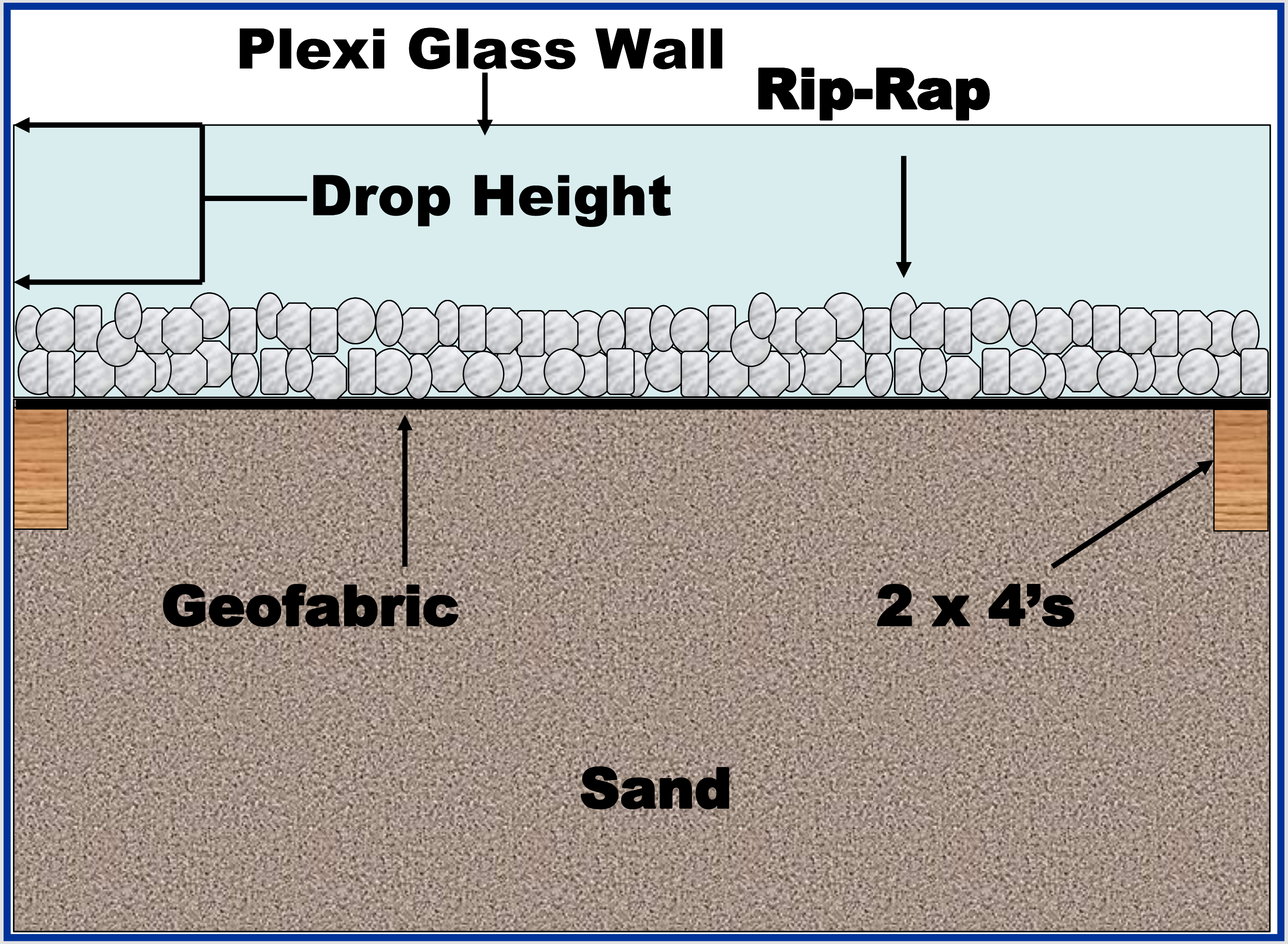


Experimental Setup

Rock Size Selection

D_{50} = 0.05 ft D_{50} = 0.11 ft D_{50} = 0.17 ft D_{50} = 0.29 ft

Experimental Setup



Bed Preparation

- ❖ Sand wetted well packed and level
- ❖ Geo-fabric between rock and sand
- ❖ Rock level

Test Procedure

1. Initiate discharge at a level that does not disrupt the riprap and record discharge by reading the point gage at station 49.

Test Procedure

2. Run at set flow for 15 minutes and make notes indicating observations of riprap movement.

Example Data Collection Sheet

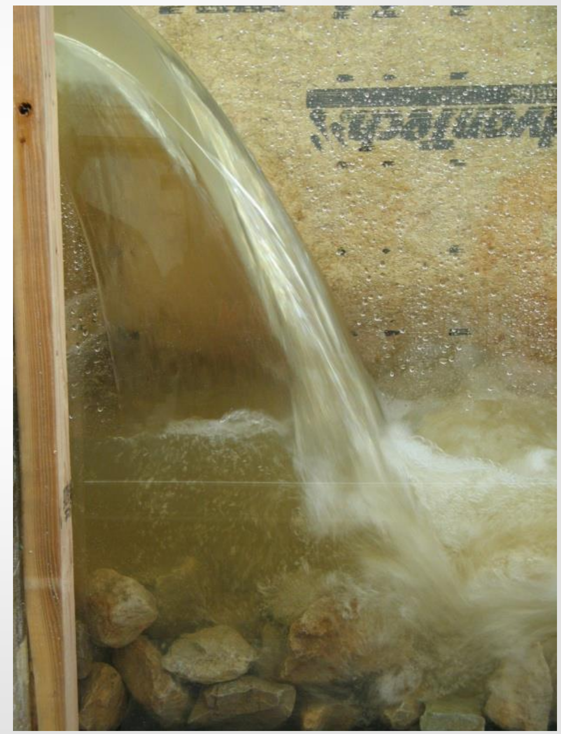
Test #	3	Drop height, ft	2		
Recorder	Jason	rock size, mm	33		
Date	4/5/2008	pt gage crest rd, ft	x= 49	y= center	z= 1.747

calibration curve: $Q = CH^{3/2}$ C = 10.26

run #	time start/end	sta. 49 pt gage rd, ft	head on crest H, ft	flume discharge Q, cfs	comments: stable/shift/scour
1	10:43	1.810	0.063	0.162	stable / no movement
	10:58	1.809	0.062	0.158	
2	11:00	1.829	0.082	0.241	1 visible rock swaying / stable overall /
	11:15	1.829	0.082	0.241	no movement
3	11:18	1.855	0.108	0.364	minor movement initially / settled quickly /
	11:33	1.854	0.107	0.359	
4	11:35	1.874	0.127	0.464	movement downstream and upstream of jet /
	11:50	1.874	0.127	0.464	scour bed 1 D50 deep
5	11:54	1.906	0.159	0.650	displacement of 1 D50 depth at jet /
	12:09	1.906	0.159	0.650	visible failure at 11:40 / complete failure at 11:43

Test Procedure

3. Increase flow of water in increments proportional to the nominal dc. Repeat step 2 for each flow increase until geofabric is exposed.



Test Procedure

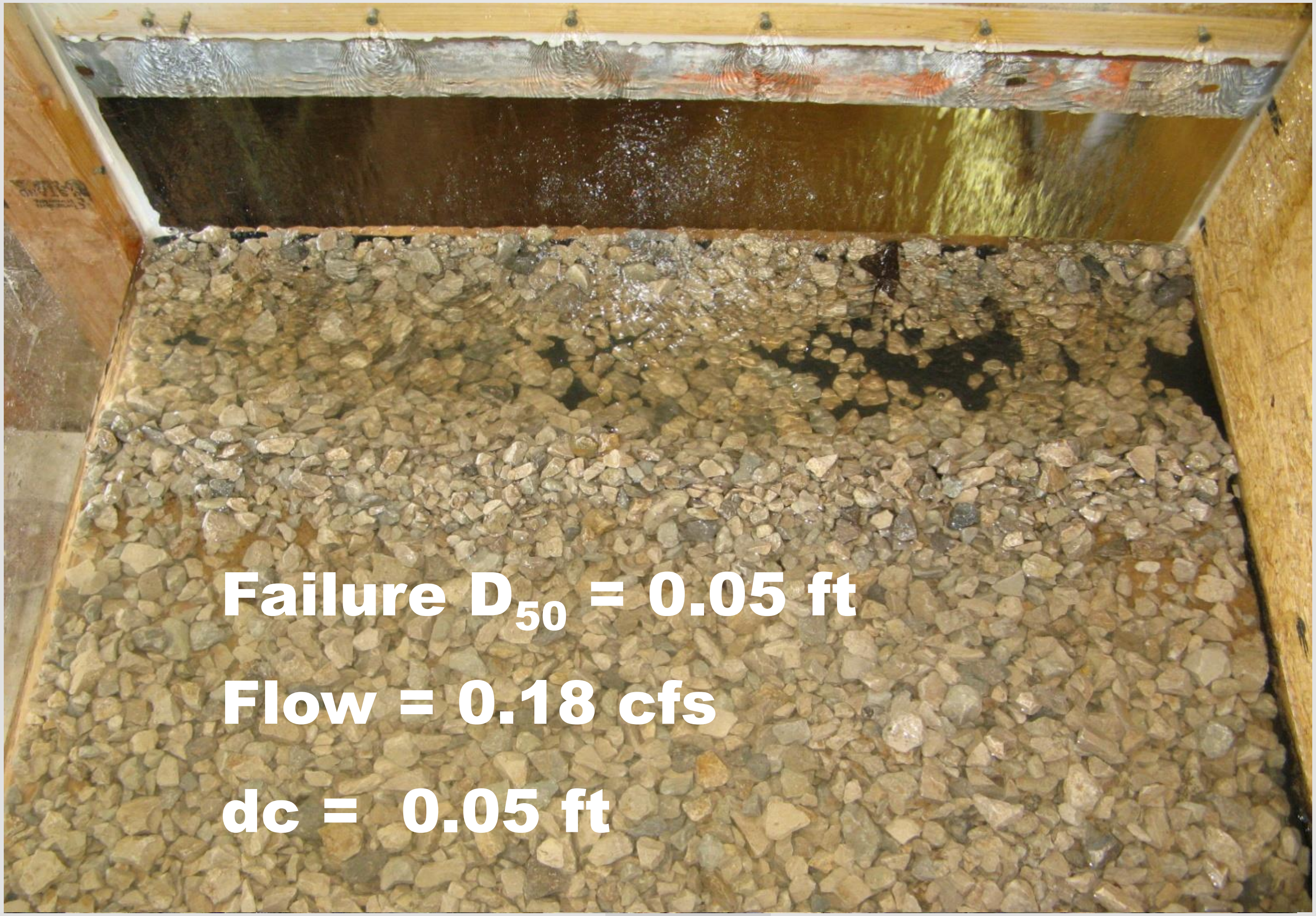
4. Once geofabric is exposed, turn off flow, and record scour.

Test Procedure

5. Repeat steps 1-3 of test set-up and 1-4 of test procedure until all rock sizes have been tested for the desired drop height.
6. Repeat the entire procedure for next drop height.
7. Conduct steps 1-6 on the third drop height (1’) for verification data.

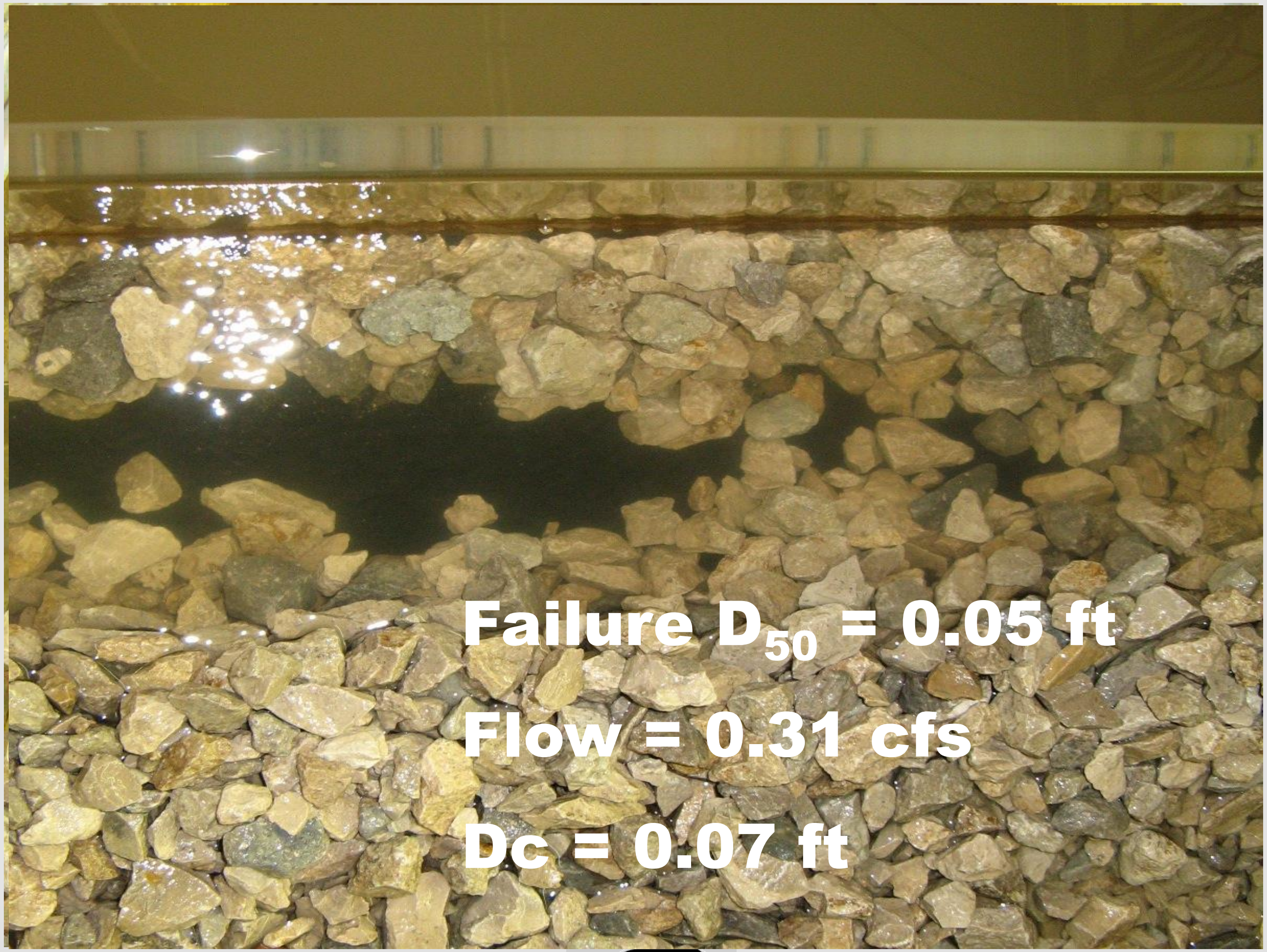
Test Results

Drop Height = 2 ft.



