Suspension Canyon and Gully Crossings for Small Scale Community Aqueducts:

A Design Guide Based on Experience and Observations From Peace Corps, Dominican Republic

By

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Table of Contents

1 Introduction and Objective 11
1.1 Summary of the Process and Procedure 12
1.2 Disaster Prevention and Mitigation 12
1.3 Economics 13
1.4 Development and Over-all Design Issues 13
1.5 Prerequisites 15
2 The Anatomy of a Suspension Bridge 16
2.1 Basic Concepts and Vocabulary 16
2.1.1 Distribution of Forces 17
2.1.2 Galileo, The Chain Curve, and Suspension Bridges 21
3 Planning: Initial Survey and Design Considerations 24
3.1 Materials 24
3.1.1 Cable and Pipe 24
3.2 Quality of Craftsmanship and Materials 27
3.3 Finding a suitable site 28
3.3.1 Bank stability 29
3.3.2 Quick length check: The string method 31
3.4 Choosing a pipe and cable size for the rough design 31
3.5 Survey 33
3.5.1 String line layout 33
3.5.2 Rod survey 33
4 Design 36
4.1 Cable and pipe path 37
4.1.1 Finding 'C' and the shape of the cable curve 39
4.1.2 Force on Cable and Anchors and Design Optimization 42
4.2 Anchors and Columns 46
4.2.1 Single Post 46
4.2.2 Column and Anchor 49
4.2.3 Integrated Column and Anchor 62
5 Field Layout and Construction 67
5.1 String line, Right Angles 67
5.2 Building of the Anchors: Tips and Tricks 67
5.2.1 Single Post 68
5.2.2 Column and Anchor 69
5.2.3 Integrated Column and Anchor 72
5.3 Preparing the Ground 73
5.4 Final Cable Adjustment 74
5.4.1 Calculating Stringer Length 74
5.4.2 Calculating the Final Cable Length 76
5.5 Attaching the Cable and Pipes 79
5.6 Finishing Touches 82
6 Design Examples 84
6.1 Flat 140+' Canyon Crossing (Peligro) 84

6.1.1 Planning 84
6.1.2 Design 85
6.1.3 Final Cable Adjustment 86
6.2 85’ Road Cut Crossing with Uneven Anchors (Hypothetical) 88
6.2.1 Planning and Survey 88
6.2.2 Design 89

List of Tables

Table 3-1: Example of Blank Survey Book for Rod Survey 34
Table 3-2 Example of survey book after field measurements are taken. 34
Table 3-3: Completed Survey Book showing how final distances are calculated. 35
Table 6-1: Survey of Crossing Site 88
Table 6-2: Elevations and locations of pipe and cable 89

List of Figures

Figure 1-1 Simply Supported Crossing good for crossings of 20 feet or less. 14
Figure 1-2 Double Cantilever Crossing, good for crossings between 20 and 30 feet. 14
Figure 1-3 A double cantilever crossing over a rockslide. (Photo provided by Kristina Katich).. 14
Figure 1-4 Double Cantilever with Supported pipe, good for crossings between 30 and 45 feet.. 14
Figure 2-1 Parts and Dimensions of a Suspension Pipe Crossing. 17
Figure 2-2 A Crossing with Uneven Anchor Points. 17
Figure 2-3 Road deck applying load to main cable through stringer............................... 18
Figure 2-4 Evenly distributed load across main cable. 18
Figure 2-5 Forces applied to section of main cable. 19
Figure 2-6 Forces on a section of main cable with an increased sag. 19
Figure 2-7 Forces on a section of main cable with a decreased sag. 20
Figure 2-8 Forces applied to a column anchor point. 20
Figure 2-9 Forces on column with anchor cable... 21
Figure 2-10 Forces on main cable with uneven anchor points. 21
Figure 3-1 7X7 Cable Cross-Section (obtained from Loos & Co., Pomfret, Connecticut) 25
Figure 3-2 7X19 Cable Cross-Section (obtained from Loos & Co., Pomfret, Connecticut) 25
Figure 3-3: Cable Clamp (obtained from Crosby Group, Buffalo, New York)............... 25
Figure 3-4 The wrong way to unroll a cable. (photo provided by Kristina Katich) 26
Figure 3-5 Christina Osborn measures the salvageable section of a tree-damaged column. (photo by Kristina Katich) 29
Figure 3-6 Topographic map of hypothetical canyon showing proposed crossing sites. . 30
Figure 3-7 Anchor placed on slope with extra excavation for added stability. 31
Figure 4-1 Elevation layout with pipe entering ground at same elevation as trench. 37
Figure 4-2 Elevation layout with pipe entering ground at trench elevation but using two GI elbows to lower pipe for the center of the crossing. 37
Figure 4-3 Elevation layout with pipe entering ground at trench elevation but using two GI 45 elbows to lower pipe for the center of the crossing. 38
Figure 4-4 Elevation layout with pipe entering below the trench elevation and using two buried plastic elbows to raise pipe to normal trench level. 38
Figure 4-5 Plan view of crossing with pipe entering the ground at an out of plane angle 38
Figure 4-6 Dimensions used in uneven anchor analysis. 41
Figure 4-7 Elevation of Single Post Anchor 47
Figure 4-8 Detail of Cable Connection for Single Post Anchor (adapted from Jordan)... 47
Figure 4-9 Elevation of anchor and column 50
Figure 4-10 Two options for attaching cable to the top of a steel column. 51
Figure 4-11: Plan view of column with two anchors at 120° angles 55
Figure 4-12 A square concrete column and anchor with cable attached. (photo provided by Eric Zalkin) 56
Figure 4-13 Cross section of standard masonry column showing the effective width. 57

Figure 4-14 Column and anchor set up where the effective length of the column will be twice the column height due to lack of side bracing. ... 58
Figure 4-15 Column and anchor set up with two guy cables, which will reduce the effective height to 0.7 of the column height. ... 58
Figure 4-16 Column and anchor set up with split anchors at 120° the column is braced and will have an effective height of 0.7 of the column height ... 59
Figure 4-17 Simple block anchor mass with dimensions used in design equations. ... 63
Figure 4-18 Tower and slab type anchor mass with dimensions used in design equations. ... 63
Figure 4-19: A tower and slab type anchor mass constructed of native limestone rubble and covered with a coat of cement plaster. ... 64
Figure 5-1: Rebar detail of single column block mass ... 68
Figure 5-2 Rebar detail for anchor mass. ... 69
Figure 5-3 Rebar bender constructed from angle iron and evenly spaced pegs. ... 70
Figure 5-4 Technique for bending square stirrups. ... 71
Figure 5-5: Workers fill excavation with concrete while the column is checked for plumb (photo by Kristina Katich). ... 72
Figure 5-6 Typical rebar layout for anchor and column unit built with stone masonry. ... 73
Figure 5-7 Exploded view of typical stringer and photo of actual stringer in place. ... 74
Figure 5-8: Correct Placement of Cable Clamps (Wire Rope Technical Board) ... 80
Figure 5-9 Two Dominican construction technicians attach a galvanized pipe to the main cable. (photo by Eric Zalkin) ... 81
Figure 5-10 Pipes are connected while a crew waits to push out the next length. (photo by Eric Zalkin) ... 82
Figure 6-1 Cross section of proposed bridge alignment. ... 88
Figure 6-2 Quick graph of cable and pipe path in relation to ground surface. ... 90

List of Equations

Equation 2-1 Galileo's Estimate for the Chain Curve. 22
Equation 2-2 Catenary Curve Equation. 22
Equation 2-3 Hyperbolic Cosine Function. 22
Equation 2-4 Arc length of a catenary curve. 22
Equation 2-5 Hyperbolic Sine Function. 22
Equation 3-1 Jordan (1980) Estimate for Horizontal Cable Tension. 32
Equation 3-2 Jordan (1980) Estimate for the Angle of Force at the Fixture Point. 32
Equation 3-3 Jordan (1980) Estimate for Total Tension 32
Equation 4-1 Catenary Equation 39
Equation 4-2 Parabolic equation 39
Equation 4-2 Uneven Fixture Point Equation 1 of 3 40
Equation 4-3 Uneven Fixture Point Equation 2 of 3 40
Equation 4-4 Uneven Fixture Point Equation 3 of 3 40
Equation 4-5: Final Uneven Fixture Point Equation 41
Equation 4-6: Angle of cable at a given distance from the apex 42
Equation 4-7 Allowable Axial force on non-slender reinforced masonry column 59
Equation 4-8 Allowable Axial force on slender reinforced masonry column 59
Equation 4-9 Allowable bending moment on reinforced masonry column 59
Equation 4-10 Combined Bending and Axial equation for combined bending and axial loads on a column. 60
Equation 4-11: Combined Bending and Axial equation for steel pipe column 61
Equation 5-1 Proportional Change in Length for Steel Cable (Wire Rope Technical Board) 77
Equation 5-2 The Starting Length in relation to the Final Length 77

List of Examples

Example 4-1: Calculating the 'C' Constant using Design Charts.................................... 39
Example 4-2: Calculating the 'C' Constant for an Uneven Anchor set up using Design Table 41
Example 4-3: Calculating the Forces Applied to an Anchor, Cable Sizing, and Design Optimization 43
Example 4-4: Design of a Single Post Anchor 48
Example 4-5: Design of a separate column and anchor.. 51
Example 4-6: Design of anchor in anchor and column layout.. 53
Example 4-7: Design of masonry columns... 60
Example 4-8: Design of steel pipe columns 61
Example 4-9: Design of mass block anchor 64
Example 5-1: Calculating the Length of the Stringers.. 75
Example 5-2: Calculating the Untensioned Length of the Main Cable 77
Example 5-3: Calculating the Unloaded Sag.. 79

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1 Introduction and Objective

Lack of clean consistent drinking water is an issue that affects over a billion people worldwide (World Health Organization, 2002). A cost effective method of bringing potable water to mountainous rural areas are small-scale community built and maintained aqueducts. These systems are efficient, relatively inexpensive, and easy to maintain and operate. Projects such as these have been met with considerable success in Nepal, (Jordan, 1980), Honduras (Simpson, 2003; Reents, 2003) and in the Dominican Republic (Niskanen, 2003).

The mountainous terrain that makes these aqueducts possible can also make them difficult to construct. Often pipeline must pass through or around large canyons and across permanent or seasonal rivers and streams. When such an area is encountered a suspension crossing can be a durable, technologically appropriate, and economical solution.

There are many resources on the subject of bridges and even suspension bridges in particular. But, these are more often than not written for a more technical audience in mind. And, even if the engineer has the background to follow the text, the methods can be excessively detailed and complicated for a field-engineering situation pertaining specifically to aqueduct crossings. Jordan (1980) covers a simplified method for designing suspended crossings in an appendix but does not go in to detail or address certain issues that are common during construction.

For example, Jordan simplifies the curve of the cable to a strait line when calculating cable forces and does not provide the reader with an explanation. He only presents the single pipe type of anchor system and doesn’t provide enough information to accurately design it. Additionally, the table used to design this anchor neglects a bending moment causing the design to be either extremely conservative or dangerously under-sized. The topics of cable stretch, material selection, and construction relating specifically to cable crossings are also not covered.

Accordingly, the objective of this report is to provide the reader with the method and resources to quickly and efficiently design a suspension crossing for small-scale rural aqueducts. The intended audience is someone without an engineering background, but with sufficient technical competence to design and construct a gravity-fed aqueduct. This report takes much of the complex analysis required for the design of a cable structure and simplifies it to a step-by-step process that can be followed using basic arithmetic and very simple algebra.

This report explains how forces are calculated in the cable and provides a more accurate method for determining the curve of the cable. Three distinct anchor designs are presented and instructions are provided to efficiently design each one. The topic of cable stretch is discussed as is material selection. Also, a method is presented for designing a crossing where one cable fixture point is lower than the other.

It is also an attempt to record the institutional knowledge accumulated through trial and error from Peace Corps Dominican Republic and from various aqueduct projects completed by the NGO Hermandad and designed by its lead engineer and CEO Eric Zalkin. The reader should be aware that this research report is written as a practical design guide; thus, the report highlights practical knowledge the author gained during his two years of service in the Dominican Republic as a water and sanitation engineer with the U.S. Peace Corps.

1.1 Summary of the Process and Procedure

1. Find a good location and perform rough calculations to check the feasibility of the crossing for preliminary design (Discussed in sections 3.3 and 3.4). This report covers slope stability and how to assess the quality of available materials.

2. Survey the location (Discussed in section 3.5). This report provides a method of surveying that uses techniques and equipment commonly used in the survey of gravity flow aqueducts but is better suited for deep canyon profiles.

3. Design anchor structures (Discussed in sections 4.2 – 4.2.3). Three different types of anchoring methods are outlined with step-by-step instructions for design.

4. Construct anchors (Discussed in section 5.2 – 5.2.3). Techniques specific to anchor construction and construction details are outlined to assure that the structure is built to be as strong as it was designed.

5. Perform final design of cable (Discussed in sections 5.4 – 5.4.2). The method for finalizing the length and the position of the cable is outlined. This provides the basis for reducing the stress on the pipes of the crossing.

6. Attach cable and tubes (Discussed in section 5.5). A method is given for easily attaching the cables and extending the pipes across the span.

1.2 Disaster Prevention and Mitigation

In the El Cercado municipality of San Juan de la Maguana, Dominican Republic, the vast majority of major problems in rural aqueducts stem from heavy seasonal rains or tropical storms and hurricanes. These heavy rains, in combination with deforestation, cause huge flash floods that can raise river and stream levels over ten feet in a matter of a few hours. The force of the water and debris is easily capable of destroying any pipeline in its path. Floods in this area have bent three inch galvanized steel pipes into complete horseshoe shapes. Communities have been left without water for months or even over a year while repairs are made.

Many of these damages could have been prevented if the pipeline had been lifted higher out of the canyons and gullies.

1.3 Economics

It may seem that building a large bridge over a canyon will cost a lot of money. It's true that the steel pipes, cable, and concrete can be expensive. But, when considering the cost of moving the pipeline to a narrower area or sending the pipes down through the canyon, the cost is often quite comparable. This is to say nothing of the lifetime cost of continually replacing washed out pipes.

1.4 Development and Over-All Design Issues

Often these projects are built in a community development situation where the local community will take control of the maintenance and operation of the system once the engineer is gone. A good community development project based on the Peace Corps model of development takes local knowledge and resources and uses those assets to find a sustainable solution.

Suspension crossings fit into this model. Almost all construction techniques outlined in this manual are things that a local skilled laborer would know. Most likely the people working on the system will not be able to design and build a crossing without the help of a skilled engineer, but this is also the case with gravity fed aqueducts in general. All the techniques learned while building the crossing will allow for any maintenance that may be needed in the future.

Large suspended crossings are also impressive to people who may have never seen large structures before. Knowing that they had a big part in the construction of the crossing can be a source of community pride and unity.

Although it is certain that there is an upper limit on the length of a crossing, it is not certain where it is. Pipe bridges have surpassed over 650' in length. One of the practical limiting factors is that a standard roll of cable is only 1,000 feet long.

There is a lower limit to practicality. Smaller crossings can be achieved by cantilevering galvanized iron pipes. The arrangement will depend on the stiffness of the pipes and the length. As shown in Figure 1-1 and 1-2, anything shorter than twenty feet long can be easily spanned with one galvanized steel pipe and for a bit more length a double cantilever setup can be used. By placing large masses over the ends of the pipes at the banks, the stress is reduced on the couplings.

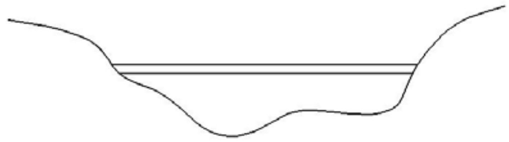

Figure 1-1 Simply Supported Crossing good for crossings of 20 feet or less.

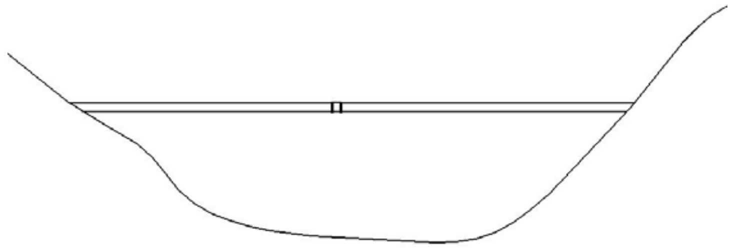

Figure 1-2 Double Cantilever Crossing, good for crossings between 20 and 30 feet.

Figure 1-3 A double cantilever crossing over a rockslide. (Photo provided by Kristina Katich)

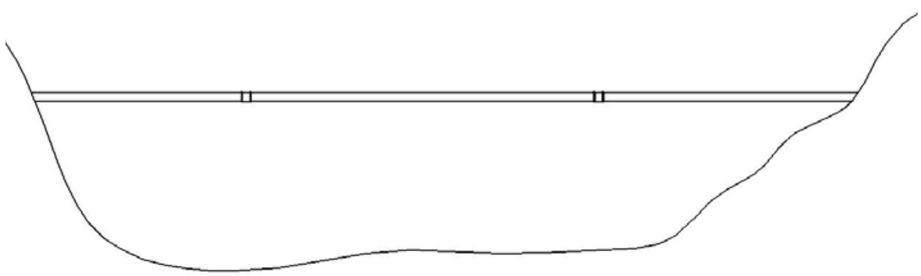

Figure 1-4 Double Cantilever with Supported pipe, good for crossings between 30 and 45 feet.

In the Dominican Republic there is at least one crossing constructed in the double cantilever with supported pipe method illustrated in Figure 1-3. It served the community of Sabana de Lino and was in good condition after many years of service. It was constructed of four inch galvanized steel pipe.

1.5 Prerequisites

To follow the method laid out in this design and construction guide it is expected that the engineer can: solve basic algebraic equations, use trigonometry (sine, cosine, tangent), understand basic statics, create and understand scale drawings, perform an accurate survey to find horizontal distances and elevations, and supervise or perform the basic construction techniques needed to build a crossing. And of course a good deal of common sense is expected. Under no circumstance is this design guide to take the place of common sense. No guide can cover every situation encountered; this is where the common sense of the engineer comes into play.

It is assumed that the designer will also be the one overseeing construction. This supervision is vital. Many dimensions will need to be checked and recalculated as the construction progresses. Additionally, one of the great advantages of being both designer and builder is the ability to take advantage of site conditions as they are uncovered or quickly change the design if a good opportunity arises.

Some recommended design tools include: a graphing calculator that can numerically solve equations (This is ideal, although a scientific calculator with hyperbolic trig functions will also work, the TI-30 SOLAR is a wonderful, durable, inexpensive calculator. It works off kerosene lamplight, but not florescent.), and graph paper.

2 The Anatomy of a Suspension Bridge

The designs represented in this guide are suspension bridges. Suspension bridges have a road deck, or in this case a pipe line, supported below a cable, or cables, running the length of the span. The Golden Gate Bridge in San Francisco, California, is an example of a suspension bridge. These are not to be confused with suspended bridges. Suspended bridges have a road deck attached directly to the cables. The bridge at the end of *Indiana Jones and the Temple of Doom* is an interesting example of a suspended bridge. The advantage of a suspension bridge over a suspended bridge for aqueducts is that with a suspension bridge the pipeline does not have to follow the curve of the cable. Which in turn allows for more durable, but less flexible, galvanized iron pipes to be used instead of PVC (polyvinyl chloride) or HDP (high density plastic).

2.1 Basic Concepts and Vocabulary

Some of the terms and definitions used in this report are not the same as terms and definitions used in traditional suspension bridge design that would be employed in the developed world. The terms and definitions used apply to the simplified design process developed for this report that is applicable for aqueduct suspension crossings designed and constructed in the developing world. Also, all terms throughout the report are used as they are defined in the following section.

A standard suspension crossing consists of a main cable hung between two sets of towers and anchors. The point where the cable first touches the tower (and is no longer hanging freely) is known as the fixture point. As shown in Figure 2-1, the pipeline runs directly below the main cable and is attached to it by a series of stringers of varying length. The horizontal distance between the fixture points is referred to as the span of the crossing. The lowest point of the cables arc is referred to as the apex. The sag is defined as the vertical distance between the highest points of the cables arc (at the fixture points) and the lowest point (the apex). The dimensions of the cable are measured from fixture point to fixture point regardless of where the actual pipeline enters the ground or it's distance below the cable.

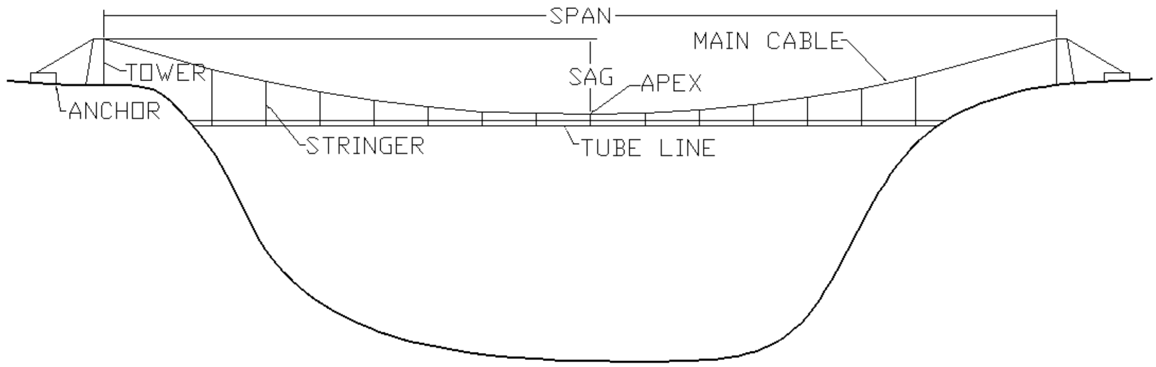

Figure 2-1 Parts and Dimensions of a Suspension Pipe Crossing.

When a crossing has one cable fixture point lower than the other, as illustrated in Figure 2-2, an additional dimension is introduced. This is the drop, which is defined as the vertical distance between one fixture point and the other. In this design guide, the sag of an uneven crossing is always measured from the higher of the two fixture points. Once again, these dimensions are measured regardless of what path the pipeline takes.

This guide will also make mention of a sag ratio and a drop ratio. These are defined as the sag and the drop divided by the span respectively. In a crossing where both fixture points are at the same height, the drop, and the drop ratio, is considered zero.

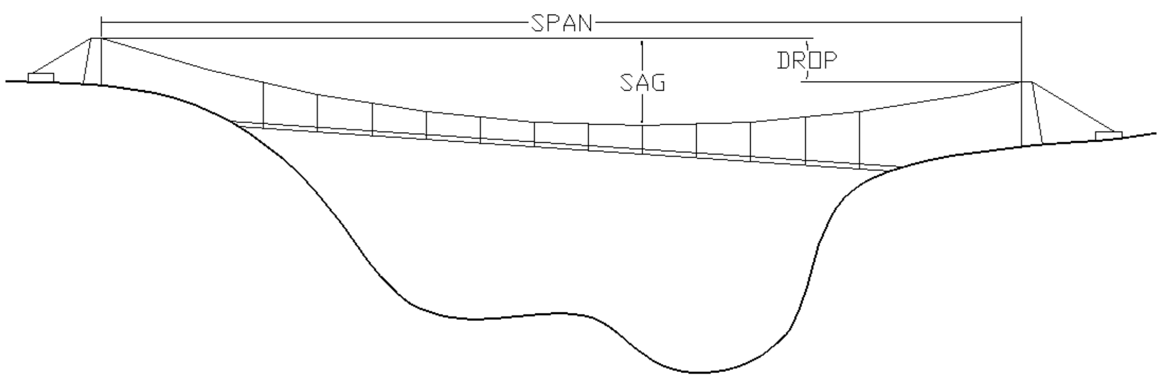

Figure 2-2 A Crossing with Uneven Anchor Points.

2.1.1 Distribution of Forces

The flow of forces start with the road deck, or in our case the pipeline. The weight of a pipe, or section of pipe, is carried by a deck cable or stringer. The stringer transfers the load to the main cable. The force is carried through the main cable to the towers and from the towers to the ground.

Let us start with the pipe. The pipe is sufficiently ridged and durable to support itself between the stringers. The stringers support the weight of a section of the road deck. See Figure 2-3.