Test Results

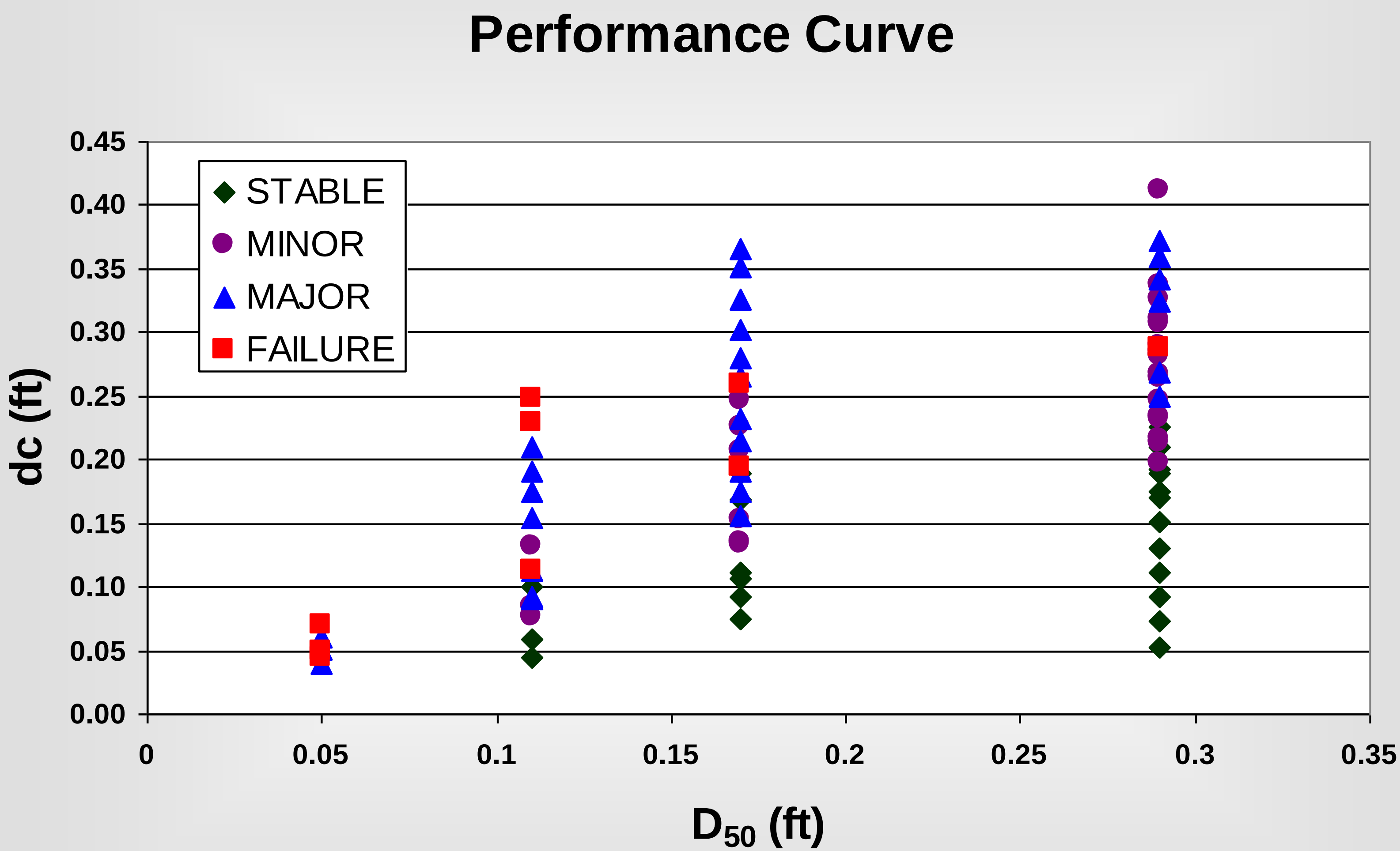
Drop Height = 0.5 ft.



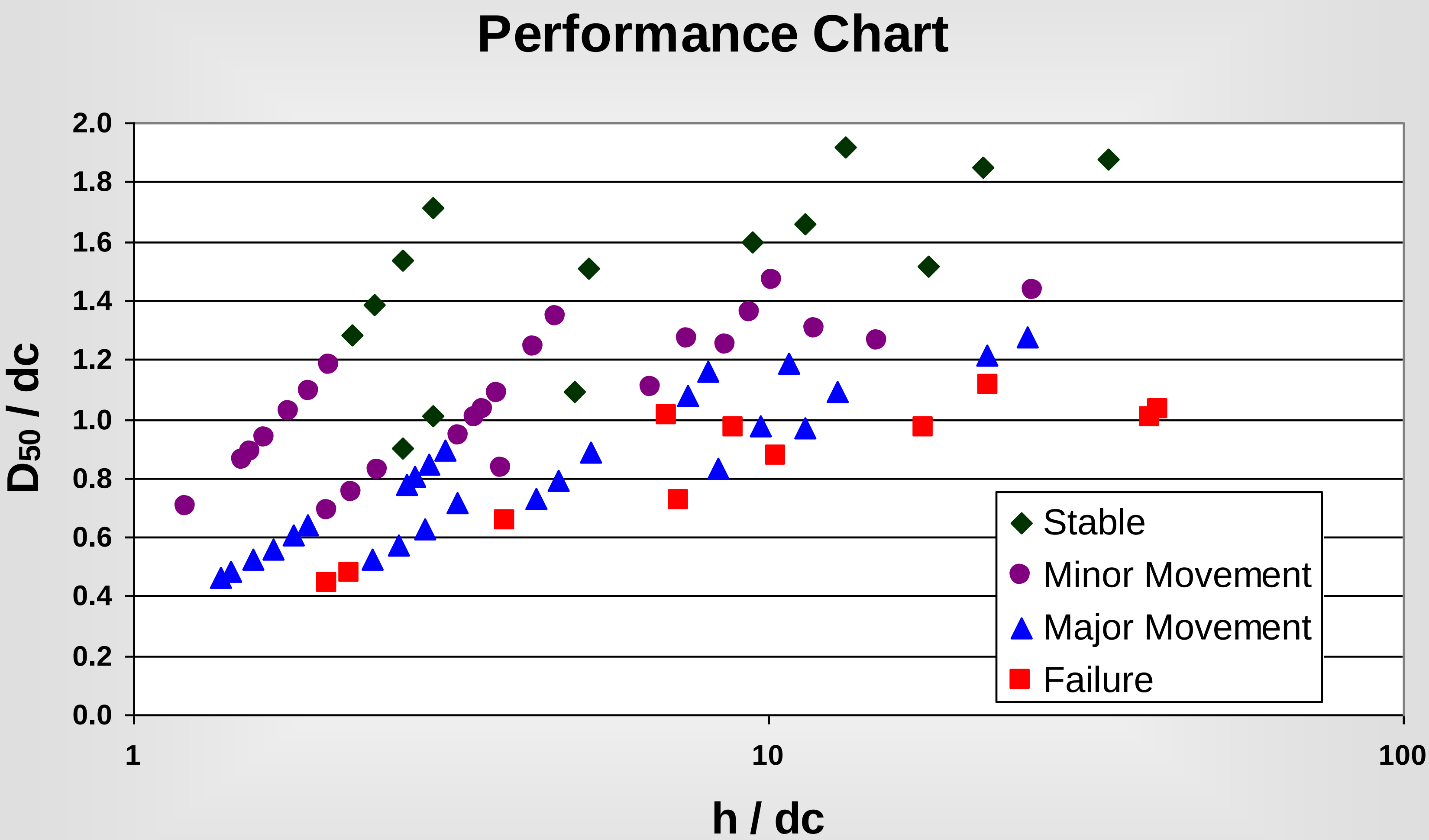
Test Results

Drop Height = 1 ft

Test Results

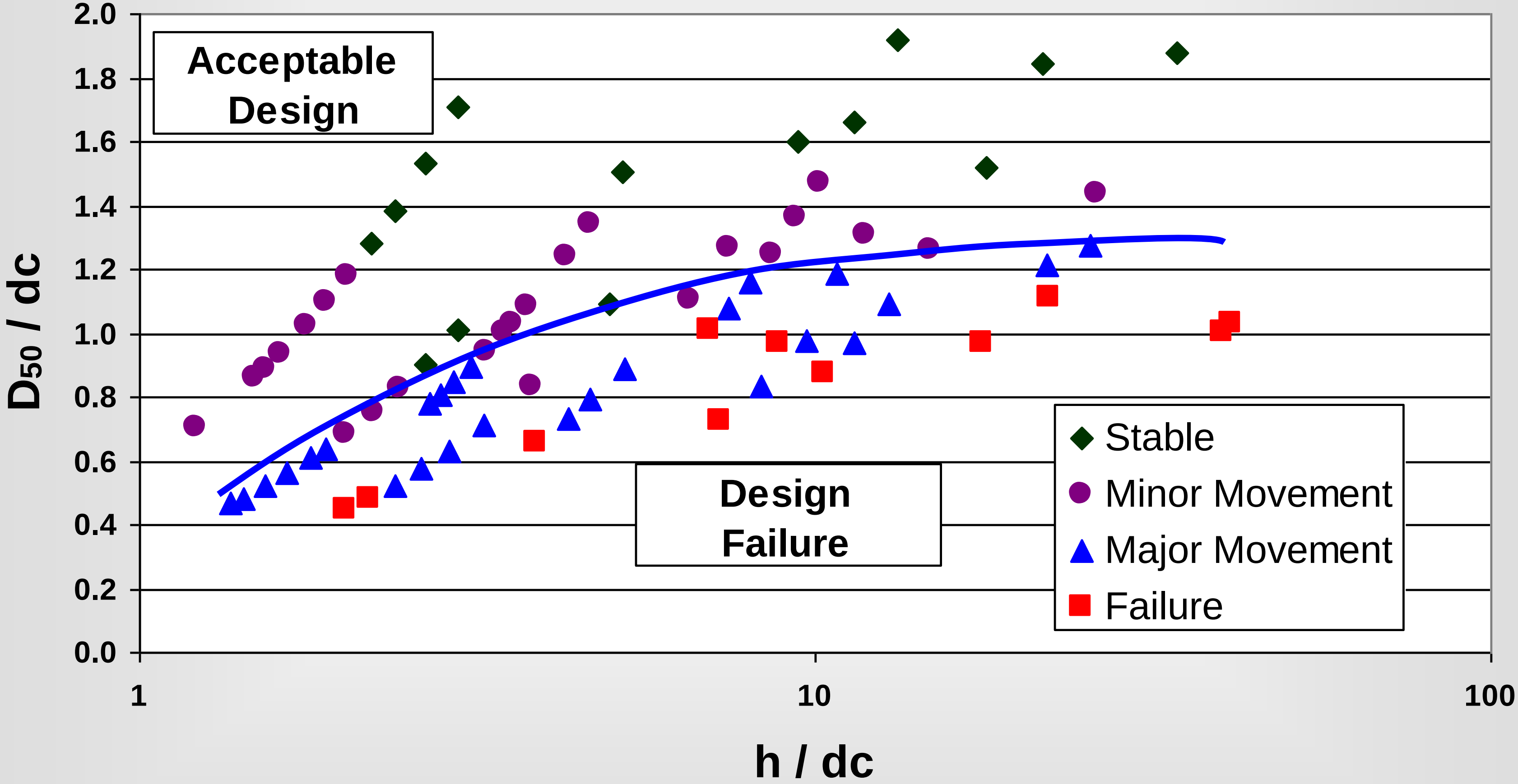


Test Results

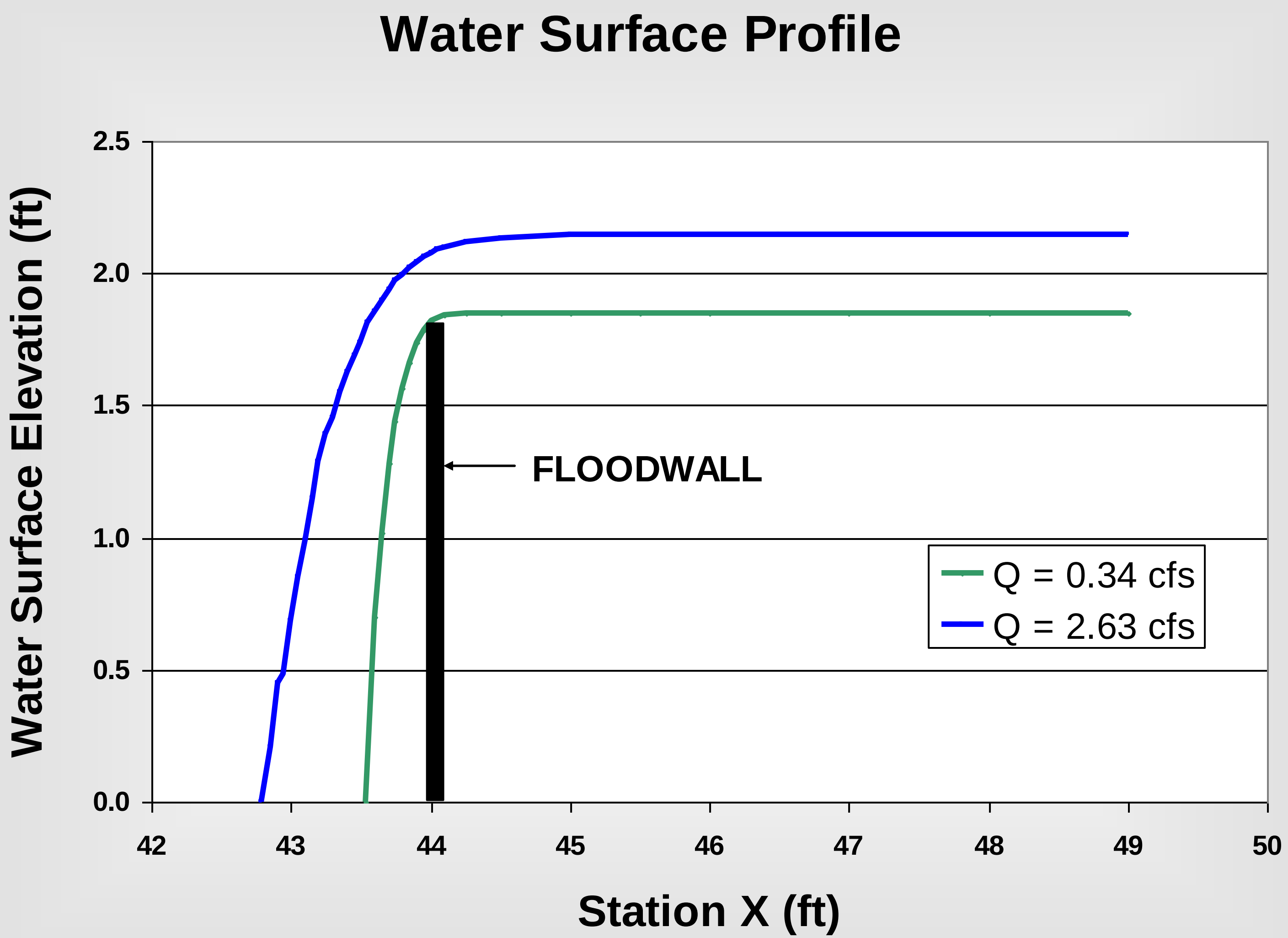


Test Results

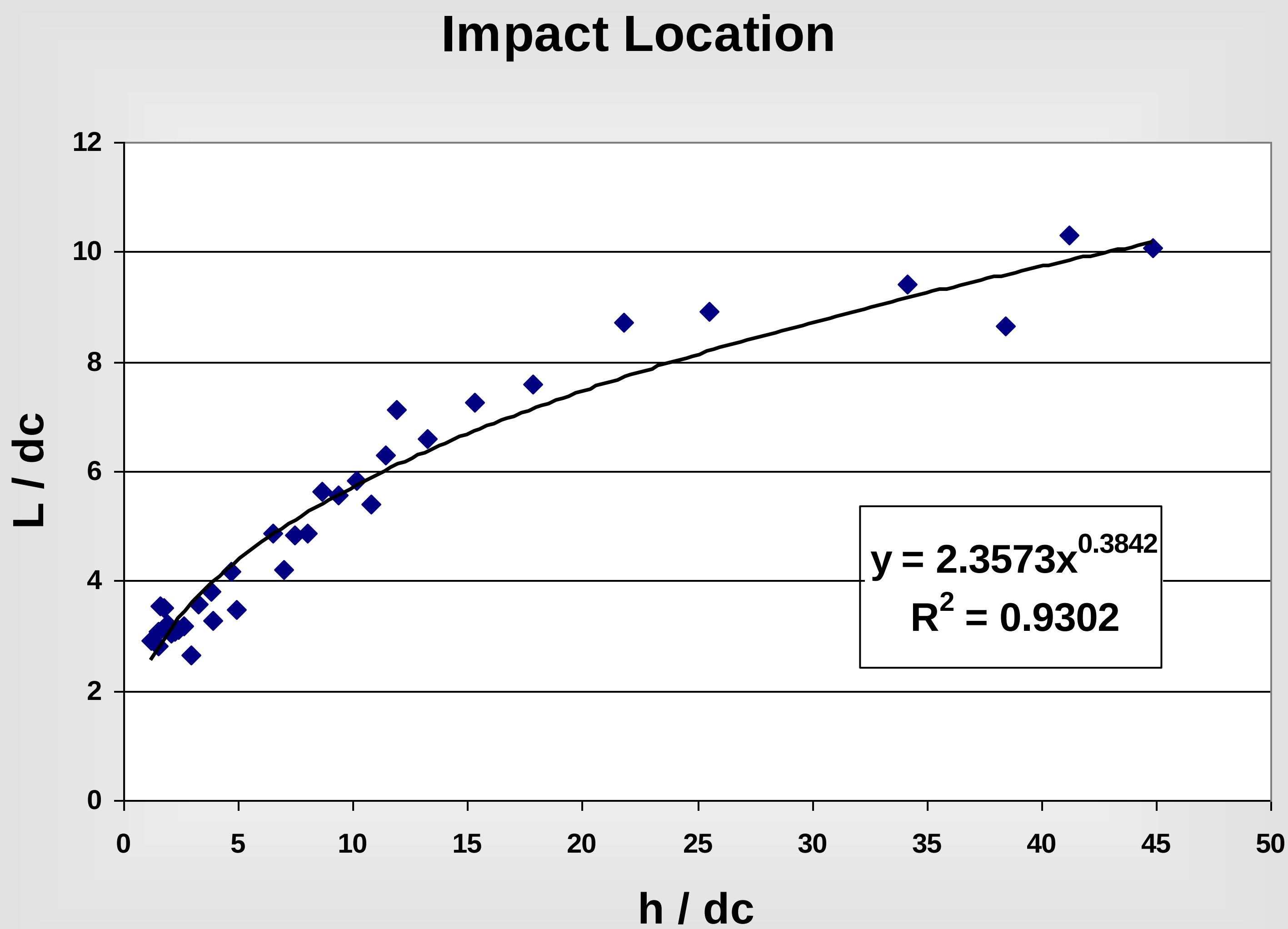
Performance Chart



Test Results

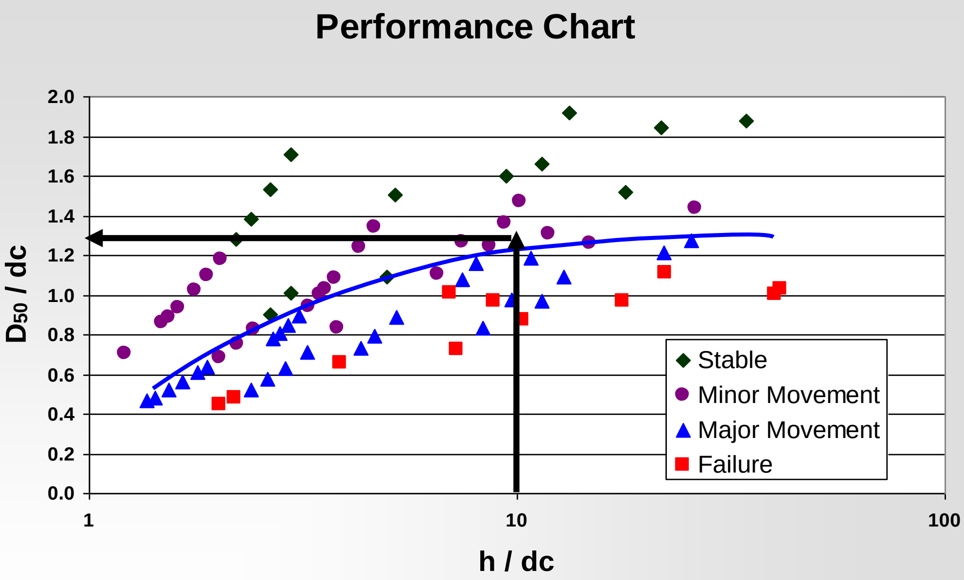


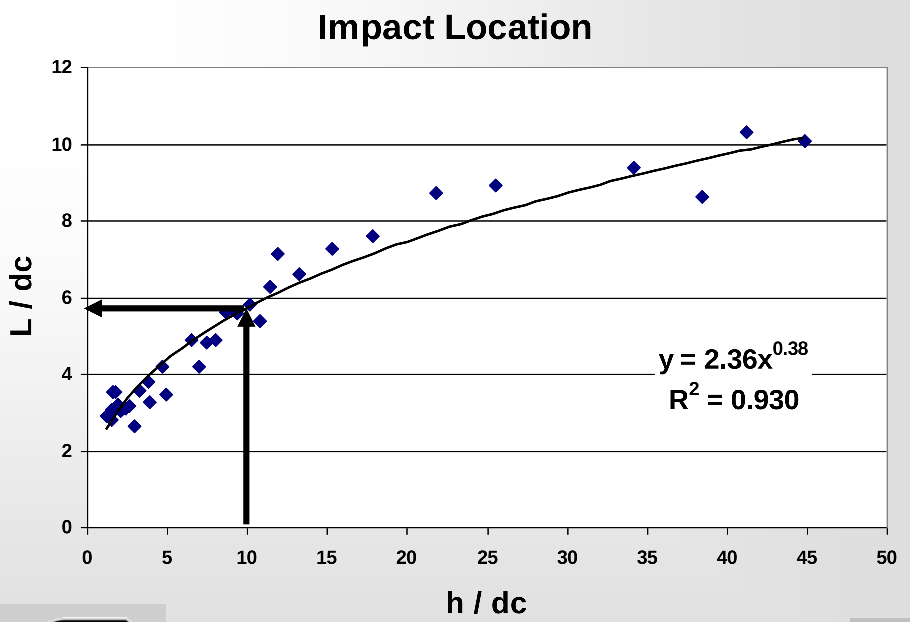
Test Results



Example Problem

- 10 foot floodwall
- No current downstream protection
- 25 year storm event produces a dc = 1 ft.
- Find D_{50} from Performance Chart
  - D_{50} = 1.3 ft.
- Find jet impact location from Impact Location Chart
  - L = 5.7 ft.



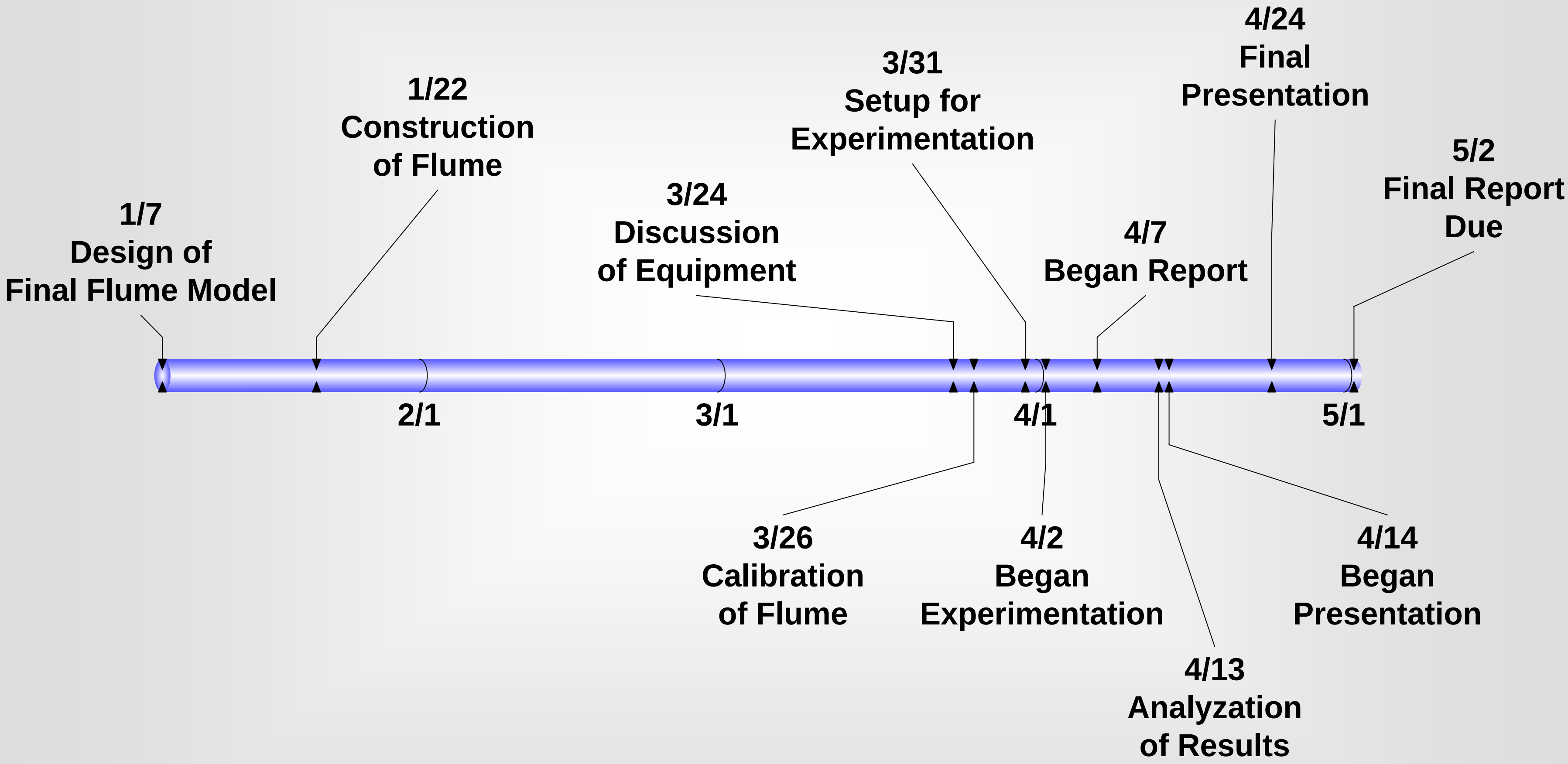


Conclusion

Further Work Necessary

- Further testing of additional ranges on model flume
- Larger scale outdoor tests for verification
- Investigation of tailwater conditions
- Investigation of various downstream conditions
    - Sloped embankments, etc.