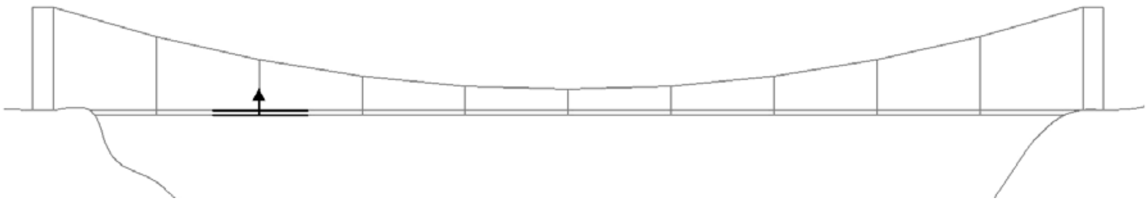

Figure 2-3 Road deck applying load to main cable through stringer.

The stringers in turn transfer the force to the main cable. The main cable carries the weight of itself, the pipe, the water in the pipe and the stringers. It will be assumed that this weight is evenly distributed along the length of the main cable as shown in Figure 2-4.

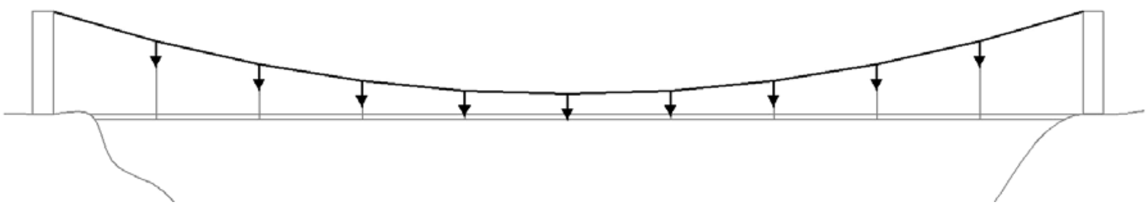

Figure 2-4 Evenly distributed load across main cable.

When the cable is placed under a distributed load it will form a smooth arc. The shape of the arc will depend on how the load is distributed and will be discussed in the following section in more detail.

Cables are only capable of carrying a tension force along the axis of the cable. This shows that a cable carrying an evenly distributed load will have a vertical and horizontal component where it is attached at an angle and a purely horizontal component at the apex where the angle is zero. A force diagram of a section of cable is shown in Figure 2-5.

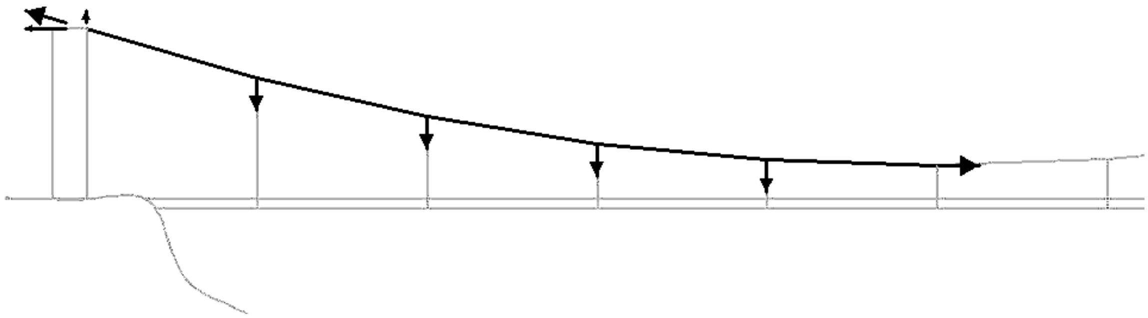

Figure 2-5 Forces applied to section of main cable.

The vertical component is equal to the entire weight of the cable and whatever pipe it carries. The horizontal component is determined by the angle at the end of the cable. Both of these forces combine to produce the full force in the cable at that point. The horizontal force at the apex will be equal to the horizontal component at the end.

If the sag is increased without increasing the span (increasing the sag ratio), the angle at the end will increase without increasing the weight. This will reduce the horizontal component and, therefore, the overall tension in the cable. This case is shown in Figure 2-6.

Conversely, if the sag ratio is decreased the angle will decrease increasing the horizontal component and the overall tension in the cable. This case is shown in Figure 2-7.

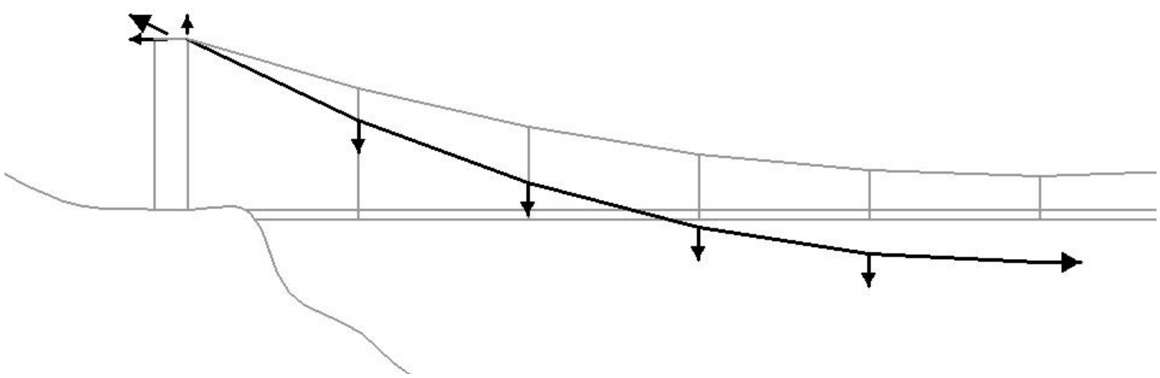

Figure 2-6 Forces on a section of main cable with an increased sag.

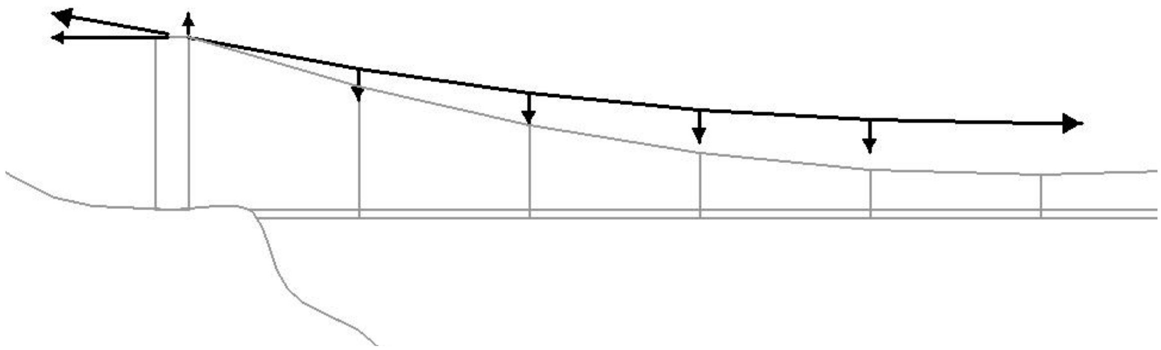

Figure 2-7 Forces on a section of main cable with a decreased sag.

The lower tension force associated with the higher sag is the reason many suspension bridges attach the cables to large towers. Raising the fixture points on towers allow for greater sags. When the cable force is transferred to the towers, the towers must in turn pass the force to the ground. The vertical force transfers directly to the ground while the horizontal force causes a bending moment at the base. A force diagram of the tower is shown in Figure 2-8.

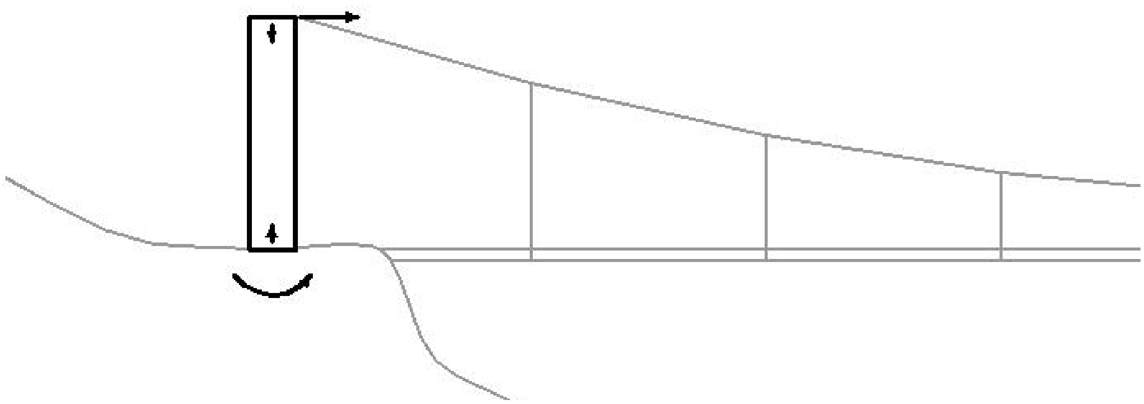

Figure 2-8 Forces applied to a column anchor point.

The cable is often extended down the other side of the tower as shown in Figure 2-9. This causes a greater downward force, but can cancel out the bending moment. This cable is then attached to a large anchor imbedded in the ground.

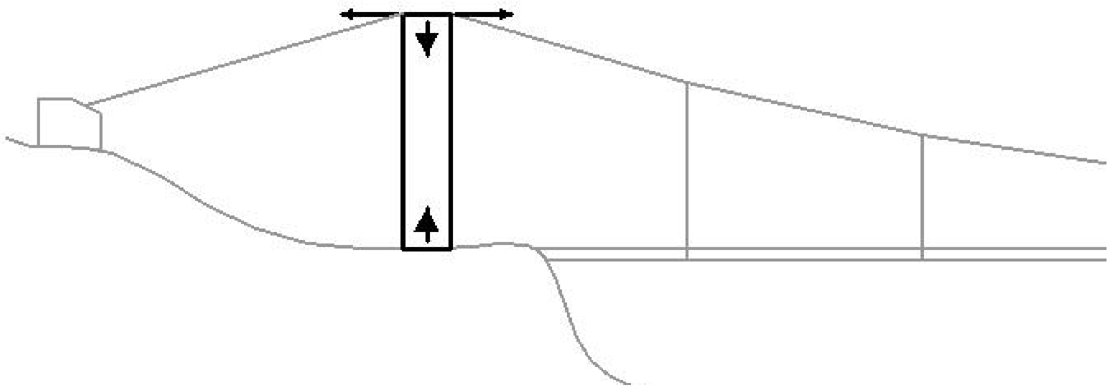

Figure 2-9 Forces on column with anchor cable.

In cases where one anchor is lower than another the cable will still assume the same shape as an even crossing. The difference is that curve will be truncated. The forces on either side can be calculated in the same manner regardless of the other side. Figure 2-10 illustrates a cable with one fixture point lower than the other. The force diagram for the section of cable on the high side is different from the force diagram for the section of cable on the low side, but both are analyzed in the same way. There are some equations that use the full length of the crossing to estimate forces. In these cases the equivalent length must be used. The equivalent length is twice the distance from the apex to the fixture point. It is the length of a level crossing that would produce the equivalent forces on the anchor.

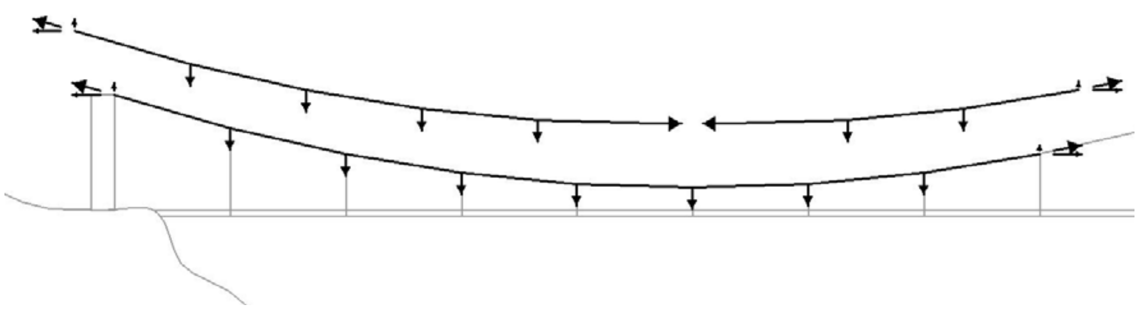

Figure 2-10 Forces on main cable with uneven anchor points.

2.1.2 Galileo, The Chain Curve, and Suspension Bridges

The chain curve is defined as the curve formed by a flexible chain hanging by the ends under it's own weight. This is also referred catenary curve from the Latin "catena" meaning, "chain". Galileo (1564-1642) estimated the catenary curve as:

$$y = \left(\frac{C}{2}\right)\left(\frac{x}{C}\right)^2$$

Equation 2-1 Galileo's Estimate for the Chain Curve.

Where x is the horizontal, y is the vertical , both in units of length, and C is a unitless constant. Galileo was close, but he wasn't correct. His estimate assumes that the weight of a chain is distributed evenly across the length of the span. This is not the case, it is actually distributed evenly across the arclength.

Jungius disproved Galileo in 1669, but the true form wasn't discovered until 1691 when Leibniz and Bernoulli derived it in response to a challenge from Bernoulli's brother. The catenary is expressed as:

$$y = C \cosh\left(\frac{x}{C}\right) - C$$

Equation 2-2 Catenary Curve Equation.

where cosh (the hyperbolic cosine) is:

$$\cosh(x) = \frac{1}{2}\left(e^{x} + e^{-x}\right)$$

Equation 2-3 Hyperbolic Cosine Function.

The arc length of a catenary curve is expressed as:

$$y = C \sinh\left(\frac{x}{C}\right)$$

Equation 2-4 Arc length of a catenary curve.

Where sinh (the hyperbolic sine) is:

$$\sinh(x) = \frac{1}{2}\left(e^{x} - e^{-x}\right)$$

Equation 2-5 Hyperbolic Sine Function.

For a suspension bridge the question of analysis now becomes, is the curve of the cable a parabola as Galileo said, or a hyperbola as Jungius said? The answer is neither. A suspension bridge has a combination of loads. The pipes apply loads distributed evenly over the length of the span, but the cable applies loads distributed evenly over the arc of the curve. The actual arc of the cable will fall somewhere in between.

To further complicate things, only the weight of the cable is applied evenly. The weight of the pipe is applied to the cable through the stringers. This acts not as an evenly distributed load, but as a series of point loads.

Fortunately, all the discrepancies between one method of analysis and another are minimal and fall well within the range of what could be considered negligible for field engineering. Also the constant C found in both equations is interchangeable. A catenary curve defined by one value of C will be closely approximated by a parabola using the same value.

It isn't critical to know the exact shape of the cable in a small bridge carrying nothing more than the weight of pipes. However, it is important to get close. This will be used later to determine the length of the stringers. If the stringers are cut poorly they won't evenly support the pipes. Uneven support will cause the pipes to bend and sag in places. At the very least, it will cause high and low spots that could trap air or sediment. At the worst it could cause the tubes to break. Steel tubes are more durable but less flexible than plastic. It is not uncommon for steel pipes to break if they are bent. The couplings are stiffer and focus the bending stress on the tubes where they enter the couplings. This is also where the pipe threads are. Not only are the threads cut into the pipe making it thinner at that point, but they are also angular, further concentrating the stress on those points. This is the most common type of break in steel pipes.

In the Dominican Republic it was typical to design crossings using the hyperbolic function to find the length and position of the cable and a triangular or parabolic estimate to find the force on the cable. In this report, all design tables were calculated using the hyperbolic function. These were calculated using a computer and since either method could be calculated just as easily, it was decided provide the more complex value. All other calculations will use the parabolic.

3 Planning: Initial Survey and Design Considerations

All of the planning should be done during the ground profile survey and aqueduct design. While it is not necessary to complete the crossing design before construction begins, it is important that the engineer has a rough idea of where the crossing will go and what size pipe is needed.

3.1 Materials

One of the most difficult things about working in the developing world is obtaining materials. Many building supplies, such as steel cable, are often not produced locally or are not produced in a full range of dimensions. Importing materials can be expensive. Design changes can also be expensive.

It is possible to design a wonderfully efficient bridge only to discover that the size of cable specified cannot be found anywhere in the country. Buying the next size larger wastes all the time spent optimizing the design and can break the budget. It is best to have a good idea what is readily available and tailor the design to that. Or, even better is to find materials salvaged from another project and use those. Good field engineering is about doing the best with what you have.

3.1.1 Cable and Pipe

Cable is specified by diameter, weave, and material type. Diameter is a nominal dimension roughly measuring the cable at it's widest. The weave is expressed by numbers such as 7X7, which stands for seven bundles of seven strands, or 7X19, which stands for seven bundles of 19 strands. The more strands a cable has the more flexible it is. A 7X19 cable will coil tighter without damage than a 7X7 cable of the same diameter.

The most common weaves found in the sizes used for these types of crossings are 1X7, 1X19, 7X7, 7X19, and 6X19. All of the analysis and design information in the guide are based on these weaves. If a different weave is encountered from a salvage or a supplier, it is recommended that additional research is done to find the cable properties. Figure 3-1 and Figure 3-2 show the cross section of two common cable weaves.

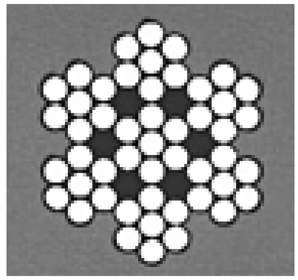

Figure 3-1 7X7 Cable Cross-Section (obtained from Loos & Co., Pomfret, Connecticut)

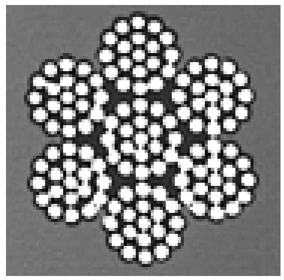

Figure 3-2 7X19 Cable Cross-Section (obtained from Loos & Co., Pomfret, Connecticut)

Cable also comes in different materials. Steel, stainless steel, and galvanized steel cables are all produced. The amount of corrosion protection needed will depend on the design life of the crossing and local conditions. The best bet for assessing how fast steel corrodes in the area is to find some old steel and see how it's holding up. Cable is sometimes manufactured with a plastic coating. This can often be an economical alternative to galvanized or stainless steel cable.

In addition to the cable it is important that the corresponding pieces are also available. Cable clamps (illustrated in Figure 3-3) and cable eyes will be needed in the same size. If the correct sizes of cable eyes are not available, a size or two larger can be used. Often this is desirable to be sure the eyelet will fit around another cable, a piece of rebar or other attachment point. Never substitute a different size cable clamp.

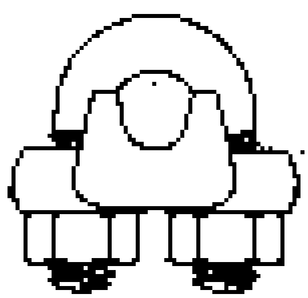

Figure 3-3: Cable Clamp (obtained from Crosby Group, Buffalo, New York)

If steel cable is to be salvaged, it is important to check the quality of cable. In addition to rust and age related issues, wire rope also can suffer from damage resulting from improper use and handling. Wire rope must be inspected for broken or deformed strands, kinks and other results of abuse. Cables previously used for cranes and winches are especially susceptible to damage.

Kinks and doglegs are common types of damage. Kinks result from improper uncoiling. If a loop is pulled tight it forms a kink. A kink is permanent and severely affects the strength of the cable. They should be removed or spliced out. To properly uncoil a cable, unroll it. Don't place the roll flat on the ground and pull an end.

Figure 3-4 The wrong way to unroll a cable. (photo provided by Kristina Katich)

Doglegs are the result of a bend. These are less serious and only need to be removed if the dogleg doesn't pull strait under tension. When a cable is unclamped from around an eyelet a dogleg is often present.

Cables that won't lay flat when uncoiled are also damaged. A tightly spiraled "pig-tail" condition is the result of a cable being pulled tightly over a small diameter drum. The strength is not significantly reduced but it makes the cables very difficult to work with.

Broken strands are also of concern, but do not mean the cable is unusable. The cable is still useable if the broken strands are limited to less than two breaks in six cable diameters of length and less than four breaks in thirty cable diameters of lengths. The judgment of the engineer will determine how much of an additional safety factor will be required. (Wire Rope Technical Board, 2005)

Galvanized Iron pipe is recommended for all the designs presented in this guide. Not all galvanized iron pipe is equal, in addition to being sold in diameters not readily available in PVC pipe such as 2.5 inches and 1.25 inches, it also comes in a wide variety of wall thickness. Even though many stores will make no mention of wall thickness, it is important to know what is available and what you are getting. Wall thickness affects the weight, strength and cost of the pipe.

Any wall thickness is acceptable for the pipeline, and obviously lighter is better. However, minor adjustments can make up for the increase in weight if a thinner variety is not available. For structural applications, however, it is important to check the wall thickness and perform the calculations specifically for that size. Wall thickness will greatly affect the bending strength of the pipe.

Hardware stores are often eager to please (or get rid of product) and will sell you what they have even if it isn't what you asked for. Local customs apply of course, but be sure to get a good look at what you are buying before it is cut or delivered.

Pro Tip: I once argued with a hardware store clerk over the strength of cable. He couldn't imagine anyone needing more than a 1/4" cable. I insisted that I need 3/8" cable and would have to go elsewhere. He explained that it could hold up a truck, even two, and was right. But, it still wasn't as strong as I needed. When dealing with materials make sure you see them and don't take the store's word for it.

3.2 Quality of Craftsmanship and Materials

Pipe, cable, and rebar will most likely come from a factory that applies international standards. The only thing to worry about is if the materials are in good condition. Obviously rusted or damaged materials will not be as strong as materials in good condition. This is not to say they are useless. Used galvanized pipes are often in excellent condition, rebar that has been sitting in the rain and weather for two years will not fair as well.

Concrete and stone will be produced or found on site. To check the quality and the skill of local builders look at other projects. Just because a mason has much experience with stone masonry does not mean they know how to do it right. For example, in the south of the Dominican Republic many irrigation canals are lined with stone. These look fabulous when finished but in reality have little strength. The local technique for stone masonry is to stack stones up and then cover the exterior with a thin layer of concrete mortar. These walls don't usually last for more than a few years and would be completely unacceptable for structural purposes.

The stones themselves may also be unacceptable. If a rock can be broken by hand or with one sharp blow with a pick it is too soft to be used for structural purposes. These can be used for anchors provided there is a good solid base of concrete to keep them all in place.

Good concrete mixing techniques can be found in other field engineering books.

Pro Tip: I hate working with "experts." They don't listen, they know one way of doing things and will do it that way even if the thing we're building is completely different. In the Dominican Republic the concrete always has too much water in it, there is never enough mortar between the stones and they don't wait for important things like leveling the site. I will often ask the brigade who has experience mixing concrete. When these individuals step forward I send them off to dig trench line and teach some of the younger workers how to do it the way I want it done.

3.3 Finding a suitable site

It is *possible* to place a crossing at almost any site encountered. It is not *feasible* or *practical* or *economical* to place a crossing at any site encountered. For this reason it is important to be able to start a rough design at any potential crossing site and estimate the cost involved. Often moving a site slightly to a narrower or more stable area can produce incredible savings.

Trees are a double-edged sword. On one hand the root system of a well forested area is ideal for controlling erosion and stabilizing banks. On the other hand large trees can cause substantial damage if they fall on a bridge. Figure 3-5 is a picture of a column that was hit by a fallen tree during Tropical Storm Alpha. How to handle placing a crossing near trees is a decision that can only be made by the engineer at the site.

Figure 3-5 Christina Osborn measures the salvageable section of a tree-damaged column. (photo by Kristina Katich)

3.3.1 Bank stability

Slope and bank stability is a topic unto itself. This guide will only briefly cover the topic with regards to what to look out for and how to avoid destabilizing the banks. A full geotechnical investigation is most likely unnecessary. Most crossings are sufficiently light and efficient that if poor soil is encountered the anchors can be moved further back more easily than the banks can be stabilized.

When performing a site investigation inspect the banks for land or rockslides. These areas are obviously more dangerous than others, but in addition can provide valuable clues to the stability of an area and the soil. If a landslide is discovered in the same type soil on a slope with a similar angle, there is evidence that the slope angle for that type of soil will be unstable over time.