Timeline



1/7
Design of
Final Flume Model
1/22
Construction
of Flume
3/24
Discussion
of Equipment
3/31
Setup for
Experimentation
4/7
Began Report
4/24
Final
Presentation
5/2
Final Report
Due
2/1
3/1
4/1
5/1
3/26
Calibration
of Flume
4/2
Began
Experimentation
4/13
Analyzation
of Results
4/14
Began
Presentation

Acknowledgements

- Special Thanks to:

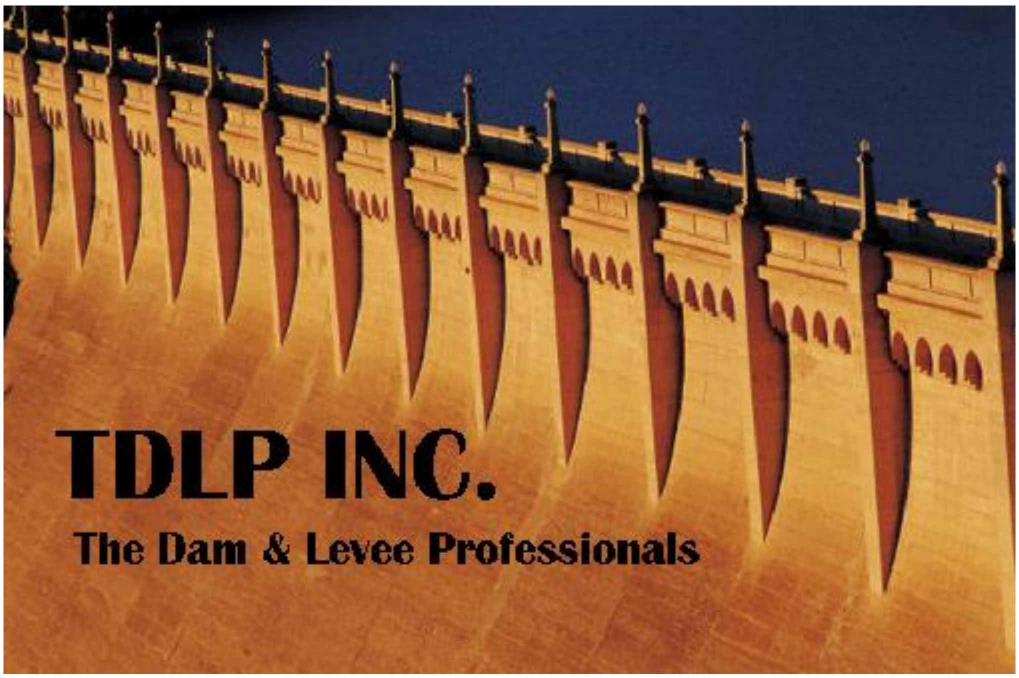
  Dr. Weckler for his guidance throughout the last year

  Greg Hanson, Sherry Hunt, Bobby Sappington and Kem Kadavy for sharing their knowledge with us at the HERU laboratory

  And Dr. Fox for all his additional help in critical depth calculations

Questions?

Fall Design Report



Kevin Chancey
Sarah Edens
Monica Murie
Jason Unruh

BAE 4012 Senior Design
Fall Report
December 5, 2007

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Mission Statement

"TDLP Inc will be the innovator of dam and levee erosion control designs that will meet and exceed our customers needs to provide them with the safety and security we all deserve. TDLP Inc will go above and beyond industry standards to provide protection of property and quality of life by designing and maintaining top notch erosion protection structures at an affordable price."

-TDLP Inc

Introduction

The United States Department of Agriculture (USDA) chief scientific research agency Agricultural Research Service (ARS) specializes in developing solutions to agricultural problems that affect Americans every day. Stillwater is home to a division of the ARS this unit is called the Hydraulic Engineering Research Unit (HERU). HERU has been in continuous operation since it was established in 1940. The lab has had a major impact on soil and water conservation engineering and is recognized nationally and internationally as a significant contributor of sound design criteria for soil and water conservation structures and channels. Most notable is the pioneer work in the design concepts for vegetated channels.

The HERU conducts experiments and trials to develop criteria for the design and analysis of structures and channels for the conveyance, storage, disposal, and measurement of runoff waters. Also to develop fundamental knowledge of the hydraulics of surface flows for use in planning measures needed to control water for flood prevention, pollution abatement, and assessing the safety of existing measures. Other aspects the lab studies are the ability of vegetation and/or various natural and manufactured materials to prevent erosion when used to manage runoff waters.

Floodwall overtopping is an example of a project that the HERU lab would investigate. Overtopping is a result of intense storm events that under the right conditions produce runoff that overtops floodwall structures. The process of overtopping can be devastating in several ways. The excess water can flood property that was intended to be protected by the wall, and also the force of the water coming over the wall can scour and deteriorate the materials and foundation of the wall on the downstream side causing failure. In accordance with the mission statement of the HERU, we will be looking at what materials can be used to reduce this erosion phenomenon called scour.

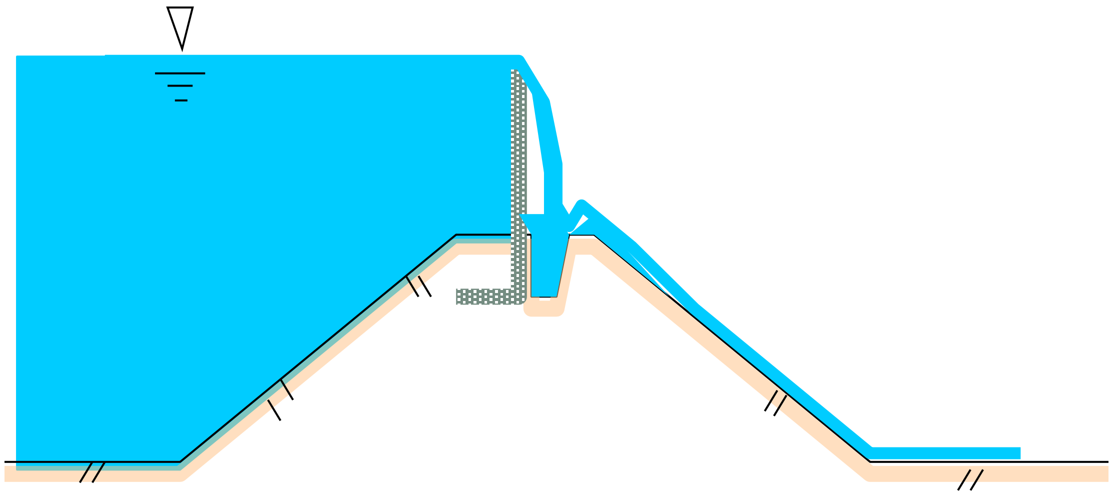

Figure 1. An illustrative example of floodwall scour.

Figure 2. An example of the dangers of floodwall overtopping and scour.

Flood wall scour happens when the design recurrence interval is exceeded and the water overtops the structure causing erosion on the opposing side that can undermine and destabilize the structure.

Figure 3. A floodwall scour path along the base of an existing floodwall.

Figure 4. Floodwall scour along the base of an existing floodwall.

The two figures above are examples of floodwalls that have experience scour, however these structures have not sustained extreme damage. Numerous methods have been developed to potentially lessen the risk of destabilization such as geotextiles, sod, concrete, and riprap. Our group will be looking into finding a product that works under certain specified conditions. We will be testing our material in a scaled flume setting in order to determine what product works best. The definition of best is based on a number of factors including performance, economics, ease of construction and design, and availability.

One of the first steps in conducting a scaled flume study is to determine the appropriate size of model, model design, range of discharges, and series of tests to be conducted along with and estimated time-line. Below is an example of a system that we intend on using. With this system we will test scale sizes of gabion and riprap.

Figure 5. An operating flume.

Figure 6. Floodwall with rip rap protection.

Problem Statement

Floodwalls are designed to provide additional storage and protection against flooding, but when floods exceed the design recurrence interval of the floodwall, waters will overtop the floodwall resulting in a waterfall effect on the downstream side. The resulting downstream impinging flow may cause scour and erosion that can undermine or destabilize the floodwall, potentially resulting in a catastrophic failure. Steps must be taken to reduce or eliminate this scouring and erosion in order to secure the integrity of overtopped floodwalls.

Statement of Work

TDLP Inc. met with the USDA-ARS HERU in September to discuss the logistics of the design problem at hand, and design objectives for a generalized approach for preventing scour and erosion downstream of floodwalls. The HERU lab asked TDLP Inc. to develop a generalized approach with consideration of an optimal ground application that would decrease scour from water overtopping floodwalls, increase ground stability in order to protect the integrity of existing floodwalls, and remain within economic constraints in order to keep the product easily applicable and marketable.

TDLP Inc. will begin this process by investigating the specific issues and problems occurring with overtopping of floodwalls. TDLP Inc. will then generate design concepts, build a prototype of floodwalls currently in existence using a flume provided by the Hydraulics Lab, determine experimental procedures for testing these concepts within the flume laboratory, model these concepts, and present concepts for evaluation.

Testing Determination

Before any experimentation is to begin, TDLP Inc. is assigned the task of creating a testing environment similar to actual environments encountered in the field. The main concern is creating a small scale model of a typical floodwall. Parameters involved when creating this design are drop height, overtopping width, flow rate, and flow area. TDLP Inc. will investigate existing floodwalls and design and construct a model for simulating the floodwall environment. Flow rate for the flume laboratory are discussed in the limitations section of the statement of work. It is anticipated that the model will be designed with a constant width but will allow for variation in drop height and overtopping discharge. The tests will be conducted to determine a generalized criteria for stable design of protective material downstream of a floodwall. The initial plan is to develop a dimensionless approach similar to the approach used by Rice and Kadavy (1991). In their study they related stable rip-rap size downstream of a straight drop basin to the critical depth of flow at the crest of the basin. An example problem of the developed equations and hydraulic parameters of importance is shown in the section "Initial Floodwall Design Calculations", presented later in this report. TDLP Inc. will work to solve a similar relationship and present our findings to Dr. Hanson for review.

Determination of Material at Scour

Literature reviewed for this design problem focused on studies looking at development of scour holes and size of material present at the hole. TDLP Inc. has been asked to propose material(s), conduct tests on the material(s), and report findings for preventing scour or minimizing the size of the scour hole downstream of a floodwall. Bed stabilization will be the major response variable investigated. Possible material or product options recommended for initial study include rock of varying sizes, gabions, interlocking blocks, shingled blocks, and soil cement.

Limitations

One limitation presented to TDLP Inc. is directly applied to the testing phase of our design. In nature, flow rates of waters overtopping floodwalls can vary anywhere from 1 cfs to 6000 cfs and above. TDLP Inc. is limited in the flow rates allowed to be tested in our flume apparatus to a maximum of 6 cfs. Another limitation is flow length downstream of the floodwall. Since the laboratory basin within which tests will be conducted in is only approximately 30ft, downstream conditions will only be known to that length or less. The final solution proposed by TDLP, Inc. will include limitations of design. These limitations arise from variation in actual floodwall design from place to place, availability of materials in different regions of the world, and geotechnical properties at individual floodwall sites. TDLP Inc. is assigned with determining a generalized approach which will hopefully be able to be expanded upon for each individual floodwall application.

Miscellaneous Issues

The USDA-ARS HERU has asked TDLP, Inc. to determine specific ranges of protection needed for varying floodwall conditions. However, there are cases that may fall out of this range. TDLP Inc. is not responsible for developing design for every single possible case. For example, there will be situations in which the design of the floodwall and the storm event may be in excess of the generalized approach presented by TDLP Inc. For cases such as this, the only solution may be direct application of concrete blocks which are out of the economic range of what TDLP, Inc. is assigned to design.

Research & Literature Review

TDLP Inc investigated several methods to reduce flood wall scour. We discovered numerous methods and designs to reduce this process. We evaluated several journal articles as well as individual market products. We also checked into several patents that are related to floodwall scour. The following are summaries from the articles that we found and the site at which they can be found.

Journal Articles

Department of Environmental Quality Riprap Guide

Riprap is rock cover used to stabilize stream banks and any other structure which can experience a large amount of erosion. The article is very descriptive in when and where to apply riprap, gives lists of sizes of riprap and their measurements.

The types of stones are discussed as far as what materials should compose them. Calculations are given in determining the depth of riprap, size of riprap, and length of the area. Tips on riprap around outlets are given, many details on designing riprap areas. Specifications for flows, depths of flows, and grades at which the rocks should be laid. The article is very helpful it was written by the DEQ and provides lots of data and numerous equations to help find needed data (DEQ, 1997).

The Use of Gabion and Reno Mattress in River and Stream Rehabilitation

Gabions come from the Italian word for "Gabbione", which means "Big cage" (Chayuck 2005). Gabions have been a popular as well as easy way to secure structures for many years. The first industrial production of these structures began in 1894 in Italy used mesh to retain rocks (Chaycuk 2005). This practice has continued and with the development of better techniques, their use continues. Gabions are an inexpensive and easy way to retain structures that can be subject to erosion. The article describes how they structures are used and work. Details on the wire and other material used are also given, as well as when to use certain wires and when not to because of the abrasive environment. The standard gabion was described as well as the Reno Mattress which is also very popular because of its construction. The Reno Mattress is more flexible because there are dividers every one meter this allows the structure to be maneuvered easier in changing slope conditions, making this structure great for scour protection and channel linings. The article describes construction of these structures as well as the preparation for them. Hints are given as to which system will better serve an individuals needs as well as designing the structure. Stone dimensions and mesh specifications are also given for the different varieties of gabions. Many images of the structures and installation are also given in the article that can be very helpful in setting up a good site. Even though gabions are simple they can be the best choice in reducing erosion conditions (Chaychuk, 2005).

Sediment Transport Modeling for Stream Channel Scour Below a Dam

In this journal article, Howard H. Chang (2001) investigates stream channel scour in California using sediment transport modeling. Although this study does not conform exactly to the study which is presented to TDLP, Inc., it has some helpful guidance for determining general scour and running various computations.

To determine the general scour, the FLUVIAL-12 model can be employed (Chang, 2001). This model takes a given flood hydrograph and simulates spatial and temporal variations in water-surface elevation, sediment transport and channel geometry. Even though Chang mainly discusses using this model for channel beds, we could investigate this model's application to flow over an embankment or levee.

This article also discusses sediment delivery. Although sediment does not seem as it would be a concern in our problem (seeing as how the overtopping water will most likely be very dilute of sediments), sediment transport may be a concern on the side of the levee which shows scour.

Scour Below an Overfall: Part I. Investigation

The journal article entitled "Scour Below an Overfall: Part I. Investigation" is a very interesting article which could provide a lot of insight towards the problem assigned to TDLP, Inc. The authors realize that scour below an overfall contributes to headcut instability and gully advance and perform various tests to investigate factors which could reduce such scour. These tests included thirteen large-scale scour tests of water flowing over a horizontal approach onto compacted soil beds of differing soil moisture and soil density (Robinson, et al., 2002).

The study was conducted using a long flume of dimensions 1.8m wide, 2.4m tall, and 29.3m in length (Robinson, et al., 2002). Sketches are found in the article which illustrate this flume. Such illustrations could be useful in the construction of a flume for TDLP's problem. The experimental procedure outlined by Robinson, et al., could also be of use as a guidance tool for the specific problem presented to our team. The only differences that may occur would be due to using different materials than just soil as our test subject. This article is full of useful figures and instruction as well as results, but does not cover the full scope of what will be needed in our problem. It will serve mainly as a guidance tool for soil conditions and scour characteristics. Perhaps the main advantage of this article is that two of the authors did this research at the lab which we will be using for our testing and will be at our disposal for further questions and assistance.

Scour Below an Overfall: Part II. Prediction

The journal article "Scour Below an Overfall: Part II. Prediction" (Hanson, et al., 2002) provides an extension to its previous journal article "Scour Below an Overfall: Part I. Introduction" (Robinson, et al., 2002). The four main objective of this article were to:

> "*(1) utilize a previously developed excess stress parameter approach, with small modifications, for the free overfall jet; (2) develop similar excess stress parameter approaches for the submerged circular jet; (3) determine and compare excess stress parameters for both overfall and submerged circular jet scour test results; and (4) compare erodibility results for each experimental system.*"

All of the above objectives apply to TDLP's design problem. Although the main material of testing in this set of experiments was soil, TDLP can apply the concepts to the materials which we test. Excess shear stress concepts are also discussed and equations for computation are given. Hanson, et al., also gives a comprehensive look into planar and submerged circular jets, and the extensive calculations used to define each. This article will give TDLP the knowledge to begin experimental setup and test procedures on the materials of our choice with precise guidance.

Velocity Field Measurements at an Overfall

One journal article which could prove to be beneficial to TDLP, Inc., as we begin our research into scour from an overfall is the article "Velocity Field Measurements at an Overfall" (Robinson, et al., 2000). This article measures and characterizes the velocities and circulation patterns for flows in the vicinity of an aerated straight drop overfall, as is the condition of our design problem. Useful parameters tested by Robinson, et al., (2000) are velocity vectors for multiple tailwater levels at constant flow rates, and velocity vectors for multiple flow rates at constant tailwater levels. A definite procedure for measuring these velocities is given and results are clearly outlined. With guidance from the procedures tested within this article, our team has a clear view of operations which might take place during our experimental testing. This article also gives insight to related work which could be functional for our team. Further investigation into the works referenced within this article may prove to be worthwhile.

Erosion of Fractured Materials

This journal discusses the natural fracture patterns that exist with in soil and rocks and how these fractures effect erosion. The objectives of the study were to investigate the dominant parameters that cause failure of a fractured block matrix. The study used matrix of blocks downstream of an overfall. They increased the discharge of water over overfall until the matrix failed. The block matrix failed due to the forces transmitted by the flow of water. The block size, block orientation, and overfall height were varied systematically over a range of flow rates. From the study the authors were able to describe a few of the parameters. Failure discharge was observed to decrease as the overfall height increased. The failure discharge was also observed to increase if the block was placed with its long axis oriented vertically. The orientation of the each block to where the weight was over a smaller area, thus requiring an increased pressure to dislodge the block. The article gives fundamental research information we need on scour holes formed in soil and rocks.

Lessons Learned using Laboratory JET Method to Measure Soil Erodibility of Compacted Soils

The article discusses a study cover the reason for accidents and failures of embankments for dams, lagoons, and levees. A key parameter that was focused on was the erodibillity of the soil materials used in the building of the structures. Soils are generally compacted to a certain specifications when being used for these structures. The jet erosion test (JET) was developed to study the erosion characteristics of soils. The laboratory version was used in the study to define the erodibillity of compacted soils. This article is good for project because it gives us a way to describe the erosion properties of compacted soils as well as the benefits of compacted soils. Also the JET is a good way for us to simulate the water overtopping the flood walls.

Plant Root Effects on Soil Erodibility, Splash Detachment, Soil Strength, and Aggregate Stability

This article covers a studied that tested in a laboratory the influence of dead roots on soil erodibility, splash detachment, and aggregate stability. The study used a rainfall simulator on a Mexico silt loam. The study found the difference in erosion and splash detachment when the type of cover was changed by type and amount. This article is helpful to use in that it gives us some insight on the type of covers and amount that are needed to significantly change erosion. However the study was only tested with rainfall so we will have to take in consideration the difference in the amount of water.

Physical Modeling of Overtopping Erosion and Breach Formation of Cohesive Embankments

This article discuses the processes and timing of dam embankment breach caused by flooding. The purpose of this study is to: (1) establish a better understanding of the erosion process of overtopped cohesive embankments, and (2) provide detailed data for future numerical model development, validation, calibration, and testing. The USDA-ARS has conducted 7 large scale tests with three different soils tested. The rate of the processes involved was observed to vary by several orders of magnitude and was dependent on the soil material properties. The study is good for our because of the modeling that is discussed in it.

Patents

Erosion control rolls

The patent number of this invention is 6,641,335. It was filed on January 7, 2000 with a current U.S. class number of 405/302.6. The reason for this invention was to control sediment and debris flow associated with soil erosion (Allard, 2000). These rolls are typically composed of fibrous materials such as straw or shredded wood and are held together with netting. These rolls are placed across a slope during construction to try and stop soil erosion and to dam as much as possible. They also direct and/or filter fluid flow as the fluid runs down the slope. Fiber rolls are more capable than silt fences because the silt fences collapse under heavy fluid flow and high winds. The construction of this patent consists of an open end, a second end, an interior space, and one more openings in the wall surrounding the interior space with the exterior of the core member (Allard, 2000). One or both ends of the core contain couplers or connectors for connecting multiple core members together (Allard, 2000). The exterior of the core member, which is a fiber roll, can be made of straw or shredded wood. Surrounding this is a porous covering material such as a woven cloth or netting (Allard, 2000). With this design an infinite amount of core members can be attached together depending on the size of the project (Allard, 2000).

Reinforced interlocking retention panels

The patent number of this invention is 6,851,889. It was filed on April 23, 2003 with a current U.S. class number of 405/32. The reason for this invention is for the prevention and/or elimination of scour beneath marine structures (Buchanan, 2003). The most common methods for preventing scour are the placement of rock protection or constructing a bulkhead (Buchanan, 2003). These methods may be efficient but will also have some disadvantages. This invention uses multiple interlocking panels to cover the area that is scoured. The panels are composed of resin impregnated carbon sheets on each side of fiberglass sheets (Buchanan, 2003). The thicker the carbon fiber is the stronger the sheets will be. Each panel that is used has a high-density polyethylene interlocks on each edge to allow each panel to slide together (Buchanan, 2003). The panels can be cut to a certain dimension to allow for a custom fit for each job (Buchanan, 2003).

Earth dam protective coverings

The patent number for this invention is 4,184,786. It was filed on March 6, 1978 with a current U.S. class number of 405/108. The reason for this invention is to protect earth dams from failure caused by overflow or internal erosion (Richards, 1978). This invention has a barrier that is placed below the dam and anchored down to prevent scouring. The barrier is made up of a flexible plastic sheet, or a combination of plastic sheets, capable of functioning as a water-tight barrier between the ground below the dam and the flowing water (Richards, 1978). Each section is anchored down with the embankment itself or with rock material (Richards, 1978). The plastic material is relatively inexpensive, easily obtainable, and quickly laid out and anchored down. This protective covering should provide protection from scouring for years (Richards, 1978). If it should happen to become damaged it can easily be fixed or replaced.

Hydraulic energy dissipating offset stepped spillway and methods of constructing using the same

The patent number for this invention is 6,059,490. It was filed on May 5, 1998 with a current U.S. number of 405/108. The reason for this invention is to prevent scouring from happening below a dam which would eventually cause the dam to fail. When the dam fails the area downstream of the dam will be flooded. The material used to prevent scouring is made of concrete blocks. Each block is dimensioned and shaped so that water cascading down the steps is caused to flow in three dimensions. The three dimensional flow generates turbulence which dissipates the kinetic energy of the water (Kauppi, 1998). The blocks are arranged in rows then stacked on top of each other in a shingle like overlap (Kauppi, 1998). Each stacked row is offset laterally from the row below to try and prevent water penetrating through each level of the blocks. The bottom row is placed on top of the toe plates to prevent the bottom layer from shifting (Kauppi, 1998). The blocks are stacked and staggered until the desired height of the spillway and embankment is obtained (Kauppi, 1998). The stepping up of the blocks will help dissipate the kinetic energy of the falling water preventing scouring of the soil below the dam. This in return will keep the dam from failing and causing massive flooding downstream.

Hydraulic Energy dissipating offset stepped spillway

One very interesting patent that was found in our search involved a design for dissipating the kinetic energy of water flowing over the top of a spillway embankment (Kauppi, 2000). Even though this patent does not directly apply to the problem proposed by Dr. Hanson of the USDA ARS Hydraulics Lab, some of the concepts behind the design could be useful in guiding our team in the right direction. In this patent, Kauppi (2000) proposes that to build a spillway "comprising of a plurality of building blocks arranged in rows which are stacked upon each other in a shingle-like overlap such that … a series of steps are defined thereby" to generate enough turbulence within the water to dissipate kinetic energy. Although this patent offers one design detail which would assist the problem presented to TDLP, Inc., it also has some shortcomings. One claim of Kauppi (2000) is that the blocks used in the design must be fabricated from concrete. This is one material which will be avoided in our design due to the economics of the problem. In the background information of the patent, it does discuss a few interesting alternatives to scour. A few of these alternatives include riprap, geotextiles, and baffle apron drops. However, the most interesting alternative mentioned is gabions (wire baskets filled with rock which are anchored to the ground). Problems with gabions include deformation under certain flow conditions. This could be a possibility for future testing.

Market Research:

Aromorflex® Brochure-

Armorflex is a product designed by Armortec™ . Armorflex is a flexible interlocking of concrete blocks which are interlocked by cables. They blocks are organized in a mat like fashion and placed on a prepared site on top of a permeable mesh. The driving force for this product is its available porosity, flexibility, and the fact that this product encourages habitat development and vegetation. The product is aesthetically pleasing and comes in a wide variety of sizes that make it easily used in all applications. This system is marketed as a articulated concrete block or ACB (Armortec, 2006).

Figure 7. **Aromorflex®** interlocking concrete.

Armorflex® Revetment System Specification for Overtopping Applications-

This article was regarding the production of the blocks themselves and also the applications they can be used for. The article gave sizes of blocks and material composition. Standards for block inspection were also given and grounds on rejection. Information was also provided on the cables and which types of cables could be used and the diameter and strength of these cables. A detailed profile on site preparation and mesh specifications was also given. Sizing blocks for your particular application and finishing of the site location were given. The article was very beneficial from taking you from a start to finish in what all must be done in order to make a structure which can stand a dam overtopping. Equations and resources to find additional information on velocities of dam overtopping were also given (Armortec, 2006).

Armorflex® Cellular Concrete Mat Specification for Erosion Control for Wave Attack-

This article pertained more to protecting a flood wall from the opposing side rather than the overtop side. This information could still prove to be beneficial when considering maintaining the stability of the entire structure. This article gave information on the different types of waves to expect and sizing blocks for those applications. This article had information on site preparation, inspection, and a start to finish layout on how the setup would done. Material makeup of the blocks was provided as well as the makeup of the cables. Cable strengths and the application in which different sized cables were needed were also provided (Armortec, 2006).

A-Jacks® Brochure-

A-Jacks® are another product by Aromortech, they differ from the articulated concrete block in that they look like a heavy duty concrete star or jack. They are designed to interlock and form a wall or structure that is rigid but yet highly permeable. They are popular in reducing bridge scour and stream bank erosion. They can be left with the voids to allow for marine habitat or can be back filled for plant life. These structures allow vegetation to be established by anchoring the vegetation down till it gets a strong start like trees and shrubs (Armortec, 2006).

Figure 8. **A-Jacks®** material.

Erosion Control Blanket Products Brochure-

Erosion Control Blankets or ECBs are normally a short time fix to erosion problems. However, with better geo-textiles, the fabric will last much longer and help establish natural vegetation and help anchor that vegetation in. These mesh blankets are cheaper then the concrete and easier to apply. They can also help give a more natural look and are a quick fix to the problem. They are not quite as sturdy as the concrete but they can still be a good solution. The company Erosion Control Blanket out of Manitoba Canada markets several of these blankets from a short term blanket to a permanent blanket (ECBP, 2007).

Soil Erosion Control Mulches, Blankets and Mats-

The article discusses several applications of erosion control blankets and turf-reinforcement mats (TRMs). The article regards the selection and installation process of theses erosion control methods. Several of the advantages that were given were protecting soil surface during and after land alteration activities. Others were raindrop impact and overflow protection. However, many other additional benefits were given as well as limitations to the blankets. Information that was also provided was design requirements and materials used.

A time table of the material life was provided and sketches of the installation. Overall the article is very helpful in the use and application of erosion control blankets.

LandLok® Supergro® Erosion Control Blankets Brochure-

Propex, a geosynthetic company also makes erosion control blankets. They make blankets that are quickly biodegradable as well as some blankets that have a life span of three plus years. The fact that they are short term may not be beneficial but they could enable a good stand of vegetation to get in place. Also incorporating these textiles with other methods could prove successful. The article gave many examples of applications the fabric was used on. As well as installation facts and benefits, this fabric is very affective on steeper slopes and holds soil particles very well. The article gives the materials used in the nets such as straw, polypropylene, and even coconut. Several sizes are given as well as shear stresses and velocities that these fabrics can with stand (Propex, 2006).

Figure 9. LandLok® Supergro® Erosion Control Blankets

Kiciman Gabion Baskets, Mattresses, Sacks, Netting, and Razor Barbed Tape

Kiciman is a leading producer of Gabion structures. Gabions are rocks netted together using high strength wire. Kiciman sells several different structures and in their brochure they list these types as well as the sizes. Gabions are designed based on the customer's needs they can be very large, small, long, wide, and the wires can differ to as well as rock sizes. These structures have many advantages they are flexible, strong, durable, and very economical. Also, from a management prospective, they are easy to maintain. The article provides many details on the wire used and the sizes of the rocks however the size needed for certain applications was not given in the article. However, with other information size could be determined.