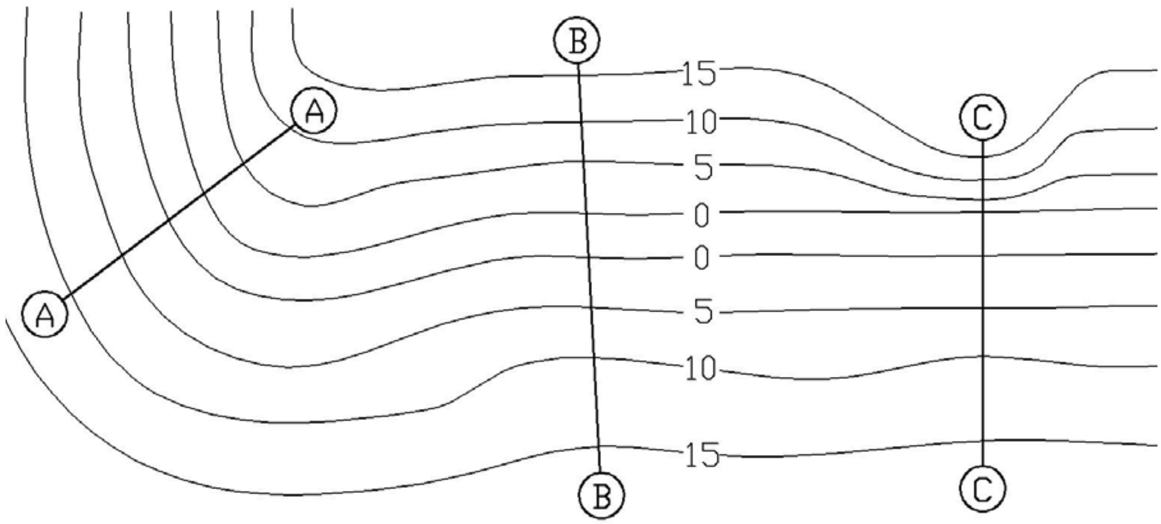

Figure 3-6 Topographic map of hypothetical canyon showing proposed crossing sites.

Using the example shown in Figure 3-4 it is possible compare different crossing sites. Imagine that a small stream is located roughly at elevation 0 and is flowing from right to left. The letters and lines in Figure 3-4 represent proposed crossing sites.

Location C would have a short span, but there is reason to be concerned over the stability of the bank. The bank on one side is considerably steeper than any other bank. This should cause concern for the designer. Why is this bank steeper than the others? Perhaps there is different geology at this point. If this is an area where bedrock or a more stable type of soil is found it is possible that this layout is perfectly fine. But if all the soil in the area were similar this would be an area of concern. What caused the other areas to find a natural slope that is much shallower than this part? It is very possible that all the other areas have conformed to a more natural slope and this section just hasn't slumped off yet.

Location A has an easy gentle slope on both sides, but it is located right at a bend in the canyon. The force of floodwaters and even small streams over time erode more heavily on the outside corners of bends. It's possible to visualize the floodwaters coming down the straightaway and hitting the bank full force before being deflected to the right. These areas should be avoided if possible.

Just based on the surface topography one can see that location B is the best choice. The slopes are not any greater than the surrounding area and are therefore probably stable. Also the stream is fairly straight in that section and there for will probably not erode any faster than any other area.

Even in a currently stable area the additional weight of a crossing can cause the ground to become unstable. One method for reducing this effect is to 'float' the foundations. That is to excavate the area of a large amount of soil, thereby reducing the final force acting on the soil below the new structure. A general cross section of this technique is shown in Figure 3-5.

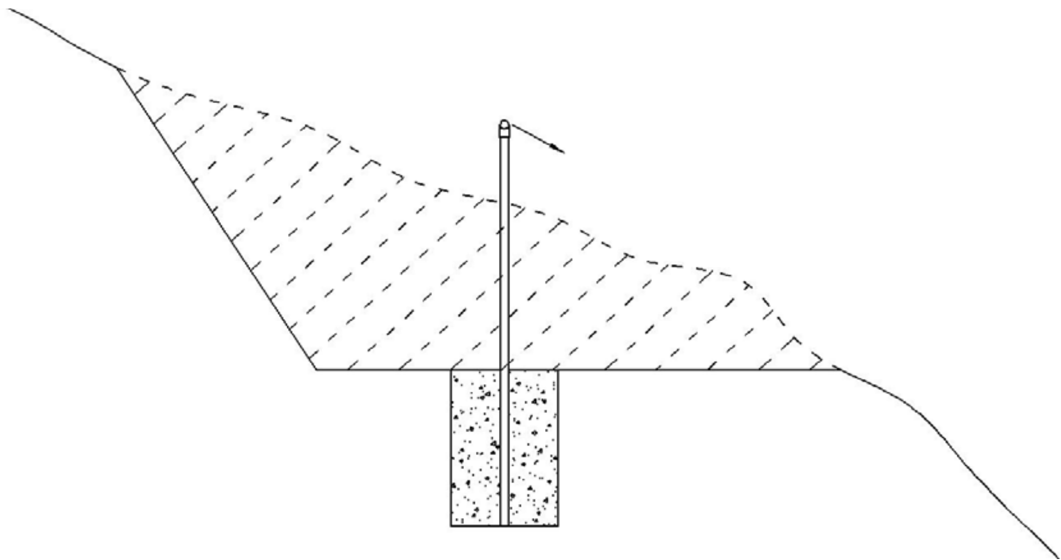

Figure 3-7 Anchor placed on slope with extra excavation for added stability.

This method can be a little extreme. This may also cause more problems than it solves. There may be stability issues with the back slope as well as what to do with the fill. It's also worth noting that post type anchors that have an anchor buried the additional weight on the slope is minimal. Excavating soil which weights 120-130 lbs/ft^3 and replacing with a concrete mass that weights 150-160 lbs/ft^3 only adds an additional 20-40 lbs./ft^3.

3.3.2 Quick length check: The string method

An easy and accurate way to measure the length of a crossing is with a string. An individual can throw or walk a string across the canyon. The string should be pulled tight and not be hung up on any branches.

The string will sag and stretch depending how much force is applied. To account for this, place a known force on the string. This can be done with a simple spring scale, or with a pulley and a known weight.

Mark the string at the distance across the canyon approximately where the proposed anchors will go. The string can then be taken to flat solid ground and a tape measure can be used to measure the string with the same force placed on it. With the same force applied the string will have the same sag, the same stretch, and therefore the same horizontal distance.

3.4 Choosing a pipe and cable size for the rough design

Selecting the pipe and the main cable size is the part where the most savings can come into play. These are usually the most expensive parts of the crossing. All the other parts don't vary as much in size or price even if the crossing is longer or shorter. By choosing a pipe and cable size before the detailed design it is possible to compare the cost of different routes without doing a full design.

The pipe size will be determined by the hydraulic profile required by the aqueduct. The cable size will be determined by how long the crossing is, how big the pipe is and how much sag is allowed.

First determine what size pipe is required for the hydraulic profile. Check to see what reducing the size of the line over the length of the crossing will do. In a long system with multiple pipe sizes it can be to a great economic benefit to reduce the pipe size for the crossing to one or two sizes smaller and then make up the difference by adding additional plastic pipes in the ground of the larger size.

Next take a look at the profile of the canyon. Decide on a convenient sag for the cable. This will be based on where, more or less, the pipes will reenter the ground and how tall the towers can be efficiently constructed.

The force on the cable can be quickly calculated with equations borrowed from Jordan (1980).

$$\text{Horizontal Tension} = \frac{(\text{Weight of Pipe per Unit Length})(\text{Length of Span})^2}{8(\text{Sag})}$$

Equation 3-1 Estimate for Horizontal Cable Tension based on parabolic model.

$$\text{Angle of Tension} = \arctan\left(\frac{4(\text{Sag})}{\text{Length of Span}}\right)$$

Equation 3-2 Estimate for the Angle of Force at the Fixture Point based on trapezoidal model.

$$\text{Total Tension} = \frac{\text{Horizontal Tension}}{\cos(\text{Angle of Tension})}$$

Equation 3-3 Estimate for Total Tension

These equations assume a cable that passes in a straight line from the anchors to the center of the crossing. This is not the same as the force produced by a true catenary, but is a good estimate. The true value only differs by one or two percent and is always less.

A safety factor between 2.5 and 3 is acceptable for this estimate. Apply the safety factor and choose a cable size from the cable available. This, along with the pipe size chosen, is enough to complete the rough design.

Pro Tip: I buy the materials at this point. The steel pipe and cable are the major purchases. The cement and rebar for the anchors can be added to or changed or moved *to fit to the pipe and cable selected if the final design is a little different. But, it is the cable and steel pipe that take the longest time to acquire. It's best to get that process moving as soon as possible.*

3.5 Survey

An accurate survey of the area will be needed. Most small-scale rural aqueducts use an Abney level and a long measuring tape to survey the route. If the designer has these tools and is familiar with their use they will have no problem with a crossing survey. The use of these materials is described in Jordan (1980), Reents (2003) and elsewhere.

3.5.1 String line layout

The first order of business is to clear the route. Clear a bit of land on both proposed anchor sites. Then clear a line directly from one site to the other so that nothing obstructs the line of sight from one side to the other. Trees and plants located lower in the canyon will not need to be cut.

Throw, or walk, a string line from one side to the other. Pull this string tight and stake it down where the bridge line is proposed. This will keep the survey on a straight line and on a single, two-dimensional, vertical/horizontal plane. On this line stake a benchmark on either side.

It is usually not necessary to survey the entire profile. Twenty feet back from the edge, or twenty feet onto solid ground, and ten feet vertically down from the edge is usually all that's needed. It is then possible to connect both sides relative to each other using the string method between the two benchmarks. Obviously, if clearance is an issue below the pipeline the entire profile can be measured. But, still use the string method between two benchmarks for accuracy in measuring the span.

It is often easier to mark the survey points first. Along the string line, place stakes at various points of interest. Place stakes at changes in grade, changes in soil, and at least every ten feet.

3.5.2 Rod survey

I have found that a rod survey is easier and quicker than a traditional Abney level survey in areas with short horizontal distances and larger vertical distances like those often found in crossing sites. A rod survey is similar to an Abney level survey except that rather than calculating vertical distances from ground distances and the angle measured the vertical and horizontal distances are measured directly.

A traditional Abney level survey over a canyon produces shorter distances and larger angles. The error introduced and then compounded with these larger angles is much higher. This has less to do with the measure of the angles and is more a mater of the difficulty in measuring the slope distance.

In a rod survey the lead surveyor uses a hand level, or an Abney level set to zero degrees, and a pole of known length. The second surveyor has the survey rod, which is a much longer pole that is marked in either feet or meters. This is nothing more than a ridged tape measure.

Moving from point to point, record the difference in elevation and the horizontal distance. The survey is more accurate if all points on one side are measured from the same point. For example, rather than measuring from the benchmark to the first point along the line and then measuring from the first point to the second, measure from the benchmark to the first then from the benchmark again to the second.

With a rod survey it is much easier to measure lower elevations from higher points. The survey can only proceed uphill if no point rises above the previous point more than the height of the pole with the level. Choose the benchmark point as the highest on the side and work to the lower points. The string can be run from any two even points.

Table 3-1 is an example of a survey book set up for a rod survey. The columns are labeled for the name of each point, where that point was measured from, the differential measurement in both the horizontal and vertical, the actual location in the horizontal and vertical and any notes about the point.

Table 3-1: Example of Blank Survey Book for Rod Survey

Point	Measured From	Horizontal (Diff)	Vertical (Diff)	Horizontal (Act)	Vertical (Act)	Notes

Table 3-2 shows typical field measurements and notes. Notice that no measurement is more precise than a quarter of a foot. This is fine for this application. Only a very general shape of the gully is needed. Each point is named and is noted from which other point it was measured. The notes indicate which is the north bank (N-bank) and that south is considered the positive direction (S Positive). BM1 has no measurements because it is the arbitrary starting point.

Table 3-2 Example of survey book after field measurements are taken.

Point	Measured From	Horizontal (Diff)	Vertical (Diff)	Horizontal (Act)	Vertical (Act)	Notes
BM1	X	X	X			N-bank (S Positive)
A	BM1	-10	2			
B	BM1	11	-3.5			Last of solid ground
C	BM1	19	-6.25			
D	BM1	25	-10			

E	D	4	-5			
BM2	BM1	82.75	0			String line measure
F	BM2	-5.5	-3			
G	BM2	-10	-6			Solid ground
H	BM2	11	4			
I	H	9	2			Great anchor site
J	H	15	5			

Table 3-3 shows how final distances are calculated. The first point is given the coordinates (0,0). Points A through D and BM2 are measured from this benchmark. Point E is measured as 4' to the south and 5' bellow point D. Point E is therefore located 29' to the south and 15' bellow point BM1. The distance between BM1 and BM2 is measured using the string method described in section 3.3.2.

Table 3-3: Completed Survey Book showing how final distances are calculated.

Point	Measured From	Horizontal (Diff)	Vertical (Diff)	Horizontal (Act)	Vertical (Act)	Notes
BM1	X	X	X	0	0	N-bank (S Positive)
A	BM1	-10	2	-10	2	
B	BM1	11	-3.5	11	-3.5	Last of solid ground
C	BM1	19	-6.25	19	-6.25	
D	BM1	25	-10	25	-10	
E	D	4	-5	29	-15	
BM2	BM1	82.75	0	82.75	0	String line measure
F	BM2	-5.5	-3	77.25	-3	
G	BM2	-10	-6	72.75	-6	Solid ground
H	BM2	11	4	93.75	4	
I	H	9	2	102.75	6	Great anchor site
J	H	15	5	108.75	9	

PRO TIP: For a survey rod, I use a fourteen-foot length of one-inch PVC pipe. With the extra PVC pipe I made a pole for the Abney level. I marked the Survey rod with red duct tape and magic marker at every foot and black electrical tape marking every quarter foot. I started the marks with zero set to the same height as the other pole. This way I don't have to calculate the vertical difference, I only have to read it off the survey Rod.

4 Design

At this point the designer has a rough idea of cable and pipe size and the location of the crossing. It is time to finalize the design. There are two basic constraints when designing: geometric constraints and strength constraints.

Geometric constraints consist of questions such as: “How high off the ground must the pipe be to allow trucks, horses, floodwaters, etc… to pass below?” and “How much space is available to build an anchor on either side of the crossing?” These questions must be answered by the designer at the site with the help of the community. There will be people there who know what needs to pass below or how high the floodwaters have reached in the past twenty years. Also, high water marks on vegetation and erosion can also provide clues.

Strength constraints consist of questions such as: “How strong must the cable be?” or “How big does the column need to be?” Obviously much of this depends on the geometric constraints. Different geometry produces different forces that require different strengths. Often the geometry of a crossing must be changed to accommodate what is possible structurally.

To design a structure such as a column or an anchor one must first know in what ways a structure can fail, known as failure modes. Then, design to cover all of the failure modes. Each design has it’s own set of failure modes which must be considered. Cables can snap, anchors can slide, and columns can buckle. Structural design is no more than analyzing the forces that contribute to a failure mode and making sure they are less than the forces that resist a failure mode.

Safety factors are applied to this process as well. A safety factor is simply the ratio of the amount of force applied to the amount of force that will cause a failure. If a steel cable can withstand a 3,000 lb load and only 1,000 lbs are applied, it results in a safety factor of 3. The safety factor is chosen by the engineer based on three criterion: how well the applied forces are known, how well the resisting strengths are known, and what are the consequences of a failure. For example, an earthen dam has a high safety factor because the building material varies, forces are difficult to calculate and the consequence of failure is often many human lives and extensive damage. The safety factor of a small steel girder bridge is relatively low because steel is produced in highly controlled factories, the force applied is limited to what a big truck can carry over it, and the consequence of failure is towing a heavy truck out of a gully and rebuilding. Safety factors will be suggested for each part of the analysis, but nothing should take the place of the judgment of the onsite engineer.

Design is an iterative process. Good efficient design is even more of an iterative process.

4.1 Cable and pipe path

The engineer must decide where the pipeline and cable will pass through the air and attach to the ground. Will the pipeline be slanted or perfectly horizontal? Will both anchors be at the same elevation or will one be lower than the other?

A plot of the proposed cross-section is a valuable tool. Most often the designer starts with this plot.

It is recommended that plastic pipe be buried at three feet below the surface. If the pipe exits the slope at this level and is perfectly horizontal the pipe will be three feet below the level of the ground surface at the anchor. The usual minimum length for a stringer (the amount of cable required to secure the pipe to the main cable) is one foot. In this simple case it is shown that the required height of the towers above the ground surface will be the sag minus two feet.

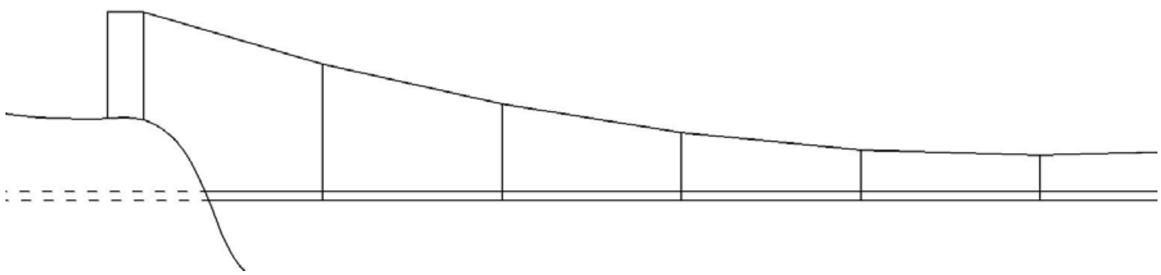

Figure 4-1 Elevation layout with pipe entering ground at same elevation as trench.

If more sag is required and the terrain permits, other pipe layouts are possible. These alternative layouts can reduce the height required for the towers, but can be more difficult to construct, requiring difficult connections in inconvenient places. Also, they may require more difficult calculations for determining the length of the stringers.

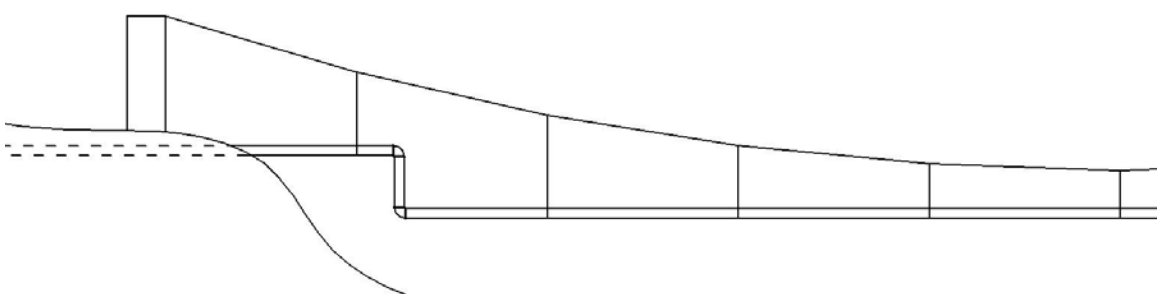

Figure 4-2 Elevation layout with pipe entering ground at trench elevation but using two GI elbows to lower pipe for the center of the crossing.

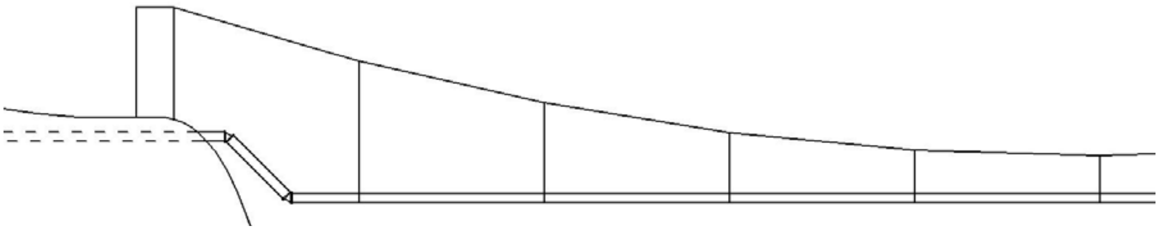

Figure 4-3 Elevation layout with pipe entering ground at trench elevation but using two GI 45 elbows to lower pipe for the center of the crossing.

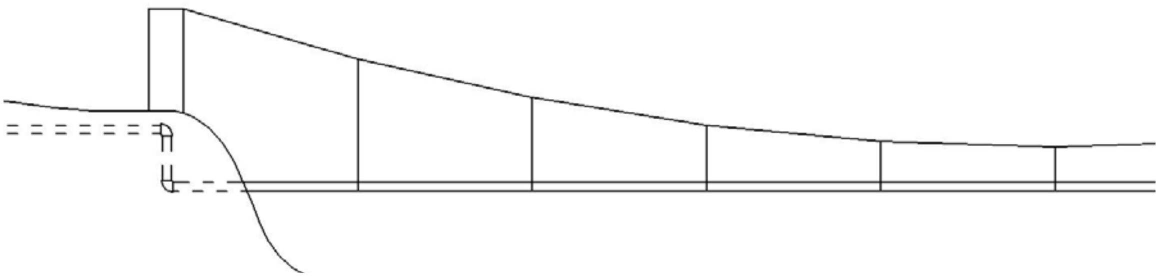

Figure 4-4 Elevation layout with pipe entering below the trench elevation and using two buried plastic elbows to raise pipe to normal trench level.

The above figures are to no particular scale and are only shown to demonstrate different arrangements that have been used successfully. It should also be noted that these figures only represent two dimensional solutions. Once the pipe is past the last stringer it could easily be turned out from under the cable (into or out of the paper) to enter the ground as shown in Figure 4-5.

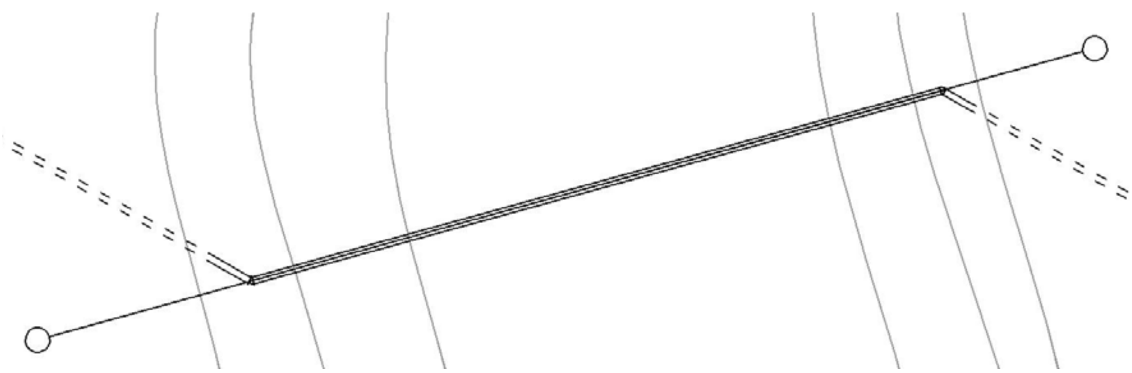

Figure 4-5 Plan view of crossing with pipe entering the ground at an out of plane angle

4.1.1 Finding 'C' and the shape of the cable curve

Finding the exact shape of the curve of the cable at this point is only important if there are clearance issues below or above the cable that will need to be addressed before construction begins. If the only clearance requirements are based on the height of the pipe, this step can be skipped until the anchors are completed. Even if it is calculated now, it will be required again after the completion of the anchors to adjust for construction errors and changes.

The constant 'C' is what gives the curve its shape. For every sag ratio there is a different 'C' value. To plot the path of the cable one must know the value of this constant for that particular curve.

$$y = C\cosh\left(\frac{x}{C}\right) - C$$

Equation 4-1 Catenary Equation

The catenary equation (Equation 4-1) will produce one value of 'C' given values of x and y.

$$y = \left(\frac{C}{2}\right)\left(\frac{x}{C}\right)^2$$

Equation 4-2 Parabolic equation

The simplest method involves using a computer or calculator with a numerical solver. Set x to half of the span, y to the sag and let the computer iterate to find C.

Another method for finding 'C' is using the chart supplied in Appendix C. This chart supplies the 'C' value for a catenary with a given sag ratio and a unit span (a span of 1 in any given set of units). Because the catenary is scaleable this can be scaled up to the full size of the crossing.