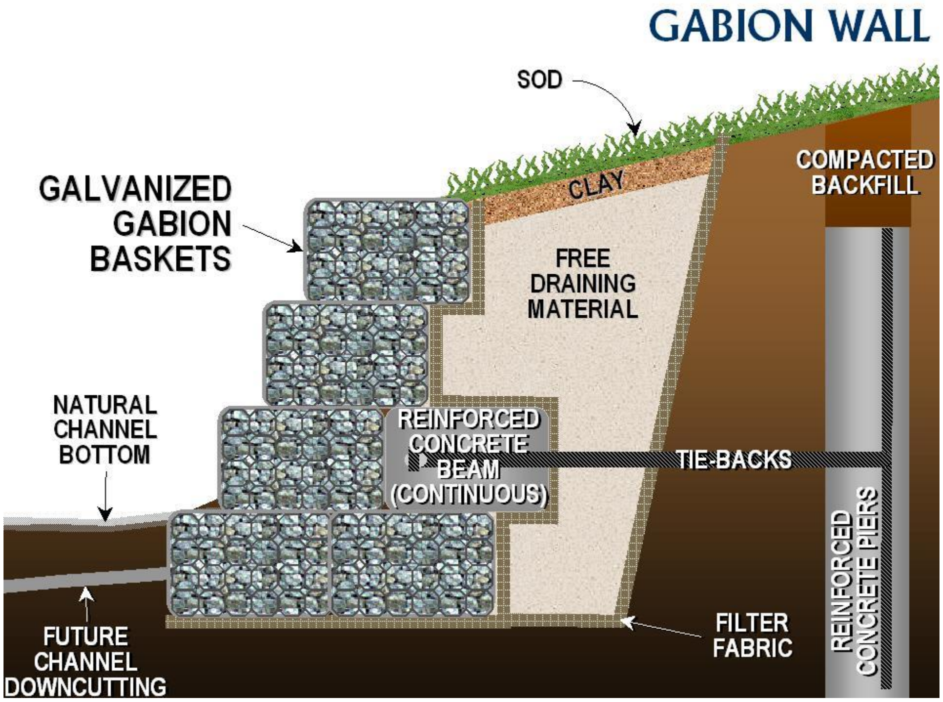

Figure 10. Example of Gabion initialization

Initial Floodwall Design Calculations

The following equations are relationships for sizing rip rap for straight drop basins. It should be noted that a similar approach may be developed for floodwall overtopping.

Critical Depth:

$$d_c = \left[\frac{\left(\frac{Q}{b}\right)^2}{g} \right]^{1/3}$$ (Rice and Kadavy, 1991)

Assumed b=3.5ft (width of floodwall)

$$d_c = \left[\frac{\left(\frac{5cfs}{3.5\,ft}\right)^2}{32.2\,{ft}/{s^2}} \right]^{1/3} = 0.39\,ft$$

Drop Height:

$$\frac{60\,ft}{14\,ft} = \frac{3.5\,ft}{y}$$

$$y = 0.82\,ft$$

$$d_2 = 2.15 d_c$$ (Rice and Kadavy, 1991)

$$d_2 = 2.15 \times 0.39 = 0.84\,ft$$

$$y_t = y + d_2$$ (Rice and Kadavy, 1991)

$$y_t = -0.82\,ft + 0.84\,ft = 0.02$$

Round Abutments:

$$\left(D_{50} / d_c \right)_{pk} = 0.054 + 0.051 \times \left(y / d_c \right)$$ (Rice and Kadavy, 1991)

$$\left(D_{50} / d_c \right)_{pk} = 0.054 + 0.051 \times \left(0.82\,ft / 0.39\,ft \right) = 0.161\,ft$$

$$\left(y_t / d_c \right)_{pk} = 0.85 - 0.25 \times \left(y / d_c \right)$$ (Rice and Kadavy, 1991)

$$\left(y_t / d_c \right)_{pk} = 0.85 - 0.25 \times \left(0.82\,ft / 0.39\,ft \right) = 0.324\,ft$$

$$\sigma = 10^{\left[-0.48 + 0.07 \times \left(y / d_c \right) \right]}$$ (Rice and Kadavy, 1991)

$$\sigma = 10^{\left[-0.48 + 0.07 \times \left(0.82\,ft / 0.39\,ft \right) \right]} = 0.465\,ft$$

$$D_{50} / d_c = \left[\left(\left(D_{50} / d_c \right)_{pk} - 0.13 \right) \times e^{\frac{\left(y_t / d_c \right) - \left(y_t / d_c \right)_{pk}^2}{\sigma^3}} \right] + 0.13$$ (Rice and Kadavy, 1991)

$$D_{50} / d_c = \left[(0.161 - 0.13) \times e^{\frac{0.051 - 0.39^2}{0.465^3}} \right] + 0.13 = 0.0114\,ft = .136 in$$

Riprap size:

$$D_{50} = 0.136 \times d_c$$ (Rice and Kadavy, 1991)

$$D_{50} = 0.136 \times 0.39 = 0.053\,ft = 0.63 in$$

Length of Riprap Bed:

$L_s = 5 \times d_c$ (Rice and Kadavy, 1991)

$L_s = 5 \times 0.39 = 1.95 ft$

Design and Setup of Experimental Flume

Existing Structures

The USDA Hydraulics Lab is providing an experimental laboratory in which TDLP Inc. can conduct its tests. The laboratory building and all incoming pipes are not insolated, therefore experiments can only be run whenever the ambient temperature is expected to remain above freezing. The floor of the lab includes a walking/observation area and a basin with 2.5 foot high walls that run 40 feet the length of the laboratory. Inside this basin is the structure to support the flume. The basin/floor is slanted towards a drain so that when water reaches the floor it will flow towards the drain and out of the lab.

The water for the laboratory is siphoned directly from Lake Carl Blackwell. Once the pipes are charged, the lab is able to receive 5 to 6 cubic feet per second of water through its 20 inch diameter pipes. The flow within the pipes can be measured using a manometer. A manometer is located on the south wall of the laboratory and the orifice plate slot is located just opposite of the manometer outside of the building. The large 20 inch diameter pipes run into a large storage tank which makes the flow more constant.

Also, in the laboratory, there is metal framing which will be used to build the base of the flume. The frame is not sloped which matched the design of real world floodwalls. Its dimensions are 18 feet long, 4 feet wide, and 5 feet tall.

Flume

The flume will be built out of wood. Its dimensions are going to be 4 feet wide, 4 feet deep, and 18 feet long. Wood is the building material of choice because it is easy to work with and inexpensive. The width and length of the flume were determined simply by the dimensions of the framing that is available at the lab. The depth was chosen by the material dimensions.

At the end of the flume there will be a 2 foot high wall representing the flood wall. The flume will be 5 feet off of the ground giving a potential 7 foot drop height. Currently we are planning on using a 3 foot drop, due to a scaling factor of ½.

Rock Box

The Rock Box is going to house the actual experiment. It is going to be 4 feet wide, 2 feet deep, and 4 foot long. The width is again based on the existing framing. The depth is based from on platform which is placed below the rock box to control drop height. The length was chosen to be 4 feet in order to give the rip rap length to move or be pushed down the direction of flow. For example, when overflow from the flume hits the rip rap bed, the rip rap placed in the rock box has a possibility of moving and we want to be able to watch this happen. One of our measurements will be displacement, so there must be enough room for this to occur without falling off of the rock box into the drainage basin.

Platform

The Rock Box is going to be set on top of a platform. The platform is going to be used to reduce the size of the Rock Box so that it is more maneuverable. Also the platform will be used to set the height of the experiment. The platform will be 4 feet wide, 2 feet high, and 4 feet long.

Experimental Design

TDLP Inc. has prepared a proposed experimental design plan for which to test the reactions and stability of all test materials. However, before any testing of materials begins, a calibration must be completed in order to obtain the correct size of orifice plate and pressure needed to provide a volumetric flow rate of 5 cfs.

It was decided to test all materials at this constant flow velocity. At first, a range of velocities were considered in order to test material reactions for a range of storm events. For example, larger storm events will deposit precipitation at a larger rate than smaller storm events, causing overtopping to flow at a greater velocity. The main goal of this design problem is to create a stable bed which will prevent scour for this entire range of storm events. When materials are tested at a maximum flow rate of 5 cfs, all designs at smaller rates will be accounted for.

After calibrations have been done to ensure constant velocity, testing of different materials may begin. After discussions with our sponsor, Dr. Hanson, TDLP Inc. has decided to focus testing on rip rap with different diameters. Along with running a separate test for each different diameter of rip rap, a range of bed depths will also be tested. For example, a rip rap bed with D_{50} (rip rap diameter) of 0.63" will be tested at a constant flow rate of 5 cfs, and at bed depths of 3", 6", and 12". The next D_{50} tested will have a different diameter but still tested at bed depths of 3", 6", and 12". For each bed depth and D_{50}, a range of drop heights will be evaluated. These drop heights will be chosen from calculations after final scaling is completed.

One of the main reactions under investigation is bed stability. In order to determine acceptable stability, a few variables will be taken into consideration: rip rap movement in the x, y, and z directions, scour depth, and percentage of rip rap displaced. Rip rap movement will be recorded quantitatively, through measurements before and after testing, and qualitatively, by taking a series of pictures that will then be recorded onto three dimensional graphs. These techniques will give TDLP Inc. a visual and analytical representation of rip rap movement and scour evolution. Once a bed is considered stable, meaning that the rip rap has stopped movement, scour and displacement will be evaluated for failure. Failure will be defined by penetration depth of scour and displacement of rip rap. For any diameter of rip rap, scour must not be allowed to penetrate to the bottom of the rock box. If this occurs, it can be concluded that soil underneath the bed will be disturbed in a real world situation. Failure will also be defined by percent of rip rap bed displaced down the direction of flow. An acceptable range of up to 50% material displaced will be monitored. Loss of more than 50% of the entire bed will be considered unacceptable. During actual testing, these numbers may change.

Costs

Our proposed expenditure list is shown in Table 1. The costs were based on purchasing materials for the following: flume design, experimental platform, and setup boxes for containment of materials. Flume design was based on critical depth calculations and the height of the existing metal frame in the Hydraulics Engineering Research Unit laboratory provided. Flume dimensions are 3-1/2' ft wide by 18' ft long. The 3-1/2' ft width was based on our critical depth scaling while the 18'ft was based on the metal frame length. A platform will be built to hold our setup boxes. The purpose of the setup boxes is to keep our rip rap catalog from becoming intermixed. Having boxes with our different setups already prepared will also allow the team to easily slide one box out of the way in order to run tests on a different size of rocks. The proposed budget is mainly based on items we will have to construct. An additional 20% is added to the budget for other items that might arise during the testing process. As for test materials, most of the rip rap sizes that we will test are available at the HERU. For any additional test sizes which we may need to order, the costs can be included in our 20% of additional costs. The grand projected total for materials to build the flume, platform, and three riprap boxes is estimated at approximately $677.26.

Table 1. Proposed Expenditure List for Flume.

Flume			
Materials	Unit	Cost/Piece	Cost
4'x8'x.75"	9	$21.44	$192.96
2"x4"x10'	15	$2.85	$42.75
2"x6"x8'	6	$3.84	$23.04
Wood Screws (1lb Box)	2	$6.97	$13.94
Water Sealer (gallon)	1	$20.00	$20.00
Silicon Caulk	5	$5.00	$25.00
Paint Roller Kit	1	$13.00	$13.00
		Total	$330.69

Table 2. Proposed Expenditure List for Platform.

Platform			
Materials	Unit	Cost/Piece	Cost
2"x4"x10'	3	$2.85	$8.55

4'x8'x.75"	1	$21.44	$21.44
		Total	$29.99

Table 3. Proposed Expenditure List for Riprap Boxes

3 Riprap Boxes			
Materials	Unit	Cost/Piece	Cost
Plexiglass	1	$173.71	$173.71
4'x8'x.75"	1	$21.44	$21.44
2"x4"x10'	3	$2.85	$8.55
		Total	$203.70
Additional Misc Costs			$112.88

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Appendix A

Gantt Chart

Appendix B

Design Drawings

Appendix C

Power Point Presentation Slides

TDLP INC
The Dam & Levee Professionals

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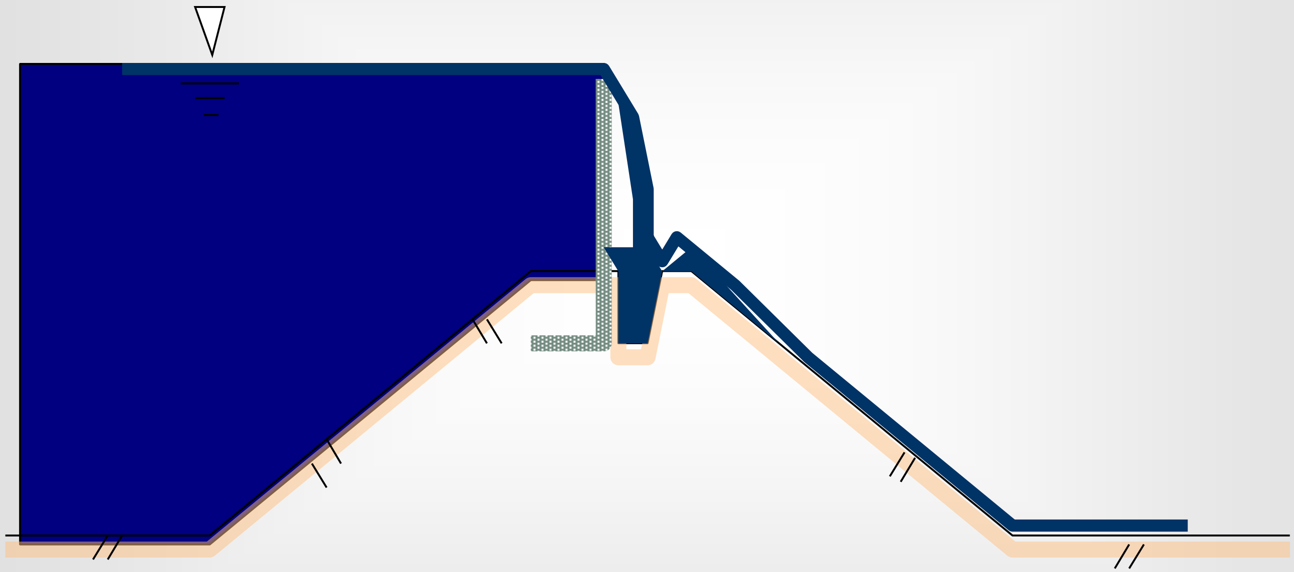
Prevention and Protection of Floodwall Overtopping Scour



Mission Statement

"TDLP Inc. will be the innovator of dam and levee erosion control designs that will meet and exceed our customers needs to provide them with the safety and security we all deserve. TDLP Inc. will go above and beyond industry standards to provide protection of property and quality of life by designing and maintaining top notch erosion protection structures at an affordable price."

Overview

- Introduction
- Problem Statement
- Patent, Literature, and Market Research
- Test Flume Design Aspects
- Experimental Design and Methods
- Equations
- Cost Analysis and Proposed Budget
- Timeline

Sponsor

- USDA-ARS HERU
  - Established in 1940
  - Located on 100 acres adjoining Lake Carl Blackwell
  - Innovator in vegetated channel design concepts

Background

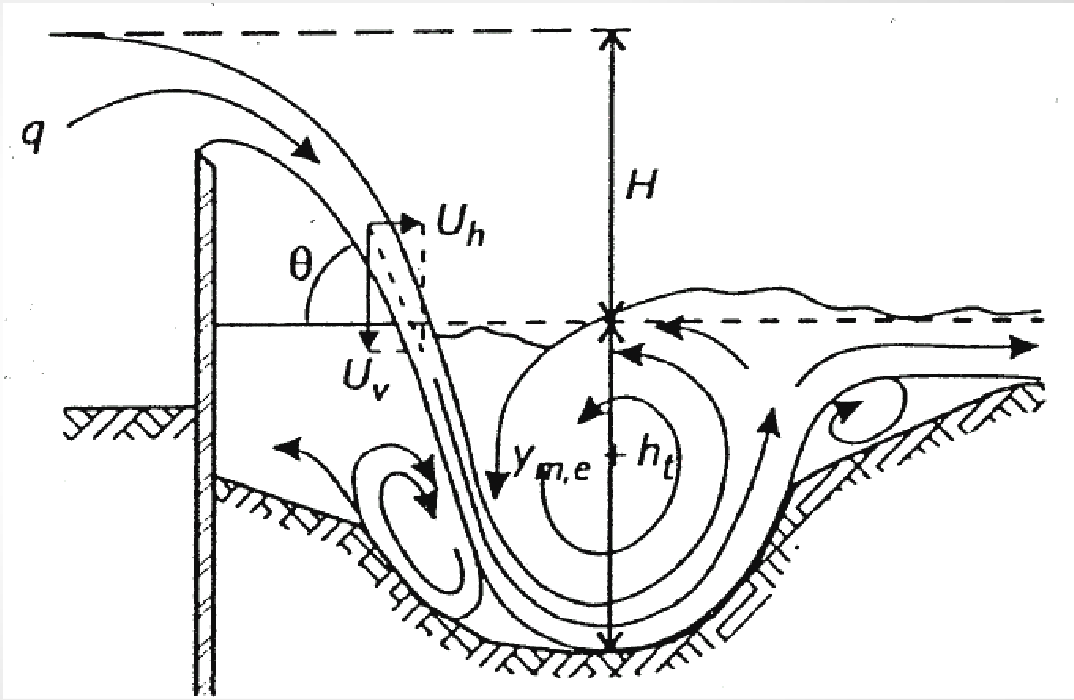
- Flood wall scour
  - The process of erosion caused by flood wall overtop.

Introduction

❖ Floodwall Scour can cause instability in the wall and cause failure.

Problem Statement

- What is the Problem?
  - Overtopping
  - Impinging Flow
  - Scour and Erosion
  - Destabilization
  - Lack of current design standards
- What can be done to prevent this?



Statement of Work

- Work to be Done
  - develop a generalized approach with consideration of an optimal ground application
  - decrease scour from water overtopping floodwalls
  - increase ground stability
  - protect the integrity of existing floodwalls
  - remain within economic constraints

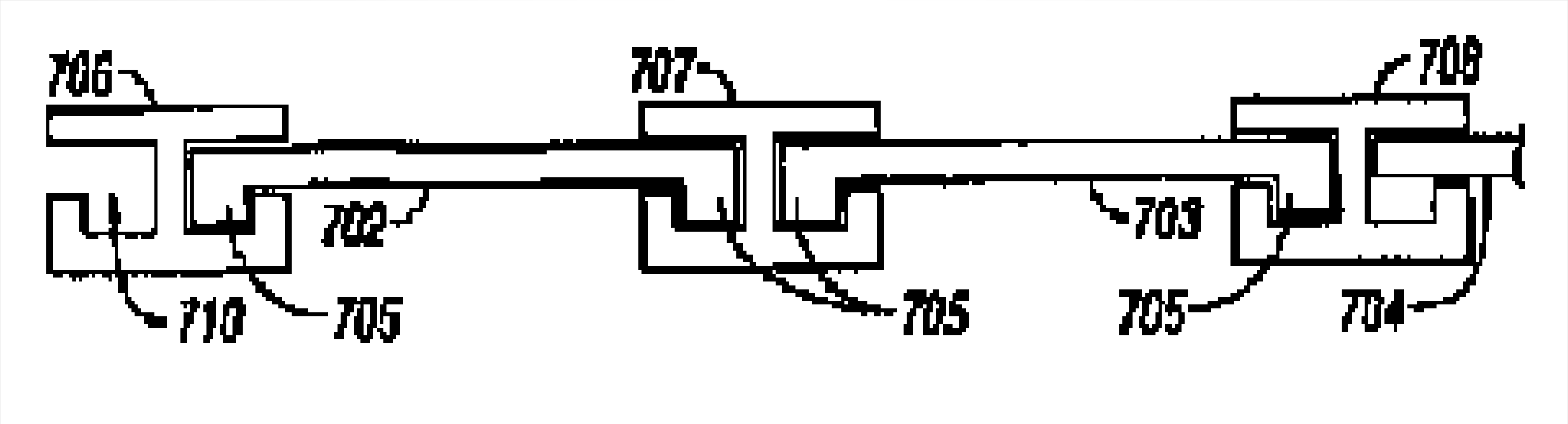
Statement of Work (cont.)

In order to accomplish all of the tasks….

- investigate the specific issues
- generate design concepts
- build a floodwall prototype
- determine experimental procedures
- model these concepts
- present findings for evaluation

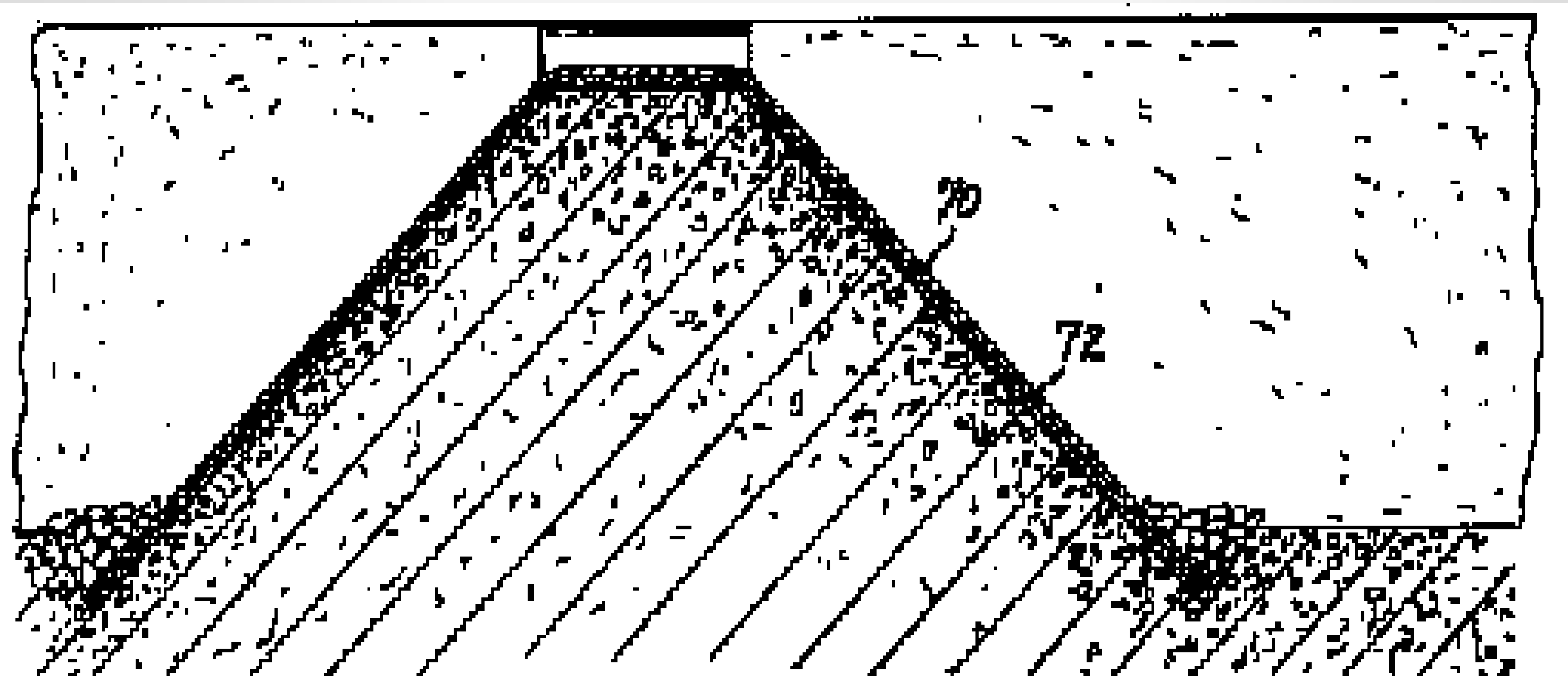
Patent Research

- ❖ **US6851889- Reinforced interlocking retention panels**
  - ❖ Prevent or eliminate scour beneath marine structures
  - ❖ Panels interlock and can be cut to size
  - ❖ Not applicable because of cost and installation time



Patent Research

- **US4184786- Earth dam protective coverings**
  - Requires the whole side to be covered



Market Research

- **Armorflex® by Armortec™**
  - Flexible interlocking concrete blocks connected by cables.
  - Product encourages habitat development and vegetation also aesthetically pleasing
  - More expensive than riprap
  - Installation cost are higher

Market Research

- **A-Jacks® by Armortec ™**
  - Heavy duty popular reducing bridge and stream bank scour
  - Designed to interlock and form a wall that is ridge but highly permeable
  - Voids allow for marine habitat can be back filled to allow vegetation growth
  - Expensive and tedious to install

Market Research

- **LandLok® Supergro® Erosion Control Blankets**
  - Very affective on steep slopes
  - Quick fix and easy to install
  - Not along term solution
  - Quickly degrade

Market Research

- **Kiciman Gabion Baskets, Mattresses, Sacks, Netting, and Razor Barbed Tape**
  - Several sizes available to meet customer needs
  - Flexible, strong, and durable
  - Management prospective easy to maintain
  - Wires can become blocked
  - More expensive than rip rap

Test Flume Design Aspects

- Existing Structures
  - Laboratory
  - Basin
  - Framing
  - Storage Tank
  - Manometer/Orifice Plates
  - Water Source/Piping
- Three Main Components
  - Flume
  - Platform
  - Rock Box

Test Flume Design Aspects

Laboratory

Flume Design Aspects

Basin

Flume Design Aspects

Water Source/Piping

Flume Design Aspects

Manometer / Orifice Plates

Flume Design Aspects

Storage Tank

Flume Design Aspects

Framing

Experimental Design

- First Step : Calibration
  - Determination of correct orifice plates
  - Verification of flow rates

Experimental Design (cont.)

- Second Step : Testing of Materials

- Constants
  - Design Flow
  - Flume Width
  - Critical Depth

- Variables
  - Rip Rap Type
  - Rip Rap Diameter
  - Rip Rap Bed Depth
  - Drop Height

Response Variable

- Bed Stabilization

- Dependent Upon:
  - Rip Rap Movement
  - Scour Depth
  - Percentage of Rip Rap Displaced

Initial Scaling Calculations

- Critical Depth

$$d_c = \left[\frac{\left(\dfrac{5cfs}{3.5\,ft} \right)^2}{32.2\, {ft}/{s^2}} \right]^{1/3} = 0.39\,ft = 4.68in$$

Initial Scaling Calculations

- Riprap Size

$$D_{50}/d_c = \left[(0.161 - 0.13) \times e^{\frac{0.051 - 0.39^2}{0.465^3}} \right] + 0.13 = 0.0114\,ft = .136in$$

$$D_{50} = 0.136 \times 0.39 = 0.053\,ft = 0.63in$$

- Length of Riprap Bed

$$L_s = 5 \times 0.39 = 1.95\,ft$$

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Supply List

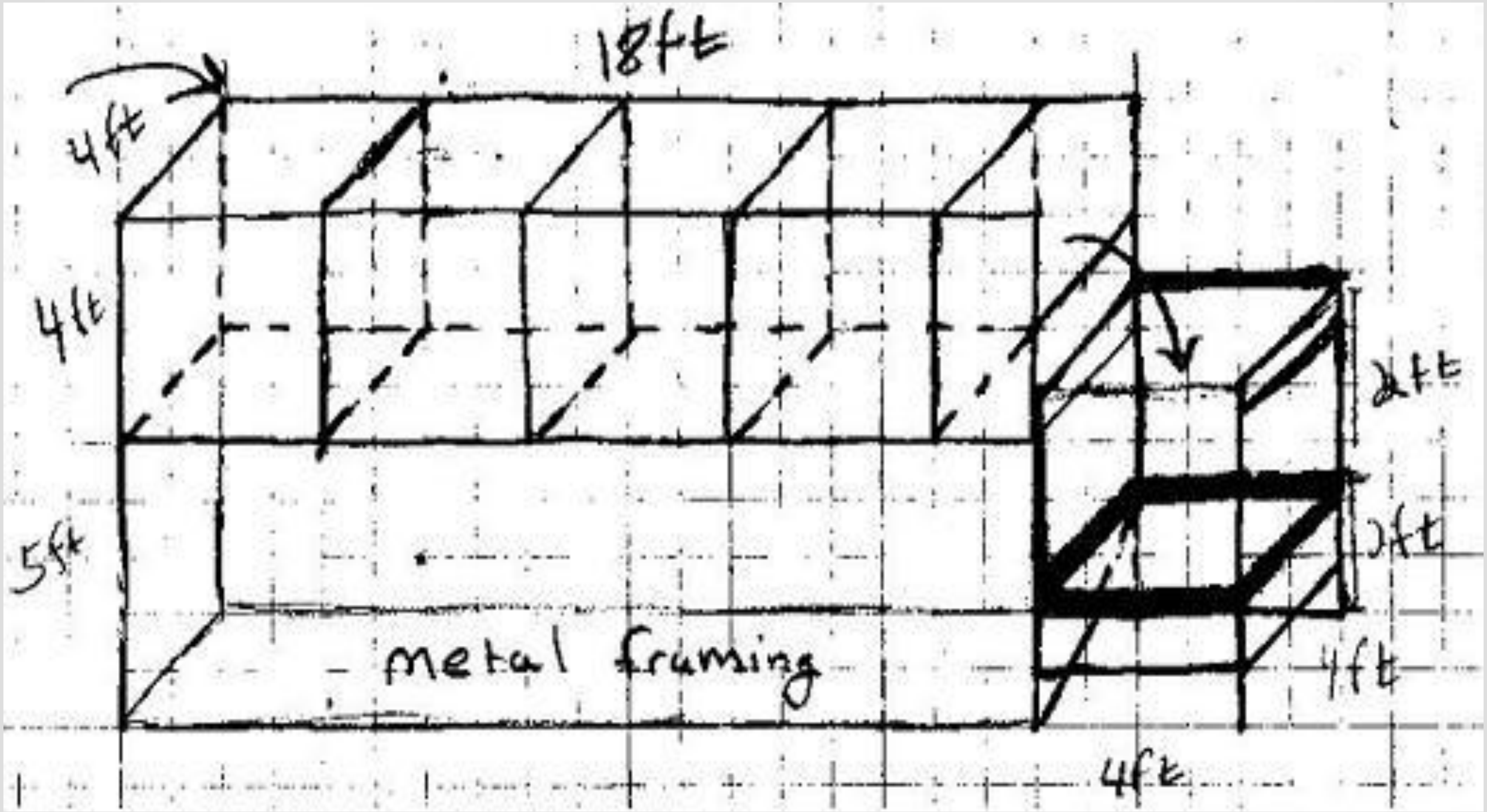
Materials

- 4’x8’x0.75”
- 2”x4”x10’
- 2”x6”x8’
- Wood Screws
- Water Sealer
- Silicone Caulk
- Plexiglass