Example 4-1: Calculating the 'C' Constant using Design Charts

A 140 ft span with a sag of 11.75 ft has a sag ratio of 0.084. This sag ratio on a level crossing produces a 'C' value of 1.501890 for a unit span. Scaling the crossing up by multiplying the unit 'C' value by the length produces a 'C' of 210.2646.

A check of Equation 4-1 will show that:

$$y = C\cosh\left(\frac{x}{C}\right) - C$$

$$y = 210.2646 \cosh\left(\frac{70\text{ ft}}{210.2646}\right) - 210.2646$$

$y = 11.76$ ft
or

$$y = \left(\frac{C}{2}\right)\left(\frac{x}{C}\right)^2$$

$$y = \left(\frac{210.2646}{2}\right)\left(\frac{70\text{ ft}}{210.2646}\right)^2$$

$y = 11.65$ ft

This is not exact, but a difference of one hundredth or one tenth of a foot over a 140 ft span is more than close enough for these purposes.

Finding the 'C' value for a cable hung between two anchor points at different elevations is a little trickier. The cable will still hang in an approximate catenary or parabolic curve, but the curve will be truncated as shown in section 2.1.1. What makes this more difficult is that the apex is not in the middle of the anchors. A 'C' value must be found that produces a y value for one x relative to one anchor and another y value for the x relative to the other anchor. Both of these x values must sum to the span. The equations are expressed as follows.

$$y_1 = C \cosh\left(\frac{x_1}{C}\right) - C$$

Equation 4-3 Uneven Fixture Point Equation 1 of 3

$$y_2 = C \cosh\left(\frac{x_2}{C}\right) - C$$

Equation 4-4 Uneven Fixture Point Equation 2 of 3

$$\text{SPAN} = x_1 + x_2$$

Equation 4-5 Uneven Fixture Point Equation 3 of 3

Where Y_1 is set to the sag desired as measured vertically from the highest anchor point to the apex and Y_2 is the sag minus the drop. X_1 is distance from the apex to the highest anchor measured horizontally and X_2 is the horizontal distance from the apex to the lower anchor point. See Figure 4 -6 for guidance.

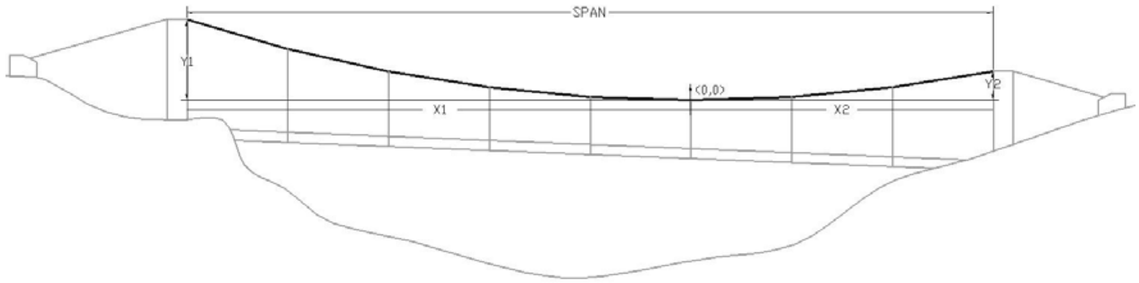

Figure 4-6 Dimensions used in uneven anchor analysis.

Through substitution, Equations 4-2 through 4-4 can be combined into the following equation and solved numerically in the same manner as Equation 4-1.

$$y_1 = C\cosh\left(\frac{\text{SPAN} - C\,\text{acosh}\left(\frac{y_2 + C}{C}\right)}{C}\right) - C$$

Equation 4-6: Final Uneven Fixture Point Equation

The ‘C’ value and the location of the apex can also be found using the design charts.

Example 4-2: Calculating the ‘C’ Constant for an Uneven Anchor set up using Design Table

Consider a 120-foot span where one fixture point will be 6 feet below the other. A sag of 10 feet is desired (measured from the higher side, see Figure 2-2 for guidance.) This is a sag ratio of 0.100 and a drop ratio of 0.05.

From the table in Appendix C , ‘C/L’ is 1.728772 and ‘X_1/L’ is 0.585. Multiplying by the length shows that for this set up C = 207.4526 and the apex is located 70.2 feet from the higher fixture point.

A check of Equation 4-1 will show that:

$$y_1 = C\cosh\left(\frac{x_1}{C}\right) - C$$

$$y_1 = 207.4526\cosh\left(\frac{70.2\text{ ft}}{207.4526}\right) - 207.4526$$

y_1 = 11.99 ft

$$y_2 = C\cosh\left(\frac{x_2}{C}\right) - C$$

$$y_2 = 207.4526 \cosh\left(\frac{49.8 \text{ ft}}{207.4526}\right) - 207.4526$$

$$y_2 = 6.01 \text{ ft}$$

or

$$y = \left(\frac{C}{2}\right)\left(\frac{x}{C}\right)^2$$

$$y = \left(\frac{207.4526}{2}\right)\left(\frac{49.8 \text{ ft}}{207.4526}\right)^2$$

$$y = 5.98 \text{ ft}$$

Once again, this is not exact, but the difference is negligible.

4.1.2 Force on Cable and Anchors and Design Optimization

As described in Section 2.1.1 the total force on the cable and anchor points are dependent on the weight of the pipe and cable and the length of the crossing and the sag of the cable.

Thomas Jordan's (1980) estimates represented in Equations 3-1 to 3-3 will most likely be sufficiently accurate for cable sizing and anchor design. But, for certain types of anchors, longer crossings, or for the sake of accuracy, it's important to know how to calculate the forces more accurately.

Start by calculating the angle of the cable at the fixture point. The angle can be found using Equation 4-6 where 'C' is calculated using the method in Section 4.1.1. X is the distance from the apex to the anchor.

$$\text{Angle} = \arctan\left(\sinh\left(\frac{X}{C}\right)\right)$$

Equation 4-7: Angle of cable at a given distance from the apex

From here the forces can be balanced. Assume a free body from the apex to the fixture point. The vertical component at the fixture point is equal to the weight of the free body. The horizontal component is calculated by dividing the vertical component by the tangent of the angle. The horizontal, and only, component at the apex is equal to the horizontal component at the fixture point.

Example 4-3: Calculating the Forces Applied to an Anchor, Cable Sizing, and Design Optimization

A 140 ft. span is selected as the best location for a crossing for 2” galvanized tube suspension bridge. It is also decided that a sag of roughly 6 ft. will be easy to construct and provide good clearance for surrounding topography. A safety factor of 3 will be used for the cable strength.

Useful information:
Weight of Standard 2” Galv. Pipe = 3.65 lbs./ft. (Appendix B)
Weight of water in 2” Galv. Pipe = 0.121 lbs./ft. (Appendix B)
Total weight = 3.77 lbs./ft.

Using Equation 3.1 through 3.3 to estimate total tension.

$$\text{Horizontal Tension} = \frac{(\text{Wieght of Pipe per Unit Length})(\text{Length of Span})^2}{8(\text{Sag})}$$

$$\text{Horizontal Tension} = \frac{(3.77\ \text{lbs./ft.})(140\ \text{ft.})^2}{8(6\ \text{ft.})}$$

Horizontal Tension = <u>1539.4 lbs.</u>

$$\text{Angle of Tension} = \arctan\left(\frac{4(\text{Sag})}{\text{Length of Span}}\right)$$

$$\text{Angle of Tension} = \arctan\left(\frac{4(6\ \text{ft.})}{140\ \text{ft.}}\right)$$

Angle of Tension = <u>9.7°</u>

$$\text{Total Tension} = \frac{\text{Horizontal Tension}}{\cos(\text{Angle of Tension})}$$

$$\text{Total Tension} = \frac{1539.4\ \text{lbs.}}{\cos(9.7°)}$$

Total Tension = <u>1561.7 lbs.</u>

Applying a safety factor of 3:

Use => <u>4685.1 lbs.</u>

From this estimate a cable size can be specified and included in the total weight.

From Appendix A:
7X7 3/16 Steel Cable has a breaking strength of 3700 lbs. and a weight of .062 lbs/ft
7X7 1/4 Steel Cable has a breaking strength of 6100 lbs. and a weight of .106 lbs/ft

The 3/16 cable is too small and the 1/4 cable is too large and an uneconomical design. Either of these can be used if the parameters are optimized. To optimize to either the 3/16 size or the 1/4 find the safe applicable load by dividing the breaking strength by the safety factor.

3/16's safe load = 1233 lbs.
1/4's safe load = 2033 lbs.

Next find a geometric design that will better fit the cable strengths. The 3/16's case will be calculated first. For a rough calculation use Equation 3-1.

$$\text{Horizontal Tension} = \frac{(\text{Wieght of Pipe per Unit Length})(\text{Length of Span})^2}{8(\text{Sag})}$$

Solve for the Sag…

$$\text{Sag} = \frac{(\text{Wieght of Pipe per Unit Length})(\text{Length of Span})^2}{8(\text{Safe Load})}$$

$$\text{Sag} = \frac{(3.77\ \text{lbs./ft.})(140\ \text{lbs.})^2}{8(1233\ \text{lbs.})}$$

Sag = 7.49 ft.
Use 7.5 ft.

For a 3/16's cable in this situation a 7.5 ft design sag is a better choice.
Using the same method for the 1/4 cable…

Sag = 4.54 ft.
Use 4.75 ft.

Using the methods found in section 4.1.1, the 'C' value for a 140 ft. span with a sag of 7.5 ft. is found to be 327.909. For the angle use equation 4-6.

$$\text{Angle} = \arctan\left(\sinh\left(\frac{X}{C}\right)\right)$$

$$\text{Angle} = \arctan\left(\sinh\left(\frac{70}{327.909}\right)\right)$$

Angle = 12.1°

The vertical component is equal to the weight of the tubes, water, and cable from the apex to the fixture point.

Vertical Component = (length from apex to anchor)x(weight of tubes, water, and cable per foot)

Vertical Component = (70 ft)x(3.65 lbs/ft + .121 lbs/ft + .062 lbs/ft)

Vertical Component = 268.31 lbs

$$\text{Horizontal Component} = \frac{\text{Vertical Component}}{\tan(\text{Angle})}$$

$$\text{Horizontal Component} = \frac{268.31 \text{ lbs}}{\tan(12.1°)}$$

Horizontal Component = 1251.6 lbs

$$\text{Total Force} = \sqrt{(\text{Horizontal Component})^2 + (\text{Vertical Component})^2}$$

$$\text{Total Force} = \sqrt{(1251.6 \text{ lbs})^2 + (268.31 \text{ lbs})^2}$$

Total Force = 1280.0 lbs

The same method can be used for the 1/4 cable design.

Assuming a pipe laid three feet below the surface and allowing one foot for the stringer attachments the apex of the cable will lay two feet from the anchor surface. The rest of the sag will have to be made up with the towers. Now the designer has two distinct options:

-- A 2.75 ft. tower (most likely a solid tower/anchor combination) with a vertical component force of 268.3 lbs and a horizontal component force of 1984.5 lbs acting on it and a 1/4" cable.

-- Or, a 5.5 ft tower (most likely a galvanized iron pipe with anchor) with a vertical component force of 268.3 lbs and a horizontal component force of 1251.6 lbs acting on it and a 3/16" cable.

The economics and feasibility of each option can only be decided by the on site engineer. This will depend on questioning whether the small anchor makes up for the additional cost of the larger cable or if the smaller cable makes up for the additional cost of the larger anchor.

Another consideration while deciding on the sag and cable is contractibility. Engineers will rarely specify an excessively large diameter cable. But, for example, if a large diameter cable is available at low cost or salvaged, it may be tempting to use it. It would also be tempting to use it to its full strength by way of using an extremely small sag. It must be remembered that humans will build this bridge. If the force required to pull the cable up into place is too great the crossing will be able to be constructed. Be sure to check the force on the cable with the proposed sag and only the weight of the cable. Also be sure to have a plan for applying a force of this magnitude on the cable and maintaining it long enough to secure it.

4.2 Anchors and Columns

The cable is attached to some form of structure at the end. This structure must be able to withstand the forces of the cable and of any other loading. This can include anything from kids swinging on it to trees falling on it. Often the cable is attached to two separate parts, a tower or column to lift the cable up to a convenient height and a large anchor to resist the force in the cable. The type of anchor and column set up will depend on how high the cables must be elevated to allow for clearance below and how much force is on the column.

More than one type of anchor will work for any given situation. It is up to the designer to decide which will be most economical and easiest to construct.

4.2.1 Single Post

The simplest anchor consists of a single piece of galvanized iron pipe anchored in the ground with a base of concrete. Single pipe anchors are best suited for smaller crossings with large sags and small pipes. They are not as strong as the column and anchor type system described in the following section. They also can be more expensive due to an inefficient use of materials. However, they are used frequently in the Dominican Republic and are a featured type of anchor in ‘A Handbook of Gravity-Flow Water Systems’ (Jordan, 1980). They are included in this report primarily on possibility that the designer will encounter one in the field during either a repair or expansion of an existing aqueduct. The designer should think twice before choosing a single post anchor on a new project.

The cable is attached to the top of the pipe column. Usually a ‘T’ is screwed into the top of the pipe with two small pieces of pipe attached to either side. The cable is wrapped around this and clamped to itself as shown in Figure 4-7.

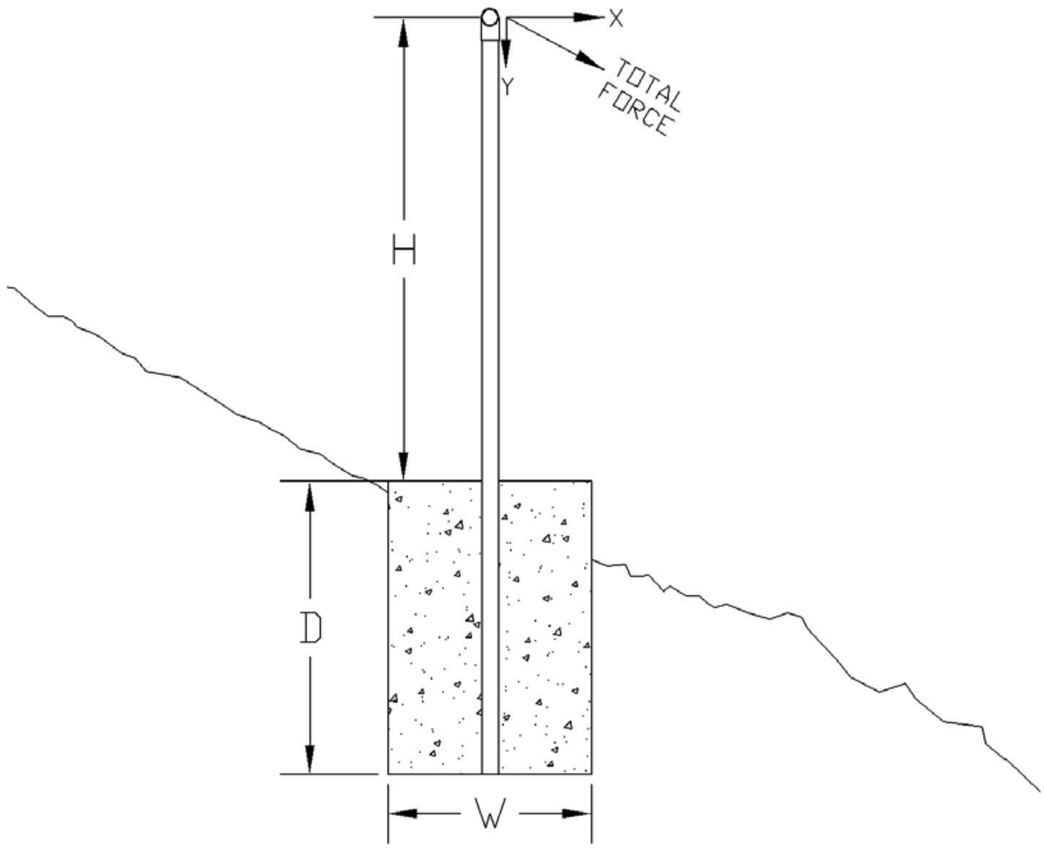

Figure 4-7 Elevation of Single Post Anchor

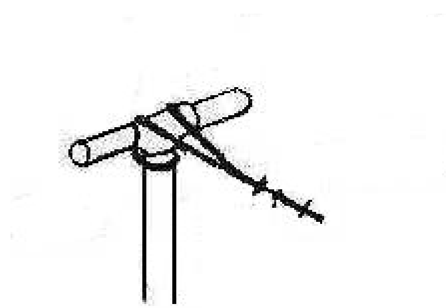

Figure 4-8 Detail of Cable Connection for Single Post Anchor (adapted from Jordan)

The failure modes are: a bending failure at the base of the pipe, and overturning of the whole structure.

To check for bending failure, first calculate the moment applied at the base of the pipe by the horizontal component then apply the formula for bending stress. Add this to the stress applied by the vertical component, the force divided by the cross-sectional area of the pipe. A safety factor of at least 2 is recommended. To design for bending failure, calculate the moment applied at the base, multiply by the desired safety factor and chose a pipe size from Appendix B.

To check for overturning failure sum the moments that cause over turning and compare to those resisting. The overturning force is the horizontal component applied by the cable at the top of the pipe. Resisting forces are the vertical component of the cable and the weight of the concrete mass. Some would argue that the soil pressure on the front face of the mass also resists the overturning. This is true, but this pressure is difficult to calculate accurately, the pipeline and trench often run right in front of the anchor compromising this strength, and in the case of heavy erosion, the anchor will remain stable even if all the soil is washed away from in front. A safety factor of at least 3 is recommended.

Another issue is the structural integrity of the concrete mass. It is designed to resist force with its weight and not with its strength. A flat slab type mass (one where the W dimension is larger than the D dimension, see Figure 4-6) will be prone to the types of failures where the moment on the pipe cracks the concrete mass. Keeping the mass taller than it is wide, or at least cubical will reduce the stress on the mass and avoid these failures. Also, keep D equal or greater than half of H.

If there is a chance that the mass will be submerged underwater the design process will be changed slightly. The weight of the mass per cubic foot will be reduced by 63 lbs/ft^3. This is the weight of water and represents what will happen if the mass "floats". Of course the designer can ignore this situation if this case is already considered a failure. For example, the anchor may be submerged by floodwaters, but in this case the pipeline would also be destroyed regardless of the anchors.

Example 4-4: Design of a Single Post Anchor

Previously Calculated (this roughly estimates the forces applied by a 1" tube over a 80ft crossing with an 8 ft sag):
Horizontal Force on Anchor = 200 lbs
Vertical Force on Anchor = 80 lbs
Height (H) required = 4'

Maximum Bending Force (located where the column meets the concrete) = (Horizontal Force)x(Height)

Maximum Bending Force = (200 lbs)x(48 in)

Maximum Bending Force = 9600 in-lbs

To have a safety factor of 2 the selected pipe must withstand a 19,200 in-lb moment. Looking in Appendix B, it's shown that a standard 2" galvanized pipe can withstand a 20,183 in-lb moment.

Site investigation shows that the anchor foundation should be dug to about 4’ below the surface.

Summing the moments around the lower front edge of the concrete mass (positive in the clockwise direction):

$$\Sigma M = 0 = (\text{Horizontal Force})x(H+D)x(\text{Safety Factor}) - (DxWxWx(\text{Weight of Mass per cubic foot}))xW/2$$

$$(\text{Horizontal Force})x(H+D)x(\text{Safety Factor}) = (DxWxWx(\text{Weight of Mass per cubic foot}))xW/2$$

$$\frac{2x(\text{Horizontal Force})x(H+D)x(\text{Safety Factor})}{(Dx(\text{Weight of Mass per cubic foot}))} = W^3$$

$$\sqrt[3]{\frac{2x(\text{Horizontal Force})x(H+D)x(\text{Safety Factor})}{(Dx(\text{Weight of Mass per cubic foot}))}} = W$$

$$\sqrt[3]{\frac{2x(200\text{lbs})x(4\text{ft}+4\text{ft})x(3)}{(4\text{ft}x(120\text{ lbs/ft}^3))}} = W$$

W = 2.7 ft

Use 3 ft in the design for simplicity.

4.2.2 Column and Anchor

A column and anchor set up involves two distinct parts, the column and the anchor. The column lifts the cable to the appropriate height and the anchor resists the horizontal force on the cable. The advantages of this method over the single post is that by extending the cable back down to the anchor it is possible to reduce or even almost completely eliminate the bending moment on the column.

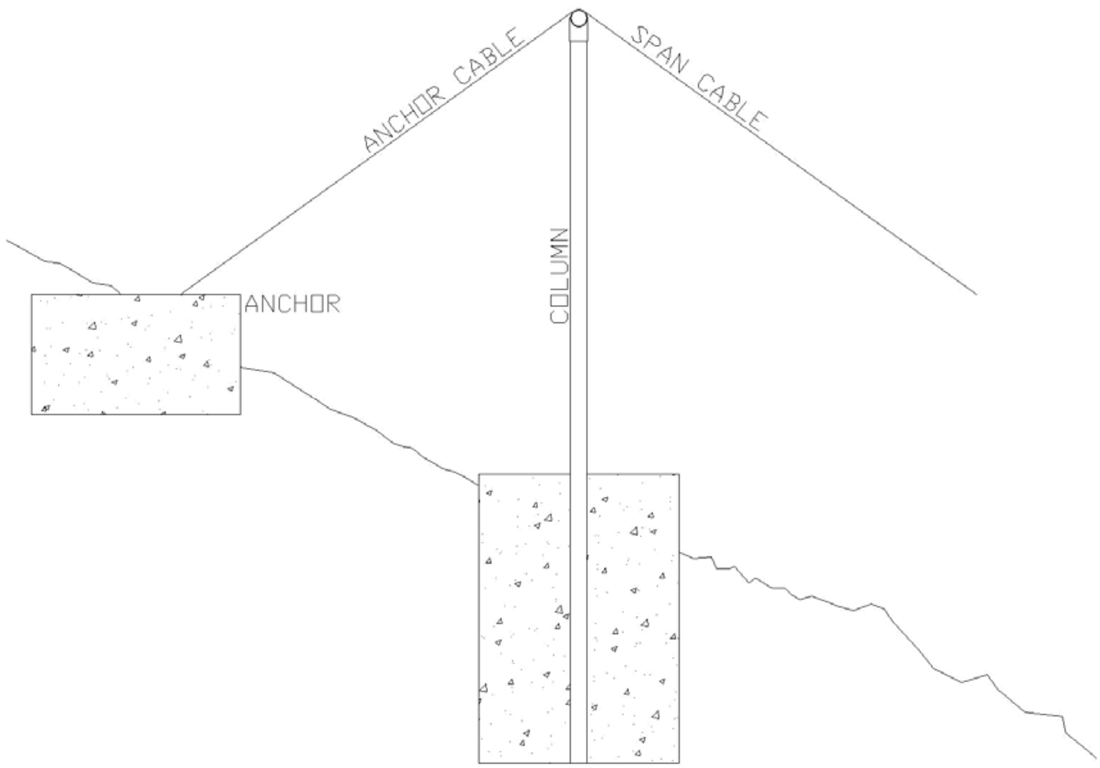

Figure 4-9 Elevation of anchor and column

The main failure modes to design for are: uplift of the anchor, bending failure of the column, and buckling failure of the column.

The first step in the analysis is to decide if the cable will be fixed to the top of the column or merely pass over. If the cable merely passes through both the part of the cable that spans the crossing and attaches to the anchor will have the same force. If the cable is attached, it is possible to adjust the tension on both cables independently using turnbuckles. While most connections that pass through will not be entirely frictionless and therefore have some additional horizontal forces, these forces are difficult to predict, impossible to count on, and better left assumed to be zero.

Figure 4-9 shows two different methods for attaching cable to the top of a steel column. The attachment on the left has the cable pass over a groove cut in the steel pipe. The anchor force will be identical to the span cable force. (Also note the construction detail, pieces of half inch PVC pipe were placed over the cut edges to protect the cable.) The attachment on the left has the span cable wrapped around and clamped in the same manner as Figure 4-7 and also has the anchor cable wrapped and attached the same way. In this set up the tension on the anchor cable can be adjusted independently.