Tools

- Drill
- Circular Saw
- Paint Roller/Pan
- Tape Measure
- Drill Bits

Assembly Sketch



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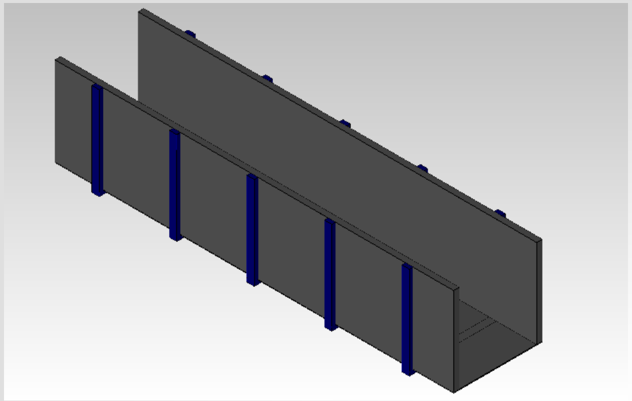
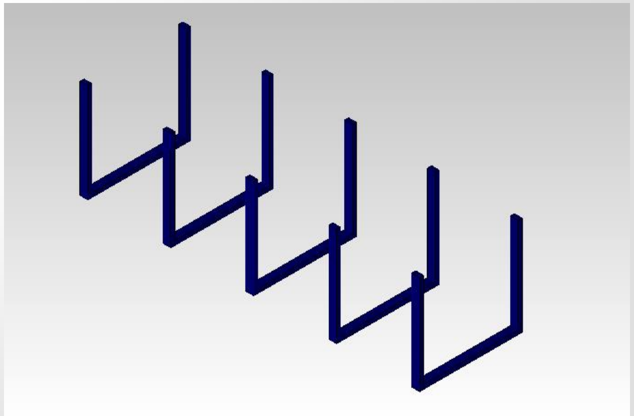


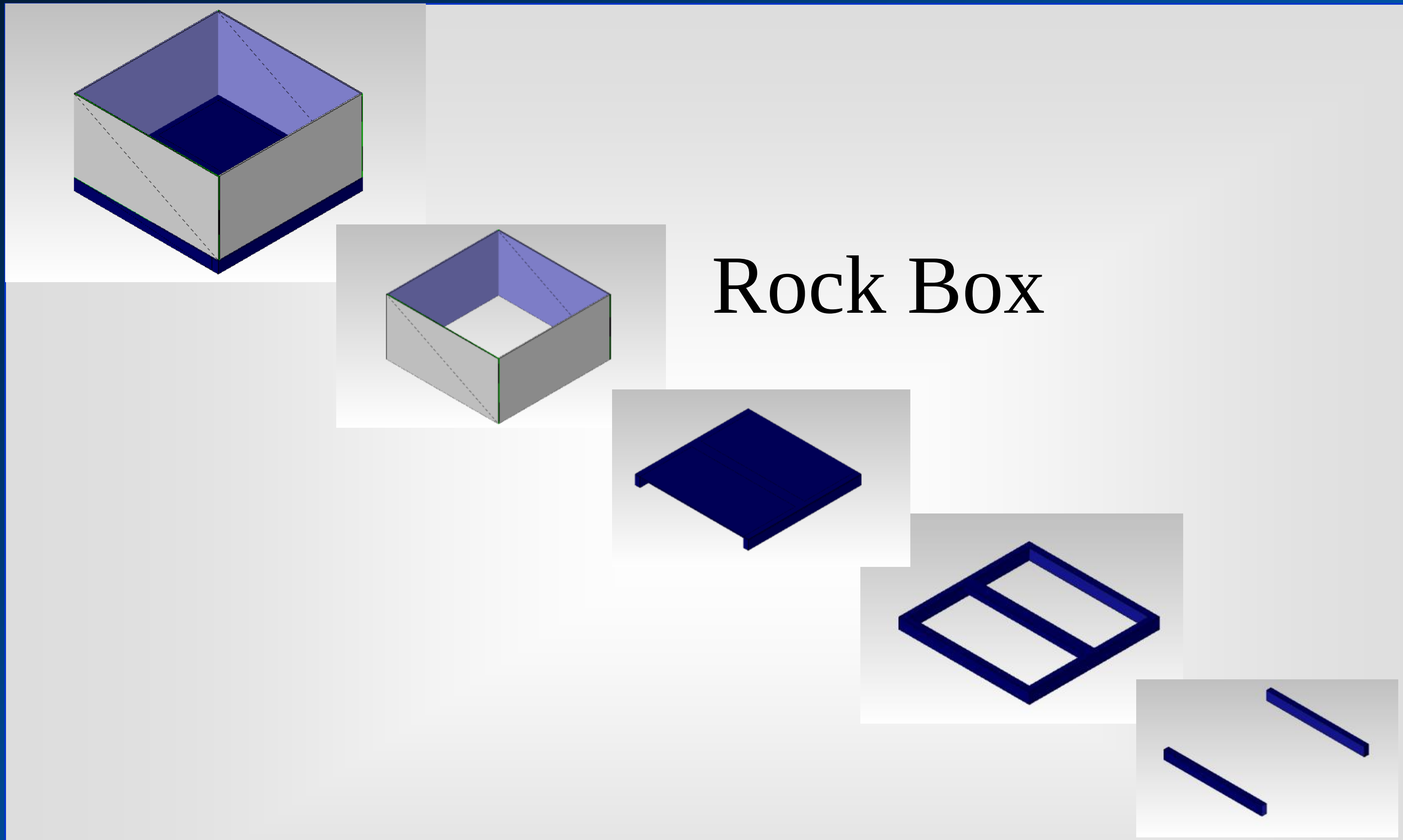
Flume



Flume Materials

Materials	Unit	Cost/Piece	Cost
4'x8'x.75"	9	$21.44	$192.96
2"x4"x10'	15	$2.85	$42.75
2"x6"x8'	6	$3.84	$23.04
Wood Screws (1lb Box)	2	$6.97	$13.94
Water Sealer (gallon)	1	$20.00	$20.00
Silicone Caulk	5	$5.00	$25.00
Paint Roller Kit	1	$13.00	$13.00
		Total	$330.69

Rock Box



Rock Box (3) Materials

Materials	Unit	Cost/Piece	Cost
Plexiglass	1	$173.71	$173.71
4'x8'x.75"	1	$21.44	$21.44
2"x4"x10'	3	$2.85	$8.55
		Total	$203.70

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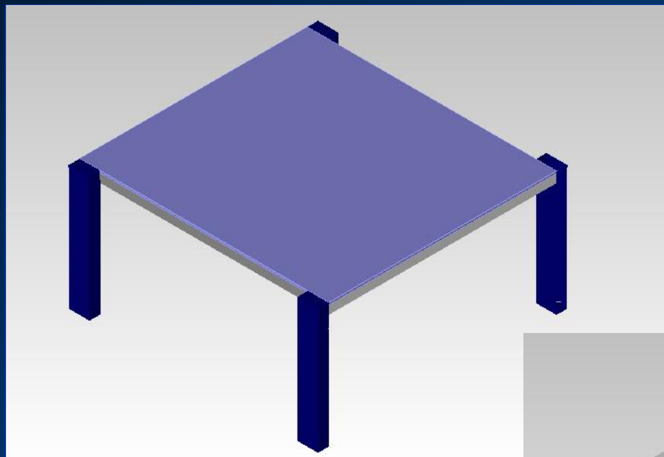
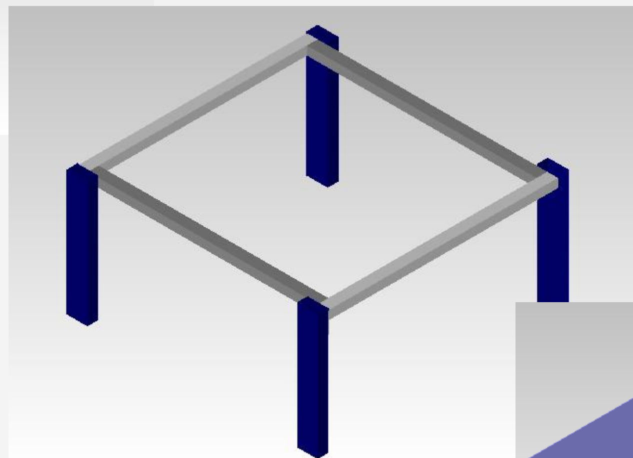
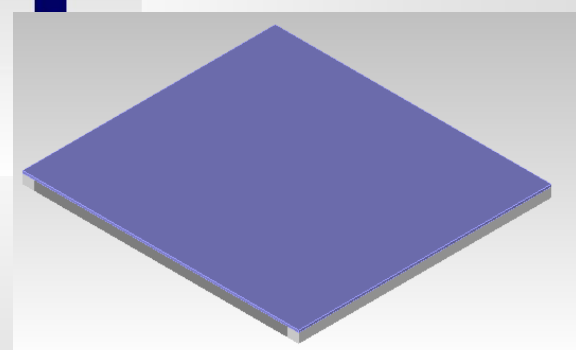


Platform





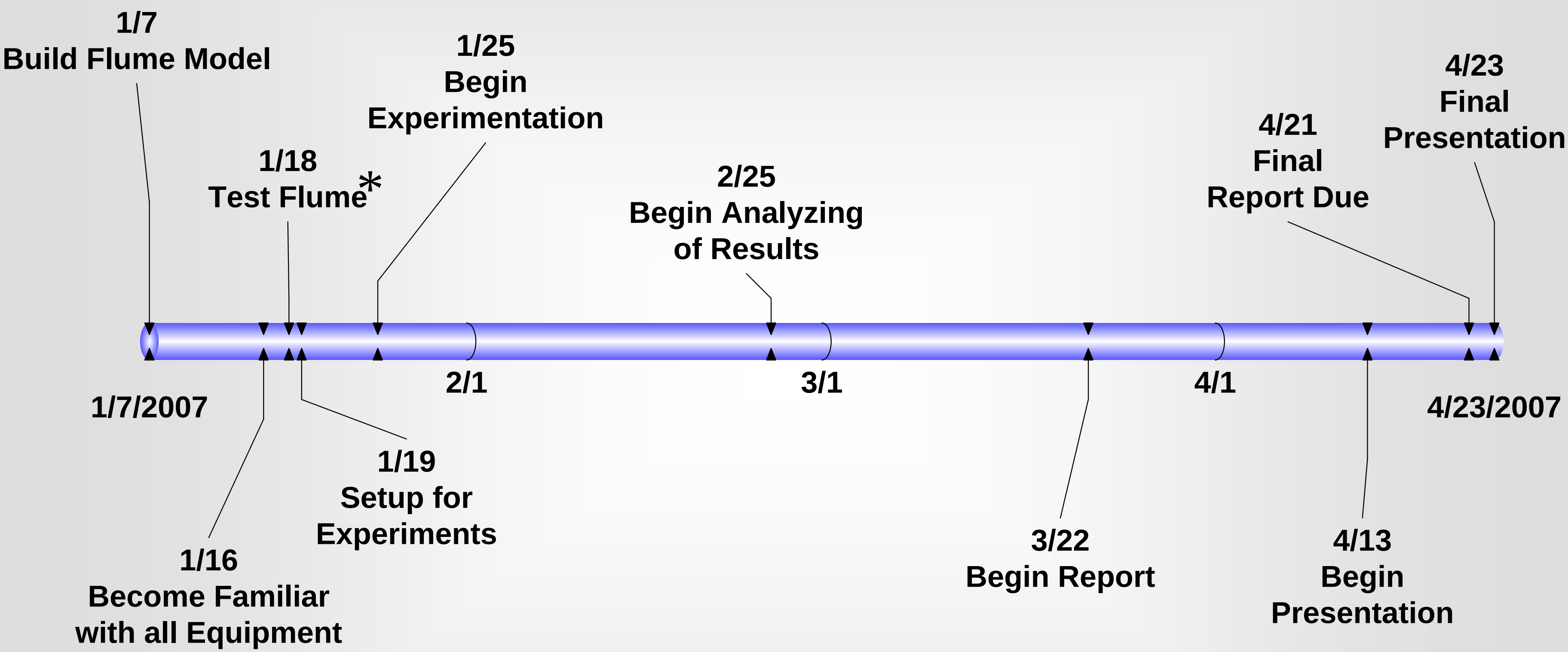
Platform Materials

Materials	Unit	Cost/Piece	Cost
2"x4"x10'	3	$2.85	$8.55
4'x8'x.75"	1	$21.44	$21.44
		Total	$29.99

Approximate Cost

- Total: $564.38
- We added an additional 20% for misc. materials
- New Grand Total: $677.26

Timeline



*** Weather permitting**

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Questions
are
guaranteed in
life;
Answers
aren't.

Acknowledgements

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