Figure 4-10 Two options for attaching cable to the top of a steel column.

Balance the forces at the column. The force and the angle applied from the cable across the span will be set by the sag and length of the span. If the cable is attached at the top the force on the anchor cable can be adjusted to the point where no horizontal force, and therefore no bending moment, is transferred to the column. If the cable is not attached, the forces are the same and the only method for reducing the horizontal force is by adjusting the angle by moving the location of the anchor.

To assure a good solid connection with the ground, the same minimum dimensions should be used for the concrete mass under column as used in the single post style.

Example 4-5: Design of a separate column and anchor.

Consider 7 ft tall column. A 2,000 lb force is applied through the span cable at a 10° angle from horizontal. Using an anchor and column set up there are four distinct options for design and balancing the forces.

Option 1: Adjust angle of the anchor cable, by moving or changing the anchor such that the bending moment on the column is zero.

If the angle from the span cable is 10°, the angle on the anchor cable will also be 10°. The resulting force on the column is calculated as follows.

$\Sigma F_Y = 0 =$ Axial Column Force - (Span Cable Force)$\sin\theta_S$ + (Anchor Cable Force)$\sin\theta_A$

$\Sigma F_Y = 0 =$ Axial Column Force - (2,000 lbs)sin10°+ (2,000 lbs)sin10°

Axial Column Force = 694.59 lbs

Use 695 lbs

The anchor will have to be positioned to be sure that the cable forms a 10° angle. If the anchor is flush with the ground this would be roughly 40 ft from the column, making this arrangement excessively large. If the ground is sloped, such as in Figure 4-6, the anchor could be placed closer.

Option 2: Adjust the force applied by the anchor cable such that the bending moment in the column is zero.

Assume that the anchor is placed in a convenient solid location. From this location the anchor cable attaches at a 19° angle. Because the anchor cable will have a different force applied than the span cable the cable must be fixed to the column.

$\Sigma F_x = 0 = (\text{Span Cable Force})\cos\theta_S - (\text{Anchor Cable Force})\cos\theta_A$

$\Sigma F_x = 0 = (2{,}000 \text{ lbs})\cos 10° - (\text{Anchor Cable Force})\cos 19°$

Anchor Cable Force = 2,083.11 lbs

Use <u>2,084 lbs</u>

$\Sigma F_y = 0 = \text{Axial Column Force} - (\text{Span Cable Force})\sin\theta_S + (\text{Anchor Cable Force})\sin\theta_A$

$\Sigma F_y = 0 = \text{Axial Column Force} - (2{,}000 \text{ lbs})\sin 10° + (2{,}084 \text{ lbs})\sin 19°$

Axial Column Force = 1,025.78 lbs

Use <u>1,026 lbs</u>

The anchor cable will have to be tensioned during construction using a turnbuckle. A simple method for applying the proper tension is outlined in section 5.2.2.

Option 3: Adjust the angle of the column until the bending moment in the column is zero.

Assuming the same location of the anchor as used previously and identical cable force, the bending moment can still be eliminated from the column by tilting. By splitting the difference of the cable angles the proper column angle can be found. With a 19° angle on the anchor cable and a 10° angle on the span cable the column should be tilted back, toward the anchor, 4.5°. This would cause both the anchor cable and the span cable to act on the column at an angel of 14.5° relative to the column.

$\Sigma F_y = 0 = \text{Axial Column Force} - (\text{Span Cable Force})\sin\theta_S + (\text{Anchor Cable Force})\sin\theta_A$

$\Sigma F_y = 0 = \text{Axial Column Force} - (2{,}000 \text{ lbs})\sin 14.5° + (2{,}000 \text{ lbs})\sin 14.5°$

Axial Column Force = 1,001.52 lbs

Use <u>1,002 lbs</u>

Option 4: Allow a bending moment in the column.

In this case the anchor cable will not be used to cancel the bending moment, but only to reduce it.

$\Sigma F_x = 0 =$ (Span Cable Force)$\cos\theta_S$ - (Anchor Cable Force)$\cos\theta_A$ – Horizontal Column Force

$\Sigma F_x = 0 = (2{,}000)\cos 10° - (2{,}000)\cos 14.5°$ – Horizontal Column Force

Horizontal Column Force = 33.32 lbs

Use 34 lbs acting on the top of the column.

$\Sigma F_y = 0 =$ Axial Column Force - (Span Cable Force)$\sin\theta_S$ + (Anchor Cable Force)$\sin\theta_A$

$\Sigma F_y = 0 =$ Axial Column Force - $(2{,}000)\sin 14.5°$ + $(2{,}000)\sin 10°$

Axial Column Force = 848.06 lbs

Use 849 lbs

At the base of this column, where the forces are most critical, these components will translate to a vertical force of 849 lbs and a bending moment of 238 ft-lbs. Both will need to be considered when sizing the column.

The anchor must be sufficiently heavy to keep from sliding under the force of the cable or being lifted. The forces acting are the vertical and horizontal forces of the cable and the forces resisting are the weight of the anchor and the friction with the soil. Values for these can be found in Appendix G. When designing with soil safety factors of 3 or even up to 4 would not be out of line. Soil behavior is difficult to predict and the cost of adding the safety is often limited to a little additional concrete. As mentioned in section 4.2.1 reduced weights must be used if the anchor will be submerged.

Example 4-6: Design of anchor in anchor and column layout

An anchor is set in a silty-sand (friction angle, $\varphi = 27°$, Appendix G). The force on the anchor cable is calculated to be 2084 lbs acting on a 19° angle. The terrain suggests a 4ft by 5ft pad. The anchor will be constructed of concrete (density = 150 lbs/ft^3, Appendix G)

Designing the depth (thickness) of the pad for sliding:

$\Sigma F_x = 0 =$ (SF)(Cable Force)($\cos\theta_A$) – (Normal Force)($\tan\varphi$)

$\Sigma F_x = 0 = (3)(2{,}084 \text{ lbs})(\cos 19°) – (\text{Normal Force})(\tan 27°)$

Normal Force = 11,601.7 lbs

Normal Force = (Weight of Anchor) - (Cable Force)($\sin \theta_A$)

11,601.7 lbs = (Weight of Anchor) - (2,084 lbs)(sin 19°)

Weight of Anchor = 12,280.2 lbs

Weight of Anchor = (Length)(Width)(Thickness)(Density)

12,280.2 lbs = (5 ft)(4 ft)(Thickness)(150 lbs/ft^3)

Thickness = 4.09 ft.

Use 4.25 ft

Check for uplift:

ΣF_x = 0 = (Weight of Anchor) - (SF)(Cable Force)($\sin \theta_A$)

ΣF_x = 0 = (12,750 lbs) - (SF)(2,084 lbs)(sin 19°)

SF = 18.8

This anchor is in no danger of lifting. Sliding is the controlling failure mode in this case. If the safety factor had been less than 3, or another value unacceptable to the engineer, the anchor would have to be resized to compensate.

An alternative method for laying out the anchors is to have two anchors placed at 120 degrees from the span cable. This method is incredibly beneficial for reducing the possibility of buckling as will be shown in the next section. It is important to note that this arrangement will NOT reduce the force on the anchor cable. Even though the force is split between two cables it is not reduced because the forces will be acting out of plane.

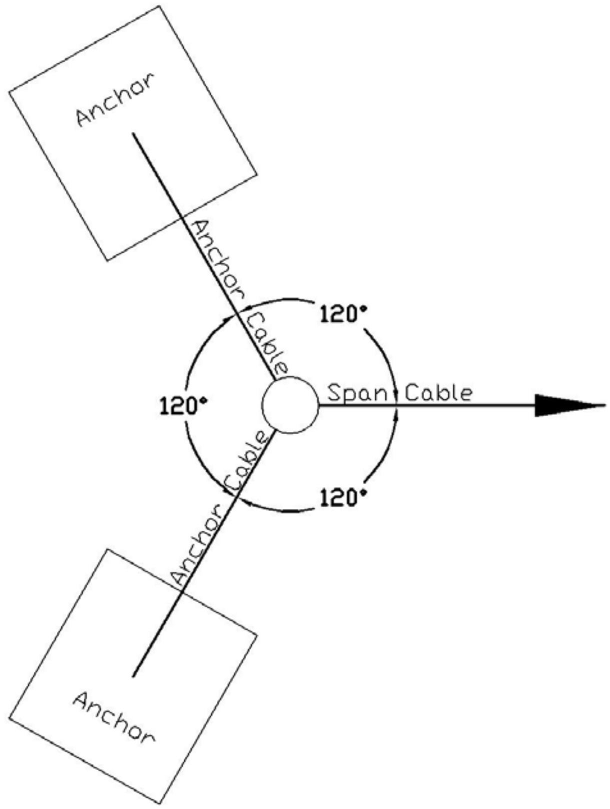

Figure 4-11: Plan view of column with two anchors at 120° angles

4.2.2.1 Concrete Column

A concrete column can be cast in place, prefabricated, or built up by masonry. Either way, the concrete and the reinforcing steel will carry the forces. Reinforced concrete is complicated to design and the quality is often difficult to monitor and control. This section represents a simplified design method based on the Uniform Building Code (UBC). The solutions will be conservative. To simplify further, only columns with a square cross-section will be used. Those designers with more knowledge and experience in civil/structural engineering are welcome and encouraged to refine the designs. Figure 4-11 shows a concrete column and anchor setup constructed near San Jose De Ocoa.

Figure 4-12 A square concrete column and anchor with cable attached. (photo provided by Eric Zalkin)

The failure modes are material failure (crushing or breaking of the concrete, masonry, or steel) and buckling failure. Roughly defined, buckling is the condition where a column fails from bending when only an axial force is applied. Consider a slender column with a large axial force applied. After construction, a minimal, practically immeasurable moment is placed on the column. This could be caused by imperfection in the construction or an additional load such as some one leaning on the column. This moment causes the column to bend slightly. The slight bend causes the axial load to act on the column with a slight eccentricity. This in turn causes another moment, which causes a bigger bend, which causes a bigger eccentricity. This escalates until the column fails catastrophically. These types of failures are sudden and complete. Whether a column will buckle or not is a function of the ratio of height to width, the force applied and the material of the column.

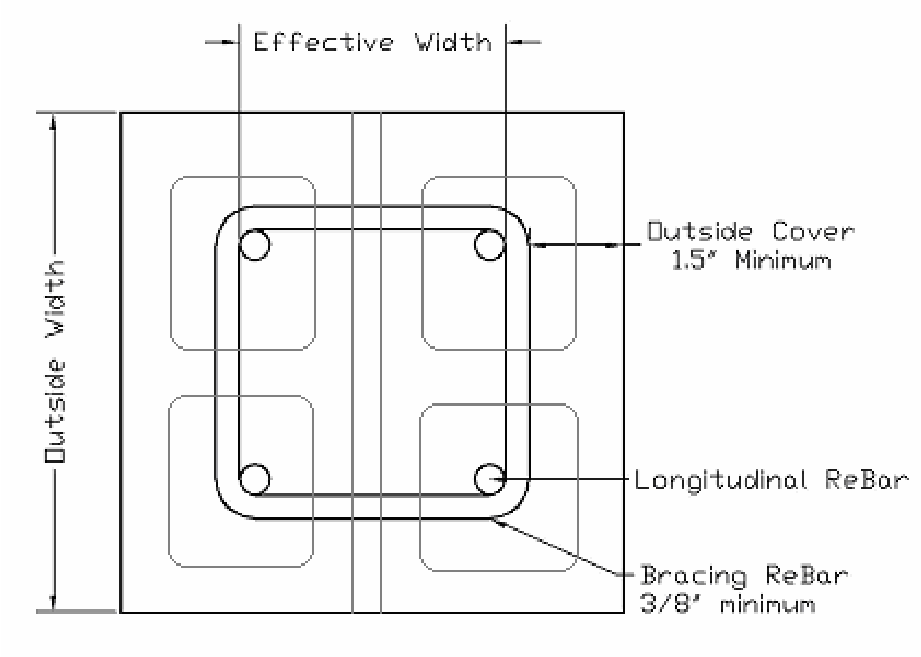

Figure 4-13 Cross section of standard masonry block column showing the effective width.

As shown in Figure 4-12, the Effective Width is considered to be the concrete inside the reinforcing steel. The concrete outside the steel is thin and may break off or crack during extreme loadings, it cannot be counted on for strength and its main function is to protect the steel.

The effective height of a column with regards to buckling considers the actual height of the column and how well it is braced. A column that is not braced out of plane, for example a single anchor and span but no bracing cables like shown in Figure 4-13, will have an effective height of the actual height times two. A column that is braced at the top with cables either with a split anchor layout as shown in Figures 4-9 and 4-15, or a regular set of cables and two guy-cables, as shown in Figure 4-14, will have an effective length of 0.7 times the actual height.

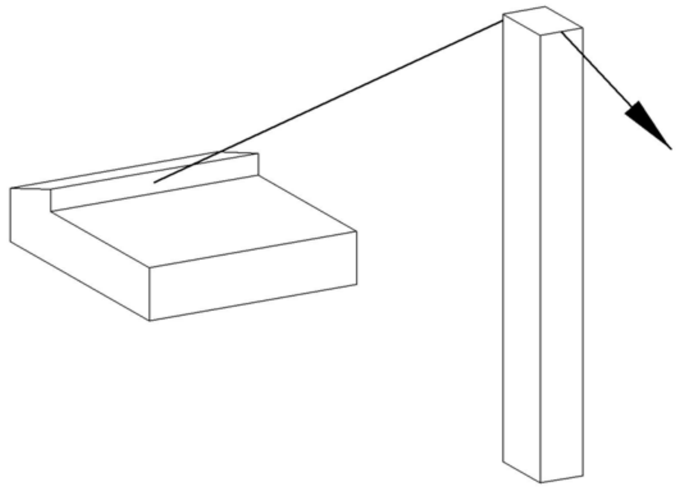

Figure 4-14 Column and anchor set up where the effective length of the column will be twice the column height due to lack of side bracing.

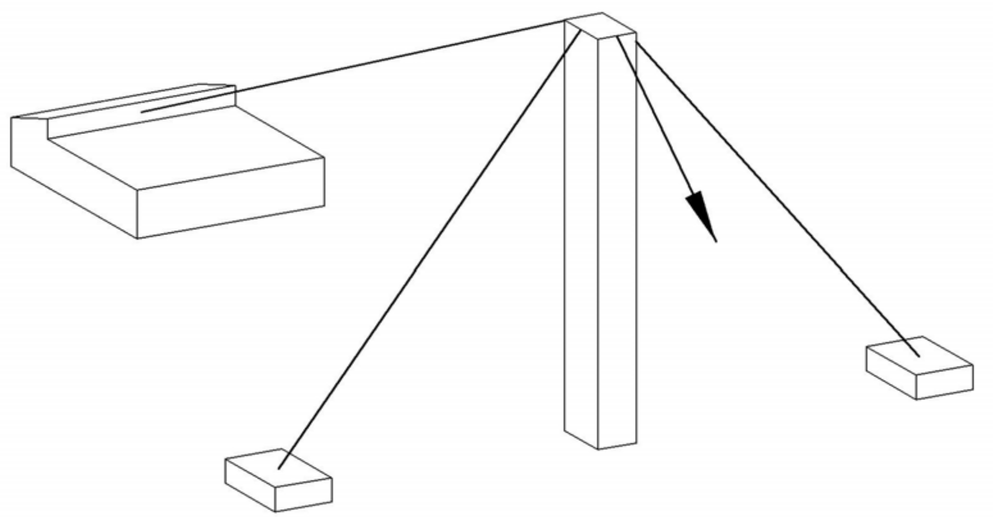

Figure 4-15 Column and anchor set up with two guy cables, which will reduce the effective height to 0.7 of the column height.

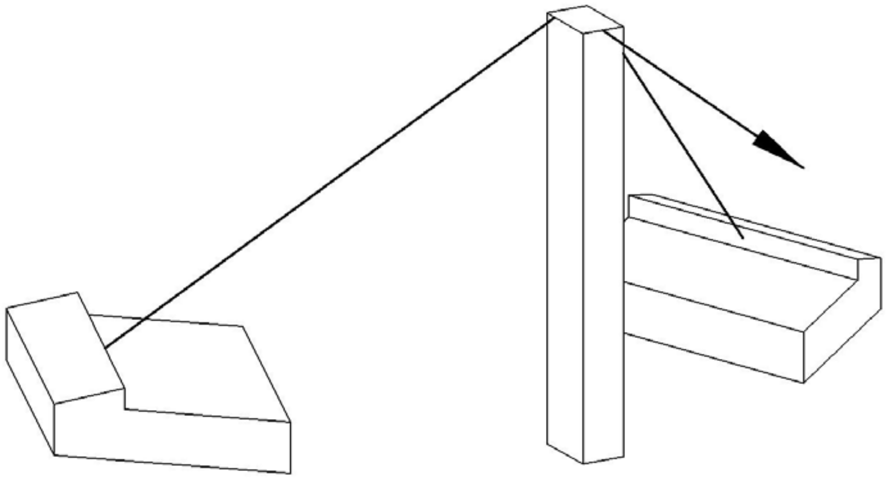

Figure 4-16 Column and anchor set up with split anchors at 120° the column is braced and will have an effective height of 0.7 of the column height

The UBC uses a method where safety factors are used not for the force applied to the structure, but to the materials used. The safety factor applied to the masonry is 4 because it is a non-homogeneous material subject to the skill of the mason. The safety factor applied to the steel is roughly 1.5 because it is a homogeneous material produced under factory conditions and controls. It also takes buckling into consideration.

$$(\text{Allowable Axial Force}) = [0.25(\text{Masonry Strength})(\text{Effective Masonry Area}) + 0.65(\text{Steel Strength})(\text{Steel Area})][1-(\text{Height}/40(\text{Width}))]^2]$$

for Height/Width less than 29

Equation 4-8 Allowable Axial force on non-slender reinforced masonry column

$$(\text{Allowable Axial Force}) = [0.25(\text{Masonry Strength})(\text{Effective Masonry Area}) + 0.65(\text{Steel Strength})(\text{Steel Area})](20(\text{Width})/\text{Height})^2$$

for Height/Width greater than 29

Equation 4-9 Allowable Axial force on slender reinforced masonry column

If an additional bending moment is applied to the column additional rebar can be added to account for this.

$$(\text{Allowable Bending Moment}) = 0.25(\text{Masonry Strength})(\text{Width})^3$$

Equation 4-10 Allowable bending moment on reinforced masonry column

The column will be able to handle both a compression axial load and a bending load together provided the combined load doesn't over stress the column. Equation 4-10 can be used to check the combined load , if the sum of the ratio of applied loads to allowable loads, is less than or equal to one the column will be stable.

$$\frac{\text{(Applied Axial Force)}}{\text{(Allowable Axial Force)}} + \frac{\text{(Applied Bending Moment)}}{\text{(Allowable Bending Moment)}} \leq 1$$

Equation 4-11 Combined Bending and Axial equation for combined bending and axial loads on a column.

Example 4-7: Design of masonry columns

Consider 7 ft tall column. A 1,026 lb axial force is applied at the top and there is no external bracing.

Assume a masonry column 8" x 8". After allowing 1.5” cover and 0.375” for the bracing stirrups on each side, the effective width will be 4.25".

The effective height is 168".

Height/Width = 40.

Masonry compressive strength will be assumed to be 250 lbs/in^2. Based on the guide in Appendix F.

Steel strength will be assumed to be 36,000 lbs/in^2. This is based on the standard strength of steel; rebar is often stronger.

Four 3/8 rebar will be used with a cross sectional area of 0.11 in^2 each.

Using Equation 4-8:

(Allowable Axial Force) = [0.25(Masonry Strength)(Effective Masonry Area) + 0.65(Steel Strength)(Steel Area)](20(Width)/Height)^2

(Allowable Axial Force) =
[0.25(250 lbs/in^2)(18.1 in^2) + 0.65(36,000 lbs/in^2)(0.44 in^2)](20(4.25 in)/168 in)^2

Allowable Axial Force = 2,925 lbs > 1026 lbs

<u>Column is stable.</u>

Consider the same column, but with an axial force of 849 lbs and a bending moment of 238 ft-lbs.

(Allowable Bending Moment) = 0.25(Masonry Strength)(Width)^3

(Allowable Bending Moment) = 0.25(250 lbs/in^2)(4.25 in)^3

Allowable Bending Moment = 4,798 in-lbs

238 ft-lbs = 2,856 in-lbs

$$\frac{(\text{Applied Axial Force})}{(\text{Allowable Axial Force})} + \frac{(\text{Applied Bending Moment})}{(\text{Allowable Bending Moment})} \leq 1$$

$$\frac{849 \text{ lbs}}{2925 \text{ lbs}} + \frac{2856 \text{ in lbs}}{4798 \text{ in lbs}} = 0.89 \leq 1$$

Equation 4-10 is satisfied. The combination of axial and bending force does not overstress the column. Therefore, the column is stable.

4.2.2.2 Pipe Column

A steel pipe column has the advantage of being strong and easy to construct. Because it is pre-made, its strength is not as dependent on the quality of the construction. The most critical failure mode is a buckling failure.

The design method in this section is based entirely on the American Institute of Steel Construction LRFD Design Manual (American Institute of Steel Construction, 1998). The method has been reduced into the following equation with all appropriate safety factors applied.

$$\frac{(\text{Applied Axial Force})}{(0.55)(\text{Critical Axial Force})} + \frac{(\text{Applied Bending Moment})}{(0.60)(\text{Critical Bending Moment})} \leq 1$$

Equation 4-12: Combined Bending and Axial equation for steel pipe column

The values for allowable axial force and allowable bending force have been tabulated for standard pipe sizes in Appendix D. To use the chart find the size pipe selected and then check the critical force listed for the effective height. The values for critical bending moment are provided in Appendix B.

The pipe column uses the same definition of effective height as the masonry column, illustrated in Figures 4-13 to 4-15.

Example 4-8: Design of steel pipe columns

Consider 7 ft tall column. A 1,026 lb axial force is applied at the top and there is no external bracing.

The effective height is 14 ft.

Steel strength will be assumed to be 36,000 lbs/in^2.

Using Equation 4-11:

$$\frac{\text{(Applied Axial Force)}}{\text{(0.55)(Critical Axial Force)}} + \frac{\text{(Applied Bending Moment)}}{\text{(0.60)(Critical Bending Moment)}} \leq 1$$

$$\frac{\text{(1026 lbs)}}{\text{(0.55)(Critical Axial Force)}} + \frac{0}{\text{(0.60)(Critical Bending Moment)}} \leq 1$$

$$\text{(Critical Axial Force)} = 1866 \text{ lbs}$$

Appendix D:

A Standard 2" pipe has a Critical Axial Force at 14 ft of 2945 lbs.

Use Standard 2" pipe

Consider the same column, but with an axial force of 849 lbs and a bending moment of 238 ft-lbs.

238 ft-lbs = 2856 in-lbs

$$\frac{\text{(Applied Axial Force)}}{\text{(0.55)(Critical Axial Force)}} + \frac{\text{(Applied Bending Moment)}}{\text{(0.60)(Critical Bending Moment)}} \leq 1$$

$$\frac{\text{(849 lbs)}}{\text{(0.55)(2945 lbs)}} + \frac{\text{(2856 in lbs)}}{\text{(0.60)(20183 in lbs)}} \leq 1$$

Column is stable.

4.2.3 Integrated Column and Anchor

An integrated column and anchor is nothing more than an efficiently designed concrete mass that is heavy enough to withstand the forces applied and tall enough to supply the required sag. These are the simplest form of anchor. The main failure modes are overturning or sliding. Overturning occurs when force of the cable causes the back of the anchor to lift off the ground. Sliding occurs when the force of the cable causes the entire anchor to shift forward.

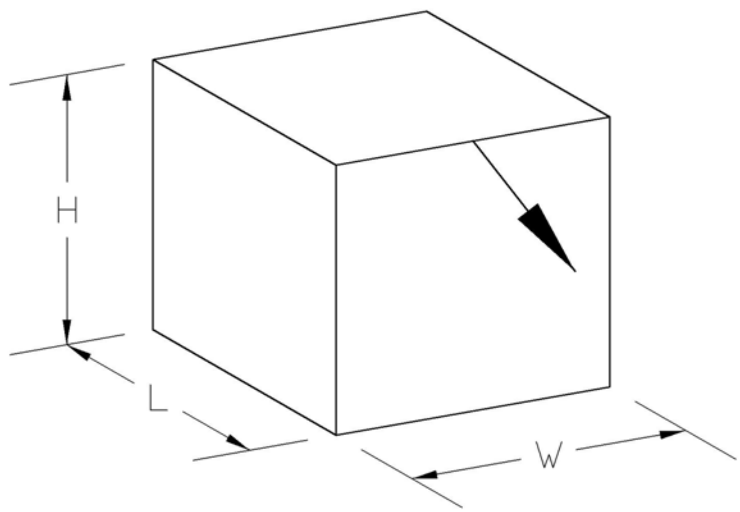

Figure 4-17 Simple block anchor mass with dimensions used in design equations.

The block anchor, as illustrated in Figure 4-16, works best in steep banks where the anchor can be mostly or entirely buried. In this case it amounts to simply digging a hole to the required dimension, placing the reinforcing and filling the hole with masonry. The cable is attached to a rebar loop sticking out of the anchor.

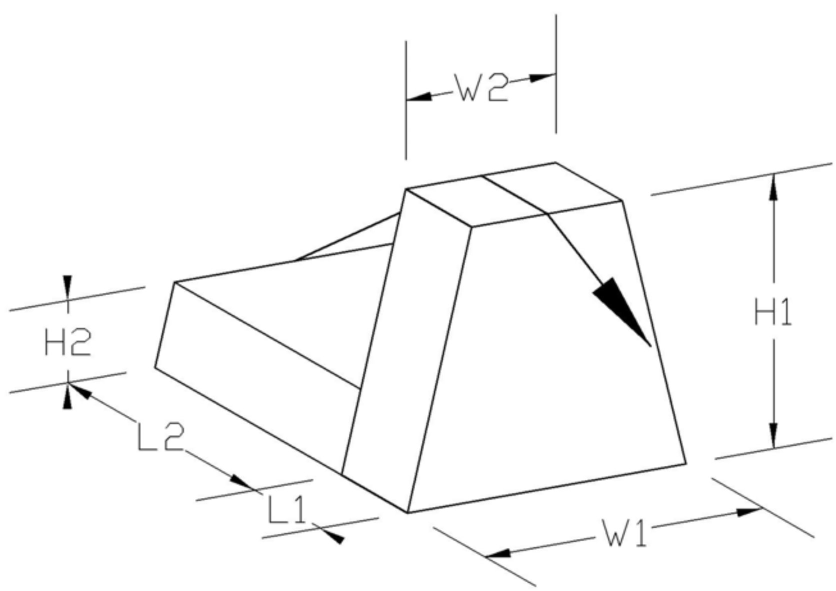

Figure 4-18 Tower and slab type anchor mass with dimensions used in design equations.

The tower and slab type anchor, as illustrated in Figure 4-17, fits best in canyons with sudden drop offs and mostly flat building surfaces. The cable passes up over the tower and then attaches at the back to a rebar loop.

Figure 4-19: A tower and slab type anchor mass constructed of native limestone rubble and covered with a coat of cement plaster.

The stability of either anchor is analyzed by simple balancing of forces. To check for over turning, balance the moments. To check for sliding, balance the forces in the horizontal. A safety factor of 2 to 3 is recommended depending on the construction. Rubble masonry tends to be less uniform and often has large voids while pure concrete is more uniform.

Example 4-9: Design of mass block anchor

An anchor is needed with a 2.75 ft. tower. The anchor is subject to a cable load with a vertical component force of 268.3 lbs and a horizontal component force of 1,984.5 lbs. Soil conditions suggest setting the base of the anchor at least 1.5 ft bellow the surface on a solid sand layer.

Choosing a simple block and anchor mass. The anchor will be buried to 1.5 ft, this gives the anchor a height (H) of 4.25 ft. Width (W) is chosen as 3 ft. Design the required length for a stable structure. See Figure 4-13 for illustration.

Summing the moments around the front bottom edge:

$\Sigma M = 0 =$ (Horizontal Force)x(H)x(Safety Factor) –

(LxWxHx(Weight of Mass per cubic foot))xL/2

$\Sigma M = 0 = (1985 \text{ lbs})x(4.25 \text{ ft})x(3) -$
$(Lx\ 3 \text{ ft } x\ 4.25 \text{ ft } x(150 \text{ lbs/ft}^3))xL/2$

$(1985 \text{ lbs})x(4.25 \text{ ft})x(3) = (Lx\ 3 \text{ ft } x\ 4.25 \text{ ft } x(150 \text{ lbs/ft}^3))xL/2$

$(1985 \text{ lbs})x(4.25 \text{ ft})x(3) = (Lx\ 3 \text{ ft } x\ 4.25 \text{ ft } x(150 \text{ lbs/ft}^3))xL/2$

$25{,}308.75 \text{ ft-lbs} = 956.25 \text{ lbs/ft } x(L^2)$

L = 5.14 ft

Use <u>5.25 ft</u>

Check for sliding:

$\Sigma F_x = 0 =$ (SF)(Horizontal Force) – (L)(W)(H)(Weight per cubic foot)(tan φ)
– (Vertical Force)

$\Sigma F_x = 0 = (SF)(1985 \text{ lbs}) - (5.25 \text{ ft})(3 \text{ ft})(4.25 \text{ ft})(150 \text{ lbs/ft}^3)(\tan 29°) - (268 \text{ lbs})$

Safety Factor = 2.9

<u>The mass is stable.</u>

The same anchor is redesigned as a tower and slab type anchor:

Using the dimensions and labels used in Figure 4-17. H1 = 4.25 ft; H2 = 2 ft; W1 = 3 ft; W2 = 1.5 ft; L1 = 1.5 ft; Design the required L2 for a stable structure.

$\Sigma M = 0 =$ (Horizontal Force)(H1)(Safety Factor)
$- ((W1+W2)/2)(L1)(H1)(\text{Weight/ft}^3)(L1)/2 + (W1)(L2)(H2)(\text{Weight/ft}^3)(L1+(L2)/2)$

$\Sigma M = 0 = (1985 \text{ lbs})(4.25 \text{ ft})(3)$
$- ((3 \text{ ft} + 1.5 \text{ ft})/2)(1.5 \text{ ft})(4.25 \text{ ft})(150 \text{ lbs/ft}^3)(1.5 \text{ ft})/2$
$- (3 \text{ ft})(L2)(2 \text{ ft})(150 \text{ lbs/ft}^3)(1.5 \text{ ft} + (L2)/2)$

$\Sigma M = 0 = 25{,}308.75 - 1{,}613.67 - 1{,}350(L2) - 450(L2)^2$

$\Sigma M = 0 = 23{,}695.08 - 1{,}350(L2) - 450(L2)^2$

Applying the quadratic equation (Appendix G):

L2 = 5.91 ft

Use 6 ft

Check for sliding:

$\Sigma F_x = 0 = (SF)(\text{Horizontal Force})$
$- (((W1+W2)/2)(L1)(H1) + (W1)(L2)(H2))(\text{Weight}/ft^3)(\tan \varphi) - (\text{Vertical Force})$

$\Sigma F_x = 0 = (SF)(1985\ lbs)$
$- (((3\ ft + 1.5\ ft)/2)(1.5\ ft)(4.25\ ft) + (3\ ft)(6\ ft)(2\ ft))(150\ lbs/ft^3)(\tan 29°) - (268\ lbs)$

$\Sigma F_x = 0 = (SF)(1985\ lbs) - (4454\ lbs)$

Safety Factor = 2.2

The mass is stable because all resisting forces are greater than the applied forces with an adequate safety factor.

In comparison, both masses withstand the same forces with comparable results, but through the efficient placement of material the simple mass uses 67 ft^3 of material while the tower and slab uses only 51 ft^3 of material.

5 Field Layout and Construction

Once all the calculations are complete, the hard part begins, taking what looks great in pencil and paper and making it work with concrete and steel. The design is only as good as the construction that follows it. The design techniques outlined above make many assumptions about the quality of construction. They assume that all pieces will be well constructed and joined. The construction details in this chapter are based entirely on experience and are provided to help assure that the assumptions made in the design process are valid.

It is preferable that construction is taken into consideration throughout design. It is assumed that basic construction techniques are understood and followed. The following chapter outlines tips and tricks specific to building cable crossings.

Construction of a crossing usually begins when the pipeline has reached the canyon. This makes things much easier in that the water from the aqueduct can be used to mix the concrete on site rather than hauling it from far away.

This type of work is generally easier in a smaller group of six to seven. It's fairly technical and work that can't be taught to just anyone. If working in large groups it is often advisable to send some workers off to dig pipeline while a smaller group remains to work on the crossing.

5.1 String line, Right Angles

A string line is the easiest method for laying out the construction. If the original survey stakes remain these can be used as a guide. If not, two new benchmarks will have to be staked and measured with the string method from Section 3.3.2.

The staked out strings will keep all the parts in line. It is crucial that the both abutments are in a line. If they are crooked it will cause out-of-plane horizontal forces, which may not be accounted for.

5.2 Building of the Anchors: Tips and Tricks

The following sections describe various methods for constructing the designs outlined in this report. This is also where suggestions for design details are made. In some cases the details described in this section will be vital to the structural integrity of the crossing.

On the subject of curing concrete; it would be easy to say that all concrete must be cured for a full twenty-eight days. To anyone who has worked in the extreme conditions and locations often involved in community aqueducts located in the developing world, it is known that this is easier said than done. The designer will know what is feasible for the location and when the load will need to be applied to the structure. It is better to design for an under cured concrete strength rather than lose a structure because someone forgot to hike up in the mountain everyday for a month. It would however, be irresponsible to allow the concrete to dry out before at least three days of curing. See Appendix F for more detail on concrete strengths and curing.

All mortar referenced in the following sections is assumed to be a Portland cement based mortar, not a lime mortar. Additional lime is acceptable, and can greatly improve the workability and therefore the final product. However, lime should not be the primary cementing agent because it is not as strong as Portland cement.

5.2.1 Single Post

The most important detail in a single post anchor is to ensure that the block mass is solid and rigidly connected to the post. The rebar detail shown in Figure 5-1 shows how the block mass is connected to the post. The spacing on the rebar grid should be no greater than 12 inches and all intersections should be tied.

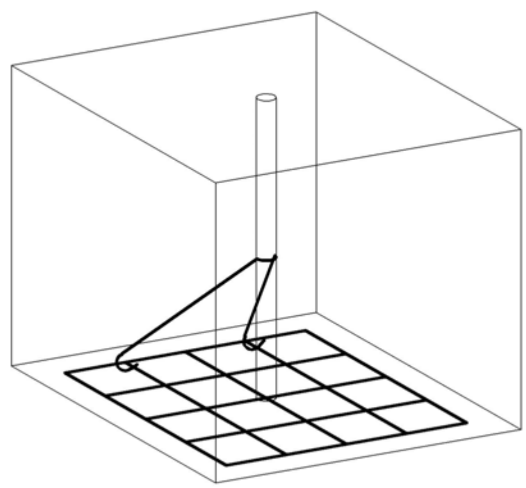

Figure 5-1: Rebar detail of single column block mass

Large rocks from the area are often used to fill out the mass and conserve cement. If rocks are used they should be clean and clear of dirt and should not be placed next to the rebar. All rebar should be surrounded by concrete to ensure a good bond.

If the column is to be filled with concrete it is advisable to do this ahead of time for convenience and then tip up the tube. If the tube is to be filled often extra rebar is placed in the bottom of the tube and bent over. This rebar can be connected to the base grid to improve the connection.

When laying the rebar in the bottom of the foundation hole lift the rebar off the soil by placing it on small (2” diameter) rocks. This will let the concrete surround the rebar when placed. Laying a 4 to 6 inch bed of gravel down first also helps by allowing the foundation to bear on the stiffer gravel rather than the native soil..

5.2.2 Column and Anchor

In this type of anchor, set up it is vital on the structural integrity of the structure. The column, no mater what type of construction, will be more difficult to line up. It is preferable to place the column and then lay out the anchor based on the true alignment of the column and not the planned alignment.

A suggested rebar detail for the anchor unit is shown in Figure 5-2. The size of the pad can be reduced if the pad is covered with something, such as rock, that can provide the required dead weight. It is suggested by this author to have a pad at least one foot thick. As a bonus to the rock topping it can be used to cover up the cable hardware, which will make it less vulnerable to both malicious intent and the curious hands of children.

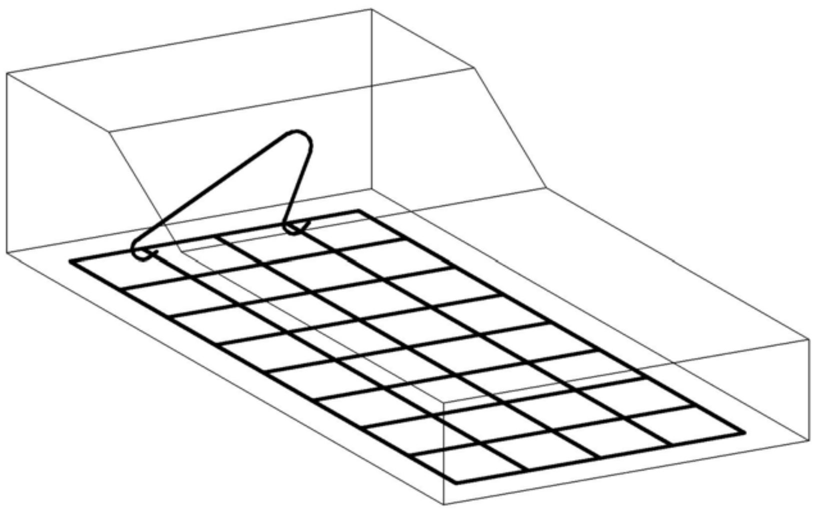

Figure 5-2 Rebar detail for anchor mass.

5.2.2.1 Concrete Column

Concrete columns can be built up with masonry units, cast in place, or cast on the ground and then tilted up into place. An in-place pour is NOT recommended because the resulting column will be tall and thin and extremely difficult to construct. The formwork will be difficult and it is difficult to impossible to maintain a consistent mix throughout the column if the concrete is dropped in from the top. A better solution is to construct the column on the ground and then tip it into place once it is cured.

The formwork can be expensive, but can also be reused. To space the rebar in the center of the form a common technique is to hang the rebar cage from the forms. Nails are driven into the tops of the forms and tie wire is used to suspend the rebar in the center of the mold. Once the concrete is placed and the voids are shaken or pounded out of the formwork the tie wire can be taken off of the forms and bent over into the semi-wet concrete. Timing is important, too soon and the concrete isn't solid enough to keep the rebar in place, too late and the concrete is too hard to push the wire in. It's better to err on the dry side if the wires can't be forced in the worst thing that happens is that they stay out and are a little unattractive.

The bracing rebar, also called stirrups or column ties, should be bent sharply and cleanly. The tie should over lap at a corner at least two inches in each direction. They should be spaced at a distance no greater than the width of the column. Stirrups can sometimes be purchased at common sizes. It is more important that all the ties be uniform than to a specific size.

If the stirrups are to be made on site a rebar bender is an invaluable tool. A rebar bender, shown in Figure 5-3 is constructed of a 12 to 18 inch length of angle iron with sides of at least one inch. Pegs are welded to one leg of the angle iron. The pegs are evenly spaced from each other and are placed just far enough from the back leg of the angle iron to allow a piece of rebar to fit. One way to get a good weld on the pegs is to drill holes in the angle iron. The square pegs are fit inside the round holes and the extra space is filled with weld metal. Often additional holes will be drilled in the back of the bender so that it can be nailed to a tree or a wall. This will make it even easier to bend good sharp corners. It is likely that a weld shop has built these before and will know exactly what to do without direction.

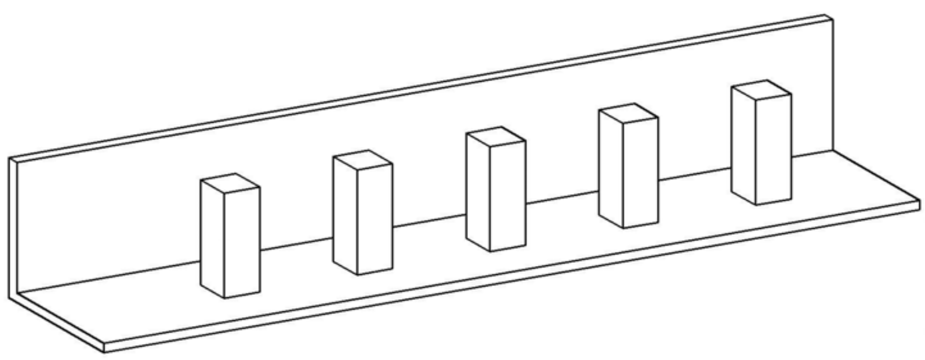

Figure 5-3 Rebar bender constructed from angle iron and evenly spaced pegs.

To bend sharp corners use a small (12 inch) galvanized tube. Half-inch tube works the best for 3/8's rebar. Don't expect to use the tube for anything else as the threads will be destroyed on the bending side. First bend a little corner, this corner will then hook on the peg that corresponds with the size needed. The next corner is bent and the stirrup moves around in a circle. See Figure 5-4 for illustration. Even if the sides of the square aren't exactly the size specified, it is better to choose an easily reproducible size and have all the stirrups be identical.

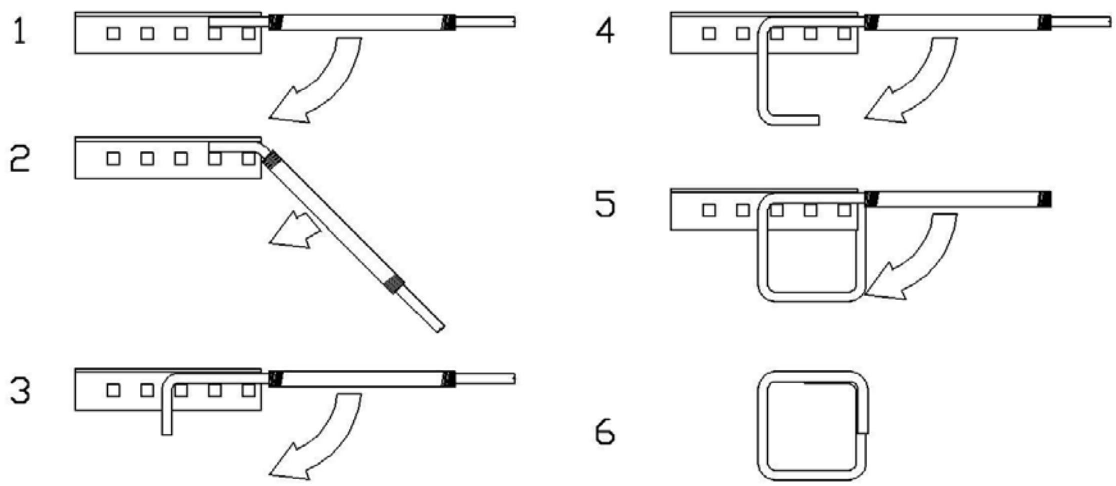

Figure 5-4 Technique for bending square stirrups.

5.2.2.2 Pipe Column

If a different tension is to put on the anchor cable than the span cable a turnbuckle will have to be used to adjust the tension. The easiest method to get the correct tension on the cables is to use a level on the column.

The point of adjusting the tension in the anchor cable is to eliminate the bending force. If the bending moment is eliminated the column will not bend. If the column is vertical when it was installed and vertical after the cable forces are applied, then the bending moment has been effectively eliminated.

Take a small level and attach it to the column where it can be seen. If the column isn't level to begin with adjust the level with a shim so it reads level. The object is not to straighten the column but to keep it the same. As the span cable is loaded with the tubes and later filled with water, adjust the turnbuckle on the anchor cable to keep the column from bending.

If the column is not plumb (out of plane) it is highly recommended that additional guy-wires be added to the design, as shown in Figure 4-14. These additional anchors and cables will also be adjusted to re-plumb the post in the same manner.

It is of course best to keep the column as vertical as possible during construction. Often one person is assigned with this specific task as shown in Figure 5-5.

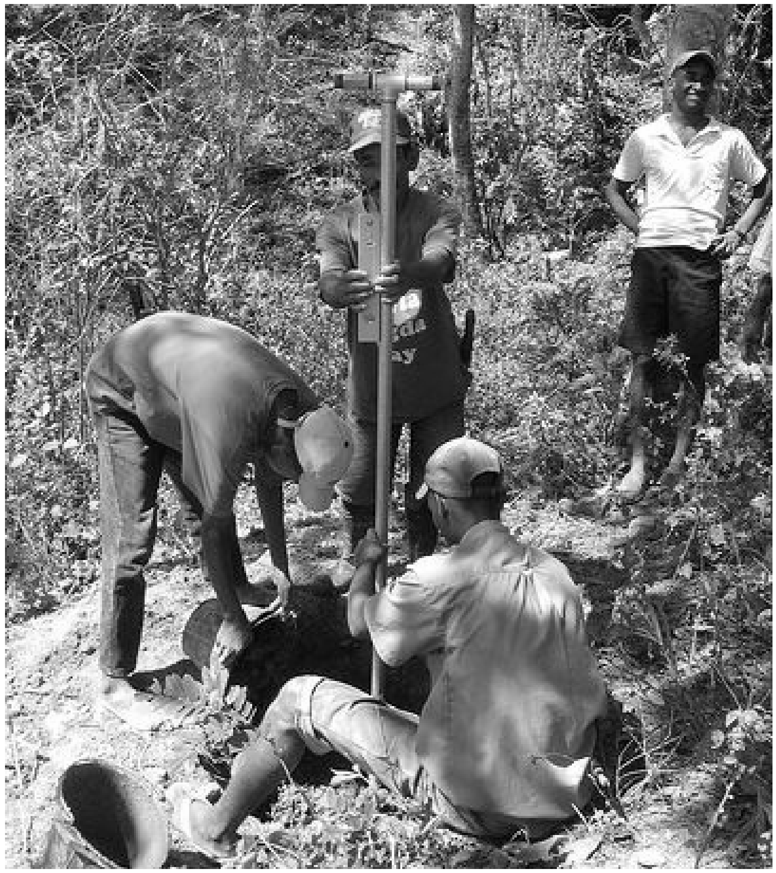

Figure 5-5: Workers fill excavation with concrete while the column is checked for plumb (photo by Kristina Katich).

5.2.3 Integrated Column and Anchor

Using stone masonry for an integrated column and anchor is an incredibly economical solution. The stones reduce the amount of concrete needed and eliminate the need for forms. Large, flat masses are easy and can be built by practically anyone. Taller masses require a more skilled hand. Stones will fall off of each other before the mortar cures and making tall stacks can cause disastrous failures during construction. One solution is to create a rebar cage that can be filled with mortar and stones. The rebar will hold every thing in place while the mortar cures. With this method moderately skilled workers can build an anchor in just a few days of work.

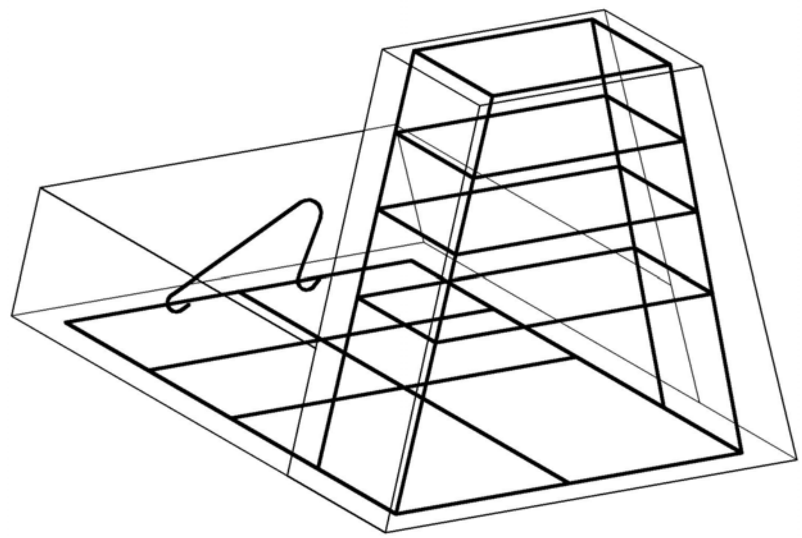

Figure 5-6 Typical rebar layout for anchor and column unit built with stone masonry.

Figure 5-6 shows a rebar layout that has been used successfully in the past. All bars are 3/8 inch with the exception of the rebar stirrups that wrap the column; these are 1/4 inch. The rebar cable attachment and the rebar in the bottom is the only rebar that is really structurally significant. The rebar in the column is primarily used to hold in the stones while the mortar sets. The rebar provides a great construction guide the builder only has to align the stones with the rebar and fill in the voids with mortar.

The rebar on the outside of the column will be exposed and must be covered to prevent corrosion. Even though the strength of the column does not depend on the rebar, corroding rebar expands and can destroy the concrete. A cover of mortar plaster can help. Sometimes the mortar mix will stick directly to the column. If the column is more irregular, a smooth finish will require a thicker layer of mortar. A wrapping of chicken wire or some other form of wire fabric will help thicker layers to stick. The thinnest, cheapest chicken wire available will be fine and provide the structure with a solid topcoat.

5.3 Preparing the Ground

Before the cable and pipes are placed, the trench where the pipes will enter the ground must be dug. It is best to wait till after the anchors are completed as to not have to work around a deep trench and to make sure it ends up in the right place.

A string pulled tight from anchor to anchor provides an excellent guide. By measuring from the string to the bottom of the trench the correct depth can be assured. Usually this is the sag value plus another 12 to 18 inches to allow for the stringers and let the pipe swing free.

The string will also make sure that the trench is straight. How far the trench extends horizontally depends on how far galvanized pipe is to be embedded into the ground. It's a good idea to allow an additional two to three feet to have enough room to put the connections together.

5.4 Final Cable Adjustment

The placement of the cable is key to the integrity of the bridge. Because it is a fine measurement, it is important to re-measure and recalculate the cable dimensions. Often a crossing will use a turnbuckle to place a fine adjustment on the cable. Even if this method is used, the cable will still need to be close enough to the final length that the turnbuckle will be able to finish it.

The anchors will need to be re-measured. Use the string method and measure directly from one fixture point to another. Re-measuring the anchors will account for any construction irregularities.

5.4.1 Calculating Stringer Length

The stringers tie the pipe to the main cable. Stringers usually consist of a thin (3/16 in diameter or smaller) steel cable doubled over at the top with two cable clamps around a cable eye and a double loop around the pipe secured with two more cable clamps.

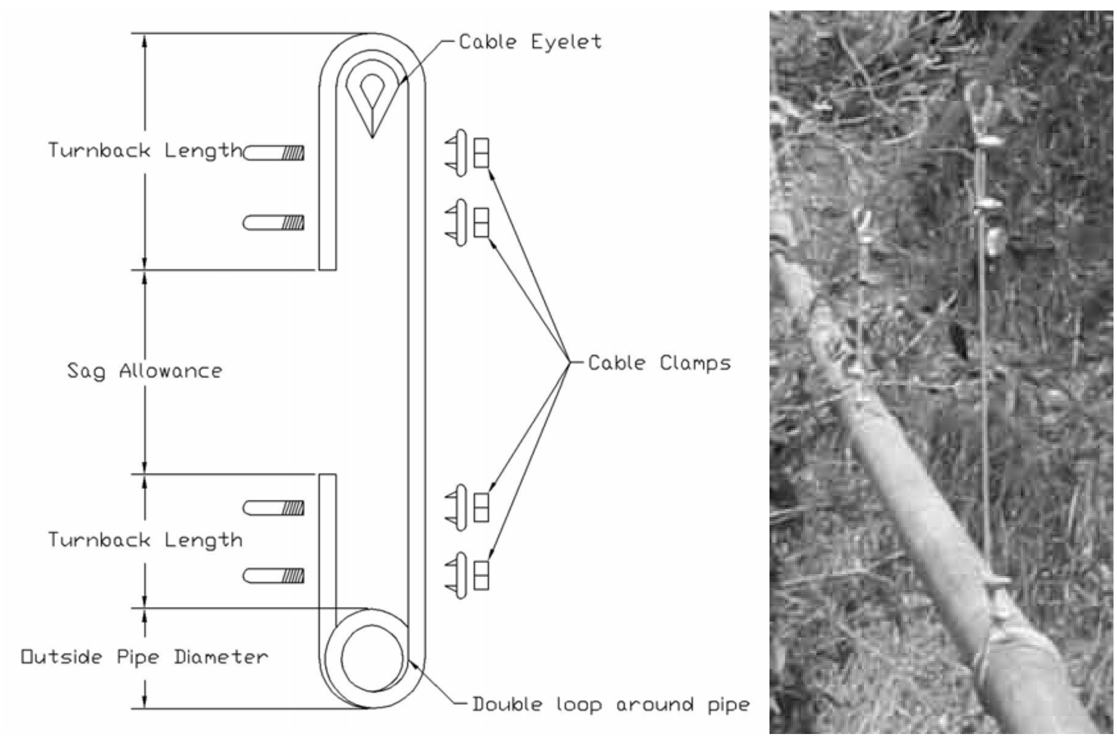

Figure 5-7 Exploded view of typical stringer and photo of actual stringer in place.

The cable will be wrapped around the tube. For the ease of construction it is advisable to spend a little more on the stringer cables. Cables with more flexible weaves cost a little more. Stainless steel cable is also easier to work with than galvanized or plastic coated cable. Stainless steel cable and high strand flexible cables are more expensive but for the small diameters and quantities used in the stringers the added ease of construction is almost always worth the extra money. One-eighth inch stainless steel is plenty strong to handle any size tube, but it looks thin. Be prepared to have people balk at the size of the cable. Three sixteenths isn't usually that much more expensive, and could be advisable for two inch pipes and above.

The stringers are most often cut and prepped the afternoon before the main cable and pipes are installed. The length of each stringer will be the length needed to compensate for the sag plus enough cable to attach to the main cable plus the enough cable to wrap twice around the pipe.

The turn back lengths will be determined by manufactures' recommendations based on cable diameters (see Appendix A) or by what is considered practical by the engineer. The sag allowance will be determined using Equation 4-1. Equation 4-1 uses a 'C' value determined by one of the methods outlined previously. The 'X' value will be the distance from the apex.

Example 5-1: Calculating the Length of the Stringers

Assume the design outlined in Example 4-2 was built, a 140 foot span with a sag of 7.5 feet. When the anchors were completed and re-measured it was discovered that the span is now 142.5 feet from fixture point to fixture point.

Using the new span length and original sag the sag ratio (sag divided by span) is 0.0526. To use the chart (Appendix C) it is bumped down to 0.052, the closest value calculated. This corresponds to a sag of 7.41 feet and a 'C/L' value of 2.412463. Multiplying by the length yields a 'C' value of 343.7760.

Stringers will be placed a 5, 15, 25, 35, 45, and 55 feet from the apex.

Using Equation 4-1:

$$y = C \cosh\left(\frac{x}{C}\right) - C$$

$$y = 343.776 \cosh\left(\frac{5\ \text{ft}}{343.776}\right) - 343.776$$

$$y = 0.0364\ \text{ft}$$

Continue for the other stringers.

Distance Sag Allowance

5	0.0364
15	0.3273
25	0.9094
35	1.7832
45	2.9494
55	4.4091

Because there is no stringer at the center, which would have a zero sag allowance, the lowest value is set to zero and the other values are reduced by the same amount. Subtracting the same amount from every stringer raises the pipe.

The stringers will be cut to a length that includes the sag allowance, the turnback lengths, enough to wrap twice around the pipe, and enough to go around the eyelet. For a 1/8" cable the recommended turn back length is 4". Allow for two lengths at the top and two at the bottom. An additional 4" is added to go around the eyelet and two pipe circumferences is 15.71". This totals 35.71" extra cable for connections.

Distance	Sag Allowance	Normalized	In inches	With connections
5	0.0364	0	0	35 11/16
15	0.3273	0.2909	3 8/16	39 3/16
25	0.9094	0.873	10 8/16	46 3/16
35	1.7832	1.7468	20 15/16	56 11/16
45	2.9494	2.913	34 15/16	70 11/16
55	4.4091	4.3727	52 8/16	88 3/16

Another method is to simply wrap a cable around the eyelet and a tube of the same diameter. The most important part is not the calculated length, but that all the connections are the same.

5.4.2 Calculating the Final Cable Length

Cable stretches under tension. The design calls for a certain sag over a certain distance. A cable marked to length on the ground without tension and then placed under tension will elongate. The longer cable will have a higher sag which means the stringers will be too short towards the banks. This will cause unnecessary and unaccounted for force on the pipes and changes the geometry of the crossing.

All of this is to be avoided by marking the cable on the ground at a length that, when placed under the weight of the fully loaded pipes, will stretch to the correct length for the given span and sag.

The first step is to find the average force in the cable. As mentioned in Section 2.1.1 the force changes from a purely horizontal force at the apex to a combination of vertical and horizontal force at the fixture point. Although it is not technically correct, it is well within the acceptable error to take the average of these two forces.

What makes steel cable more challenging to design with is that it stretches at two rates. It stretches more at the beginning as the individual strands tighten around each other and then at a lesser rate as the strands themselves stretch. These two rates depend on the weave of the cable. The first rate occurs at roughly 0 to 20% of the failure load the second occurs between 21 to 65% of the failure load.

$$\text{Proportional Change in Length} = \frac{(20\%\text{ of Minimum Breaking Strength})}{(\text{Steel Area})(13500000\text{psi})} + \frac{(\text{Total Load}) - (20\%\text{ of Minimum Breaking Strength})}{(\text{Steel Area})(15000000\text{psi})}$$

Equation 5-1 Proportional Change in Length for Steel Cable (Wire Rope Technical Board)

$$\text{Starting Length} = \frac{\text{Final Length}}{1+(\text{Proportional Change in Length})}$$

Equation 5-2 The Starting Length in relation to the Final Length

To find the length at which the cable must be at before the tension is applied is found by first calculating the arc length for the curve, Equation 2-4, and then use Equations 5-1 and 5-2.

Example 5-2: Calculating the Untensioned Length of the Main Cable

Continuing with Example 5-1, a 142.5 foot span with a sag of 7.41 feet and a 'C' value of 343.7760. 7X7 3/16's inch cable will be used to support 2 inch galvanized pipe over the crossing.

Using Equation 2-4:

$$y = C \sinh\left(\frac{x}{C}\right)$$

Where y is the arc length from the apex to a distance, x. Remember that for a level crossing apex to fixture point is half the total length.

$$y = 343.7760 \sinh\left(\frac{71.25\text{ ft}}{343.7760}\right)$$

y = 71.76 ft

The total length between fixture points would be 143.52

Equations 3-1 to 3-3 estimate Total Tension (the tension in the cable at the fixture point) and Horizontal Tension (the tension at the apex).

Horizontal Tension = 1,312.6 lbs.

Total Tension = 1,340.0 lbs

The average of these is 1326.3 lbs.

Using Equation 5-1:

$$\text{Proportional Change in Length} = \frac{\text{(20\% of Minimum Breaking Strength)}}{\text{(Steel Area)(13500000psi)}} + \frac{\text{(Total Load) - (20\% of Minimum Breaking Strength)}}{\text{(Steel Area)(15000000psi)}}$$

$$\text{Proportional Change in Length} = \frac{740\text{lbs}}{(0.0166\text{in}^2)(13500000\text{psi})} + \frac{(1312.6\text{lbs.}) - (740\text{lbs.})}{(0.0166\text{in}^2)(15000000\text{psi})}$$

Proportional Change in Length = 0.005602

Using Equation 5-2:

$$\text{Starting Length} = \frac{\text{Final Length}}{1+\text{(Proportional Change in Length)}}$$

$$\text{Starting Length} = \frac{143.52\text{ ft}}{1+(0.005602)}$$

Starting Length = 142.72 ft.

Mark the cable at 142.72 ft and then attach it so that the marks are exactly on both fixture points. The sag will be less than the final sag, but when the pipes are placed, and full of water, it will stretch to the final position.

An alternate method to setting the cable to the correct length is the pre-sag method. It has been learned through experience that this method produces better final results for bridges where the anchors are uneven and where the force on the cable is closer to the 20% loading condition.

In this method the final length of the cable and the unstretched length of the cable are calculated in the same manner as above. The sag is then back calculated based on the length of the cable with only the weight of the cable applied. Before the cable is placed, a string is run from one anchor to another at the elevation of the new sag and pulled tight. The cable is placed and adjusted until it just touches the guide string. This is where the cable should be before the pipes are placed. Unfortunately there has not yet been a method developed to calculate this method without a numerical solver.

This method is very rough and makes assumptions that are known to be invalid. For example, it is assumed that all the forces are calculated based on the geometry in the final position when it is know that the cable will ride higher without the weight of the pipes. Nevertheless, experience has shown that this method produces better results in these conditions. The method does not work with lower sag ratios and higher tensions where the unstretched length approaches the span length.

Example 5-3: Calculating the Unloaded Sag

The previous calculations show that the unstretched length of the cable is 142.72 ft. If a cable of this length is strung between the two fixture points it is possible to find the sag using Equation 2-5 and Equation 5-1.

$$y = C \sinh\left(\frac{x}{C}\right)$$

The distance x, the distance between the apex and the fixture point, will remain unchanged. The arc length will be half of the unstitched cable length.

$$71.36 \text{ ft} = C \sinh\left(\frac{71.25 \text{ ft}}{C}\right)$$

Solve for 'C' using a numerical solver.

$$C = 740.4672$$

With this new 'C' value a new sag can be calculated using Equation 2-4.

$$y = C \cosh\left(\frac{x}{C}\right) - C$$

$$y = 740.4672 \cosh\left(\frac{71.25 \text{ ft}}{740.4672}\right) - 740.4672$$

$$y = 3.42 \text{ ft}$$

Based on this estimate, the cable alone should hang 3.42 ft below the fixture points. When the pipes are placed and filled with water the cable will stretch and lower to a sag of roughly 7.4 ft

5.5 Attaching the Cable and Pipes

Once all the cable lengths are calculated, both for the stringers and the main cable, the cables and pipes can be attached. It is recommended that this step takes place all in one day so that the crossing is secured as soon as possible. Leaving the cables and the tubes hanging loose over night is inviting trouble. Even if the crossing is small, and the work is minimal, problems can arise. It is suggested that as much prep work is done ahead of time as possible. This includes preparing the stringers, measuring the cable, any calculations and the transport of heavy materials such as the pipes. The method is very quick and if all goes well can take less than an hour or two. But, if only an hour or two is allowed for construction the engineer could find themselves up in the mountains after dark struggling with a tired and grumpy work brigade.

The stringers should most definitely be prepared ahead of time. The best prep for the stringers that allows for the quickest assembly on the day of construction is to set all cable clamps but one.

First the top two cable clamps that hold the eyelet in are set at the correct turn back length. This is easiest if the bottom clamp is set first and tightened, then the upper clamp is placed directly above it but loosely. The eyelet is placed and the second cable clamp is slid up to hold it and tightened.

The bottom of the stringer is then set for the correct sag allowance. The top cable clamp is set tightly and the second is placed loosely. During construction, the double loop can be slid around the tube and the second cable clamp is slid down tight and secured. This way only one cable clamp needs to be tightened in the field and all the distances are measured and set in advance.

When attaching the cable clamps it is important to know which way they go. The cable clamp has two main parts, the staple (the horseshoe shaped bolt, or U-bolt which the nuts attach to) and the saddle (the cast steel part with the two holes in it). A cable which has been turned back and clamped to itself also has two parts; the cable which supports the load, known as the live cable, and the cable which was turned back, known as the dead cable.

The saddle always goes on the live cable as shown in Figure 5-8. The saddle grips the cable smoothly while the staple tends to pinch or bend the cable it's attached to. A way to remember this is with the phrase "Never saddle a dead horse!"

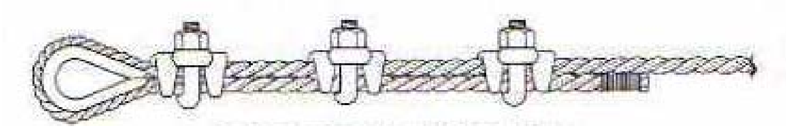

Figure 5-8: Correct Placement of Cable Clamps (Wire Rope Technical Board)

The Wire Rope Technical Board suggests using two cable clamps for all cable smaller than ½ inch and three cable clamps for ½ inch up to ¾ inch cable. It is recommended here that three cable clamps are use for ¼ inch cable and above and that an extra cable clamp is used anywhere a connection can be reached by curious hands.

The most effective method found for placing the cables is to place the main cable and then slide the pipes out one by one from a side. The main cable is threaded through the stringers before it is secured. The first stringer is then attached to the first pipe and the pipe is pushed out into the canyon. The next pipe is screwed in and secured to the stringers. The pipes continue to be pushed into the opening until the final pipe is in place and the bridge spans the distance.

Figure 5-9 Two Dominican construction technicians attach a galvanized pipe to the main cable. (photo by Eric Zalkin)

Figure 5-10 Pipes are connected while a crew waits to push out the next length. (photo by Eric Zalkin)

For longer spans with thinner tubes it is recommended that the pipes be pulled from the far side with a rope as well as pushed. This will help to keep the pipes from bending or buckling under the force.

To prep the pipes, attach a coupling to the one end and check the threads to assure they are clean and straight and will screw in smoothly. Mark the tubes with the cable placement, usually every ten feet, which would be directly in the middle of the pipe, with either a scratch of a file or a strip of tape. Tape is easier to see.

Before pushing out the first pipe, cover the opening with a cloth and secure it. The pipe may bang into the ground when it reaches the other side. If the pipe gets dirt in it, it will be very difficult to impossible to clean it out once the pipes are in place.

5.6 Finishing Touches

There are some small details that can be added to a crossing to help not only the crossing, but also the effectiveness of the whole aqueduct.

Plastic pipes are vulnerable where they connect to steel pipes. Steel pipes are stronger and are placed in areas the pipeline may be struck by something. The steel pipe may not be damaged by the impact, but it also doesn't give the way plastic pipes do. A strong jolt to a steel pipe can crack the plastic pipe at the adaptor, which is often the weakest link. To help avoid this, cover the steel pipe with large stones where it enters the ground and attaches to the plastic pipe. This will brace the end and help keep the force from transferring.

Crossings often occur at low points in the system. Because it is also a place where the pipeline is above the ground, they make excellent locations to place cleanouts. By swapping out a coupling for a ‘T’ with a male cap, a clean out is easily installed. Just be sure that it can be reached and that it won’t cause excessive erosion under the anchor when it is opened.

If somewhat counter intuitively, crossings can also be localized highpoints. A pipeline heads down at the normal grade, drops down a little for the canyon, goes straight across the bridge, and then rises up out of the canyon before continuing down at grade. A simple air release valve can be made by replacing the upper elbow (see Figure 4-4) with a ‘T’.

6 Design Examples

This chapter is intended to provide the reader an idea of how all the different aspects of design and planning come together. Less time is spent explaining the details and more is given to the overall design process. The first example is an actual crossing built by the author. The second is a hypothetical situation based on a real incident viewed on the road between Azua and San Juan de la Maguana.

6.1 Flat 140+' Canyon Crossing (Peligro)

A 3-inch pipeline descends from the spring source at an approximate 1% grade. To continue along this route the pipeline will intersect two small canyons with a little hill in between. The two canyons combine roughly 100 yards down grade. The canyon is very deep and the sides are steep. The soil on either side is a solid yet soft limestone covered with a thin layer of topsoil. The property on either side and through the canyon is owned by an old man known as 'Peligro', 'Danger' in English.

6.1.1 Planning

The bridge is sited further down grade where the two canyons join. The span will be longer, but it will only be one large crossing rather than two small ones. In addition the banks are more convenient to work on.

A quick string measure puts the span distance from bank to bank at roughly 125 ft. Adding 10 feet on either side to set the anchors back from the edge places the cable span at about 145 ft. There is no noticeable elevation difference from one side to the other. This is checked by Abney level as well. The banks are, for all practical purposes vertical.

Three inch galvanized pipes are deemed to be too expensive based on the price of the pipes alone. That is to say nothing of the cost of the additional structure to support the weight. Two inch galvanized pipes will be used.

The area is covered with soccer ball sized limestone rocks. Because of this geographical feature that provides a free and readily available building material, an integrated column and anchor seems like a good choice. These can only really be built efficiently to a height of about five feet tall. The trench is only about one and a half feet deep in this area due to tough ground conditions, but it could be dug out deeper where the pipe meets the canyon wall with minimal effort. Assuming this would be feasible for three feet below the ground surface that would give another two feet for the sag, one foot for the pipe and stringer at the apex and two for the sag. The sag should be about 7 feet or less.

A two-inch galvanized tube filled with water weighs 3.77 lbs/ft. A span length of 145 ft, and a sag of 7 ft is desired.

$$\text{Horizontal Tension} = \frac{(\text{Wieght of Pipe per Unit Length})(\text{Length of Span})^2}{8(\text{Sag})}$$

$$\text{Horizontal Tension} = \frac{(3.77 \text{ lbs/ft})(145 \text{ ft})^2}{8(7\text{ft})}$$

Horizontal Tension = 1,415 lbs.

Horizontal Tension is not the same as total tension, but it's close enough for a quick check. Applying a safety factor of three, the cable must withstand a force of roughly 4,300 lbs. Any weave of 1/4-inch cable will handle this load easily. In addition 1/4 cable is a more common size and can be found in most large hardware stores.

6.1.2 Design

Based on the planning stage it is known that an integrated column anchor constructed from available stones and concrete will be used for the anchors. A 1/4 inch main cable will support a line of two-inch galvanized tubes.

A 7X7 1/4 inch plastic coated steel cable was purchased. It weighs 0.106 lbs/ft and has a minimum breaking force of 6,100 lbs. Applying a safety factor of three gives an allowable tension of 2,033 lbs. The geometry of the crossing can be optimized to this.

$$2033 \text{ lbs} = \frac{(3.876 \text{ lbs/ft})(145 \text{ ft})^2}{8(\text{Sag})}$$

Sag = 5.01 ft

Use 5.0 ft for simplicity. But, double check the safety factor for the total cable tension.

$$\text{Horizontal Tension} = \frac{(3.876 \text{ lbs/ft})(145 \text{ ft})^2}{8(5\text{ft})}$$

Horizontal Tension = 2,037 lbs

$$\text{Angle of Tension} = \arctan\left(\frac{4(5 \text{ ft.})}{145 \text{ ft.}}\right)$$

Angle = 7.85°

$$\text{Total Tension} = \frac{2037 \text{ lbs}}{\cos(7.85°)}$$

Total Tension = 2,056 lbs.

$$\text{Safety Factor} = \frac{6100 \text{ lbs}}{2056 \text{ lbs}}$$

Safety Factor = 2.97

The designer considers this acceptable.

A sag of five feet means that with the space allowed for the smallest stringer the pipe will be six feet below the fixture point. If the pipe enters the ground at three feet below the surface then the tower will be three feet above the surface. Two identical integrated column and anchor set-ups will be used. These should be placed at least one foot below the surface. This gives a height of four feet.

Using the standard plan illustrated in Figure 4-14, H1=4ft; H2=1.5ft; W1=4ft; W2=2ft; L1=2ft. The design will be optimized by solving for L2. A safety factor of 3 will be used. The mass will be assumed to have a density of 150 lbs/ft^3.

$\Sigma M = 0 =$ (Horizontal Force)(H1)(Safety Factor) – ((W1+W2)/2)(L1)(H1)(Weight/ft^3)(L1)/2 + (W1)(L2)(H2)(Weight/ft^3)(L1+(L2)/2)

$0 = (2037 \text{ lbs})(4\text{ft})(3) - ((4\text{ft}+2\text{ft})/2)(2\text{ft})(4\text{ft})(150\text{lbs}/\text{ft}^3)(2\text{ft})/2 + (4\text{ft})(L2)(1.5\text{ft})(150\text{lbs}/\text{ft}^3)(2\text{ft}+(L2)/2)$

$0 = -450L2^2 - 1800L2 + 20844$

Using the quadratic equation.

L2 = 5.09ft

Use 5.5 ft for simplicity.

The design is now ready for construction.

6.1.3 Final Cable Adjustment

To continue the example, assume that the anchors were re-measured and found to be 143.75 ft apart. Using Equation 4-1 and a numerical solver (such as Microsoft Excel) 'C' is found to be 517.43275 for a sag of 5 ft.

If the gap from bank to bank is roughly 125 ft it would need 130 ft of pipe (six and one half, 20 foot pipes) to allow enough steel pipe to be imbedded in the ground at both ends. Centering the pipes in the span would place the stringers symmetrically at 5, 15, 25, 35, 45, and 55 feet from the apex in both directions (a total of 12 stringers, six identical pairs). 35.71 inches is added to the length for connections.

Distance	Sag Allowance	Normalized	In inches	With connections
5’	0.02415’	0’	0”	35 11/16”
15’	0.21743’	0.19328’	2 5/16”	38”
25’	0.60406’	0.57991’	6 15/16”	42 11/16”
35’	1.1842’	1.16005’	13 15/16”	49 10/16”
45’	1.958’	1.93385’	23 3/16”	58 15/16”
55’	2.9258’	2.90165’	34 13/16”	70 8/16”

The arc length of the cable is found.

$$y = C \sinh\left(\frac{x}{C}\right)$$

$$y = 517.43275 \ \sinh\left(\frac{71.875 \text{ ft}}{517.43275}\right)$$

Arc length is 72.1064 ft from apex to fixture point. Total length is 144.2127 ft.

To find the un-stretched cable length, the force on the cable is recalculated for the actual length using Equations 3-1through 3-3.

$$\text{Horizontal Tension} = \frac{(3.876 \text{ lbs})(143.75 \text{ ft})^2}{8(5 \text{ ft})}$$

Horizontal Tension = 2,002 lbs

$$\text{Angle of Tension} = \arctan\left(\frac{4(5 \text{ ft})}{143.75}\right)$$

Angle of Tension = 7.92°

$$\text{Total Tension} = \frac{2002 \text{ lbs}}{\cos(7.92°)}$$

Total Tension = 2,021 lbs

Use an average tension of 2011 lbs. Using Equations 5-1 and 5-2.

$$\text{Proportional Change in Length} = \frac{1220 \text{ lbs}}{(0.0294 \text{in}^2)(13500000 \text{psi})} + \frac{(2011 \text{ lbs.}) - (1220 \text{ lbs.})}{(0.0294 \text{in}^2)(15000000 \text{psi})}$$

Proportional Change in Length = 0.004868

$$\text{Starting Length} = \frac{144.2127 \text{ ft.}}{1.004868}$$

Starting Length = 143.51 ft.

It is worth noting that the un-stretched cable length is actually less than the span length. This may seem wrong, but it is possible.

6.2 85' Road Cut Crossing with Uneven Anchors (Hypothetical)

A highway expansion creates a road cut through a small community. A community aqueduct had previously passed under the road, but the new highway alignment had destroyed the old tube and greatly changed the surface. The aqueduct requires at least a one and a half-inch pipe for good distribution through the town.

6.2.1 Planning and Survey

A survey is completed of the proposed crossing alignment. The pipe was severed at two feet below point C and two feet below point F.

Table 6-1: Survey of Crossing Site

Point	Horizontal (Act)	Vertical (Act)	Notes
A	0	0	
B	27.6	-3	
C	42.6	-7.25	Edge of Cut
D	77.5	-42.25	Edge of Road
E	107.5	-42.25	Edge of Road
F	125.2	-24.5	Edge of Cut
G	144.6	-28.5	
H	164.4	-37.0	

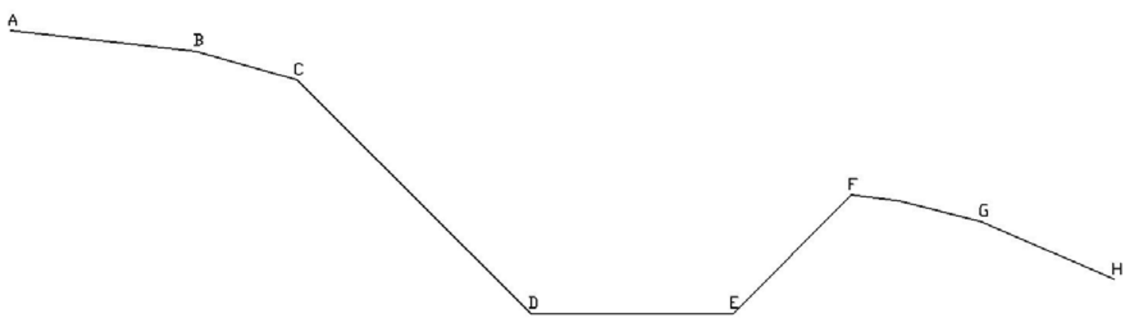

Figure 6-1 Cross section of proposed bridge alignment.

The pipe will go directly from the two broken ends. The anchors will be placed five feet back from both edges.

6.2.2 Design

The length of the crossing, point C to point F with five additional feet on both sides, is 92.6 feet. There is a 17.25 foot drop from point C to point F. To go directly from point C to F would require a sag ratio of 0.18. This would make the cable angle at the higher anchor to steep and the stringers could slide. To keep the sag at a more reasonable ratio of 0.12 the fixture point of the higher anchor will be located two feet above point C and the lower angle will be located 8.25 feet above point F. This will be a drop ratio of 0.12. A sag ratio of 0.12 can also be used which will place the apex of the cable directly at the fixture point.

The gap is roughly 80 feet. The best tube placement would probably be with 4 full-length pipes centered in the span with two shorter sections on either side cut specially to enter the ground at a convenient angle.

In a complicated layout like this with a slanting pipe and non-symmetrical cable placement a chart of the elevations and locations is a useful tool. All values were calculated using the slope of the pipe and Equation 4-1. The results are tabulated in Table 6-5. The values can also be graphed as a double check. A graph is show in Figure 6-2.

Table 6-2: Elevations and locations of pipe and cable

	X Coordinate	Elevation of Pipe	Elevation of Cable	Stringer Length
Fixture point	37.6		-5.25	
Pipe Enters	42.6	-9.25	-6.42	2.83
Stringer 1	53.9	-11.61	-8.83	2.78
Stringer 2	63.9	-13.70	-10.68	3.02
Stringer 3	73.9	-15.79	-12.27	3.52
Stringer 4	83.9	-17.88	-13.59	4.28
Stringer 5	93.9	-19.96	-14.66	5.30
Stringer 6	103.9	-22.05	-15.47	6.58
Stringer 7	113.9	-24.14	-16.02	8.12
Pipe Enters	125.2	-26.50	-16.33	10.17
Fixture point	130.2		-16.36	

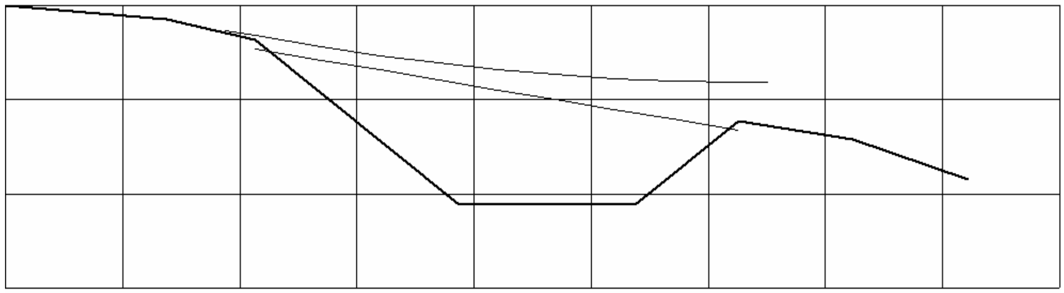

Figure 6-2 Quick graph of cable and pipe path in relation to ground surface.

A one and a half-inch pipe filled with water weighs 2.784 lbs/ft. The crossing terminates at the apex. To use Equations 3-1 – 3-3 for the tension, the equivalent length will be used. In this case the equivalent length, double the distance from the fixture point to the apex, is twice the actual span.

$$\text{Horizontal Tension} = \frac{(2.784\ \text{lbs/ft})(185.2\ \text{ft})^2}{8(11.11\text{ft})}$$

Horizontal Tension = 1074.4 lbs

This will be close enough to specify a cable size. Using a safety factor of 2 a minimum breaking strength of 2148.7 lbs would be required. 5/32 cable with a 7X7 weave has a minimum breaking strength of 2600 lbs. Its weight per foot is 0.0115 lbs. This weight is added to the calculation.

$$\text{Horizontal Tension} = \frac{(2.796\ \text{lbs/ft})(185.2\ \text{ft})^2}{8(11.11\text{ft})}$$

Horizontal Tension = 1,079.0 lbs

$$\text{Angle of Tension} = \arctan\left(\frac{4(11.11\ \text{ft.})}{185.2\ \text{ft.}}\right)$$

Angle = 13.5°

$$\text{Total Tension} = \frac{1079.0\ \text{lbs}}{\cos(13.5°)}$$

Total Tension = 1109.7 lbs.

A simple block mass anchor will be used for the upper anchor. The lower anchor will be a steel pipe column with a split anchor set up.

From the geometric design it is known that the block anchor will hold the cable two feet above the ground surface. Assuming the foundation will be dug out at least one foot would give the anchor a height of 3 feet. Three feet is also a convenient width.

$\Sigma M = 0 =$ (Horizontal Force)x(H)x(Safety Factor) –
(LxWxHx(Weight of Mass per cubic foot))xL/2

$\Sigma M = 0 =$ (1079.0 lbs)x(3 ft)x(3) –
(Lx(3 ft)x(3 ft)x(150 lbs/ft^3))xL/2

L = 3.79 ft

Use 4 ft for simplicity.

The soil conditions are unknown. A safety factor against sliding of 3 is desired.

$\Sigma F_x = 0 =$ (SF)(Horizontal Force) – (L)(W)(H)(Weight per cubic foot)(tan φ)
– (Vertical Force)

$\Sigma F_x = 0 =$ (3)(1079 lbs) – (4 ft)(3 ft)(3 ft)(150 pcf)(tan φ)
– (259 lbs)

$\varphi = 28.9°$

A friction angle of 28.9° relates to fine or even silty sand anything coarser than this will be fine. During the excavation the ground conditions can be observed if they are clay or something softer, gravel can be laid down before the anchor is constructed. (It is unlikely that the ground is this soft given the extreme angle of the road cut.)

The column will be placed so that the top is at the fixture point (130.2, -16.36) and the anchors will be roughly at point G (144.6, -28.5) forming an angle of 40.2° below vertical. The two anchors will each be out of plane 30°. This will cut the force applied in plane by one half. But, there are two anchors, which will double the force counter act this.

$\Sigma F_x = 0 =$ (Span Cable Force)cosθ_S - (Anchor Cable Force)cosθ_A

$\Sigma F_x = 0 =$ (1079.0 lbs)cos(0°) - (Anchor Cable Force)cos(40.2°)

Anchor Cable Force = 1,412.7 lbs.

Both anchor cables will have a force of 1,412.7 lbs to balance the span cable.

When calculating the axial force the force is summed in the vertical direction and the anchors both act in this plane. The anchor cable force component of the equation will have to be doubled to account for this.

$\Sigma F_y = 0 =$ Axial Column Force - (Span Cable Force)sinθ_S + 2(Anchor Cable Force)sinθ_A

$\Sigma F_y = 0 =$ Axial Column Force - (1079.0 lbs)sin(0°) + 2(1412.7 lbs)sin(40.2°)

Axial Column Force = 1823.7 lbs

The double anchor will brace the top of the column. From the geometric design the height of the column is shown to be roughly 8.5 feet. This is an effective height of 5.7 feet.

$$\frac{\text{(Applied Axial Force)}}{\text{(0.55)(Critical Axial Force)}} + \frac{\text{(Applied Bending Moment)}}{\text{(0.60)(Critical Bending Moment)}} \leq 1$$

$$\frac{\text{(1823.7 lbs)}}{\text{(0.55)(Critical Axial Force)}} + \frac{(0)}{\text{(0.60)(Critical Bending Moment)}} \leq 1$$

Critical Axial Force = 3315.8 lbs

A standard one-inch steel pipe with an effective height of six feet has a critical axial force of 3,938 lbs. To be sure the column will be stable no mater what quality of steel pipe is available it might be a good idea to specify one and a quarter inch steel pipe.

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Appendix A: Cable Properties.

Construction	Diameter (in)	Wt per ft (lbs)	Minimum Breaking Strength (lbs)	Area of Steel (in^2)
1X19	1/8	0.035	2100	0.0092
	5/32	0.055	3300	0.0144
	3/16	0.077	4700	0.0207
	7/32	0.102	6300	0.0282
	1/4	0.135	8200	0.0369
	9/32	0.170	10300	0.0467
	5/16	0.210	12500	0.0576
	3/8	0.301	17500	0.0830
7X7	1/8	0.028	1700	0.0074
	5/32	0.043	2600	0.0115
	3/16	0.062	3700	0.0166
	7/32	0.083	4800	0.0225
	1/4	0.106	6100	0.0294
	9/32	0.134	7600	0.0373
	5/16	0.167	9200	0.0460
	11/32	0.201	11100	0.0557
	3/8	0.236	13100	0.0662
7X19	1/8	0.029	2000	0.0079
	5/32	0.045	2800	0.0123
	3/16	0.065	4200	0.0178
	7/32	0.086	5600	0.0242
	1/4	0.110	7000	0.0316
	9/32	0.139	8000	0.0399
	5/16	0.173	9800	0.0493
	11/32	0.207	12500	0.0597
	3/8	0.243	14400	0.0710
6X19	1/4	0.120	5880	0.0316
	5/16	0.180	9160	0.0493
	3/8	0.260	13120	0.0710
6X36	1/4	0.120	5340	0.0303
	5/16	0.180	8320	0.0474
	3/8	0.260	11900	0.0682

Appendix B: Pipe Properties.

Nominal Tube Size	OutSide Diameter (in)	Specification	Inside Diameter (in)	Wall Thickness (in)	Area (in^2)	Moment of Inirtia (in^4)	Radius of Gyration (in)	Weight per Foot (lbs)	Weight of Water per Foot (lbs)	Critical Bending Moment (inlbs)
1/2	0.840	5S	0.710	0.065	0.158	0.012	0.275	0.53	0.014	1026
		10S	0.674	0.083	0.197	0.014	0.269	0.67	0.013	1227
		40-Std-40S	0.622	0.109	0.250	0.017	0.261	0.85	0.011	1465
		80-XS-80S	0.546	0.147	0.320	0.020	0.250	1.08	0.008	1721
		160	0.466	0.187	0.384	0.022	0.240	1.30	0.006	1896
		XXS	0.252	0.294	0.504	0.024	0.219	1.71	0.002	2078
3/4	1.050	5S	0.920	0.065	0.201	0.025	0.349	0.68	0.024	1680
		10S	0.884	0.083	0.252	0.030	0.343	0.85	0.022	2036
		40-Std-40S	0.824	0.113	0.333	0.037	0.334	1.13	0.019	2540
		80-XS-80S	0.742	0.154	0.433	0.045	0.321	1.47	0.016	3071
		160	0.614	0.218	0.570	0.053	0.304	1.93	0.011	3613
		XXS	0.434	0.308	0.718	0.058	0.284	2.44	0.005	3972
1	1.315	5S	1.185	0.065	0.255	0.050	0.443	0.86	0.040	2737
		10S	1.097	0.109	0.413	0.076	0.428	1.40	0.034	4144
		40-Std-40S	1.049	0.133	0.494	0.087	0.421	1.67	0.031	4782
		80-XS-80S	0.957	0.179	0.639	0.106	0.407	2.17	0.026	5782
		160	0.815	0.250	0.836	0.125	0.387	2.84	0.019	6851
		XXS	0.599	0.358	1.076	0.140	0.361	3.65	0.010	7691
1 1/4	1.660	5S	1.530	0.065	0.326	0.104	0.564	1.10	0.066	4500
		10S	1.442	0.109	0.531	0.160	0.550	1.80	0.059	6961
		40-Std-40S	1.380	0.140	0.669	0.195	0.540	2.27	0.054	8445
		80-XS-80S	1.278	0.191	0.881	0.242	0.524	2.99	0.046	10487
		160	1.160	0.250	1.107	0.284	0.506	3.76	0.038	12312
		XXS	0.896	0.382	1.534	0.341	0.472	5.21	0.023	14795
1 1/2	1.900	5S	1.770	0.065	0.375	0.158	0.649	1.27	0.089	5984
		10S	1.682	0.109	0.613	0.247	0.634	2.08	0.080	9353
		40-Std-40S	1.610	0.145	0.799	0.310	0.623	2.71	0.074	11743
		80-XS-80S	1.500	0.200	1.068	0.391	0.605	3.63	0.064	14825
		160	1.338	0.281	1.429	0.482	0.581	4.85	0.051	18280
		XXS	1.100	0.400	1.885	0.568	0.549	6.40	0.034	21518
2	2.375	5S	2.245	0.065	0.472	0.315	0.817	1.60	0.143	9546
		10S	2.157	0.109	0.776	0.499	0.802	2.63	0.132	15133
		40-Std-40S	2.067	0.154	1.075	0.666	0.787	3.65	0.121	20183
		80-XS-80S	1.939	0.218	1.477	0.868	0.766	5.02	0.107	26312
		160	1.689	0.343	2.190	1.162	0.729	7.44	0.081	35237
		XXS	1.503	0.436	2.656	1.311	0.703	9.02	0.064	39753
2 1/2	2.875	5S	2.709	0.083	0.728	0.710	0.988	2.00	0.208	17781
		10S	2.635	0.120	1.039	0.987	0.975	3.50	0.197	24724
		40-Std-40S	2.469	0.203	1.704	1.530	0.947	5.80	0.173	38305
		80-XS-80S	2.323	0.276	2.254	1.924	0.924	7.70	0.153	48190
		160	2.125	0.375	2.945	2.353	0.894	10.00	0.128	58921
		XXS	1.771	0.552	4.028	2.871	0.844	14.00	0.089	71895
3	3.500	5S	3.334	0.083	0.891	1.301	1.208	3.00	0.315	26767
		10S	3.260	0.120	1.274	1.822	1.196	4.30	0.301	37480
		40-Std-40S	3.068	0.216	2.228	3.017	1.164	7.60	0.267	62067
		80-XS-80S	2.900	0.300	3.016	3.894	1.136	10.20	0.239	80112
		160	2.626	0.437	4.205	5.032	1.094	14.30	0.196	103514
		XXS	2.300	0.600	5.466	5.993	1.047	19.00	0.150	123274
4	4.500	5S	4.334	0.083	1.152	2.810	1.562	3.90	0.533	44957
		10S	4.260	0.120	1.651	3.963	1.549	5.60	0.515	63403
		40-Std-40S	4.026	0.237	3.174	7.233	1.510	11.00	0.460	115722
		80-XS-80S	3.826	0.337	4.407	9.610	1.477	15.00	0.415	153768
		120	3.626	0.437	5.578	11.643	1.445	19.00	0.373	186293
		160	3.438	0.531	6.621	13.271	1.416	23.00	0.335	212335
		XXS	3.152	0.674	8.101	15.284	1.374	28.00	0.282	244539

Appendix C: 'C' Values, Apex Locations, and Arc Lengths for General Catenary Forms.

		0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.10	0.11	0.12
0.030	C	4.171657	5.055271	6.702506	16.667389									
	X1	0.500	0.550	0.634	1.000									
	L	1.002396	1.001681	1.0011276	1.0006									
0.032	C	3.911572	4.674587	6.014267	10.004330									
	X1	0.500	0.547	0.620	0.800									
	L	1.002725	1.001958	1.0013521	1.000866									
0.034	C	3.682123	4.347760	5.460797	8.157825									
	X1	0.500	0.543	0.609	0.745									
	L	1.003076	1.002256	1.0015975	1.001076									
0.036	C	3.478206	4.064053	5.004659	7.007947									
	X1	0.500	0.541	0.600	0.710									
	L	1.003448	1.002575	1.001864	1.001298									
0.038	C	3.295788	3.815422	4.621481	6.187425									
	X1	0.500	0.538	0.592	0.685									
	L	1.00384	1.002915	1.0021516	1.001538									
0.040	C	3.131644	3.595716	4.294597	5.560547	12.504116								
	X1	0.500	0.536	0.586	0.667	1.000								
	L	1.004254	1.003276	1.0024602	1.001797	1.001066								
0.042	C	2.983164	3.400149	4.012166	5.060865	8.027578								
	X1	0.500	0.534	0.580	0.652	0.821								
	L	1.004689	1.003658	1.0027899	1.002077	1.001446								
0.044	C	2.848212	3.224940	3.765517	4.650688	6.714217								
	X1	0.500	0.532	0.575	0.639	0.768								
	L	1.005144	1.004061	1.0031406	1.002377	1.001723								
0.046	C	2.725024	3.067060	3.548135	4.306553	5.872607								
	X1	0.500	0.531	0.571	0.629	0.735								
	L	1.005621	1.004485	1.0035123	1.002697	1.002007								
0.048	C	2.612128	2.924057	3.355021	4.012888	5.258605								
	X1	0.500	0.529	0.567	0.620	0.710								
	L	1.006118	1.00493	1.003905	1.003038	1.002306								
0.050	C	2.508289	2.793918	3.182270	3.758847	4.780833	10.008313							
	X1	0.500	0.528	0.563	0.612	0.691	1.000							
	L	1.006636	1.005396	1.0043187	1.0034	1.002622	1.001665							
0.052	C	2.412463	2.674983	3.026783	3.536597	4.393990	6.728070							
	X1	0.500	0.527	0.560	0.606	0.675	0.836							
	L	1.007175	1.005883	1.0047533	1.003783	1.002957	1.002169							
0.054	C	2.323759	2.565863	2.886066	3.340308	4.072071	5.728425							
	X1	0.500	0.525	0.557	0.600	0.662	0.786							
	L	1.007734	1.006391	1.0052089	1.004187	1.003312	1.002518							
0.056	C	2.241415	2.465392	2.758092	3.165535	3.798700	5.075137							
	X1	0.500	0.524	0.555	0.595	0.651	0.753							
	L	1.008314	1.006919	1.0056853	1.004611	1.003687	1.002866							

		0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.10	0.11	0.12
0.058	C	2.164771	2.372581	2.641188	3.008824	3.562886	4.591123							
	X1	0.500	0.524	0.553	0.590	0.642	0.729							
	L	1.008915	1.007468	1.0061825	1.005057	1.004083	1.003225							
0.060	C	2.093258	2.286588	2.533968	2.867439	3.356894	4.209599	8.343308						
	X1	0.500	0.523	0.550	0.586	0.634	0.710	1.000						
	L	1.009536	1.008038	1.0067005	1.005523	1.004498	1.003599	1.002396						
0.062	C	2.026379	2.206688	2.435268	2.739184	3.175078	3.897212	5.804473						
	X1	0.500	0.522	0.548	0.582	0.626	0.694	0.848						
	L	1.010178	1.008628	1.0072392	1.00601	1.004935	1.003991	1.003033						
0.064	C	1.963700	2.132258	2.344106	2.622272	3.013198	3.634674	5.008638						
	X1	0.500	0.521	0.547	0.578	0.620	0.681	0.800						
	L	1.01084	1.009239	1.0077986	1.006518	1.005392	1.004402	1.003457						
0.066	C	1.904839	2.062754	2.259645	2.515234	2.867991	3.409751	4.480943						
	X1	0.500	0.520	0.545	0.575	0.614	0.670	0.768						
	L	1.011523	1.009871	1.0083787	1.007046	1.005869	1.004832	1.003871						
0.068	C	1.849459	1.997706	2.181171	2.416847	2.736898	3.214176	4.085463						
	X1	0.500	0.520	0.543	0.572	0.609	0.660	0.744						
	L	1.012226	1.010523	1.0089794	1.007595	1.006367	1.005282	1.004292						
0.070	C	1.797261	1.936699	2.108066	2.326086	2.617876	3.042087	3.770685	7.154489					
	X1	0.500	0.519	0.542	0.569	0.604	0.651	0.725	1.000					
	L	1.012949	1.011195	1.0096006	1.008165	1.006886	1.005752	1.004726	1.003259					
0.072	C	1.747981	1.879368	2.039796	2.242087	2.509273	2.889182	3.510757	5.112336					
	X1	0.500	0.519	0.540	0.567	0.600	0.644	0.710	0.857					
	L	1.013693	1.011888	1.0102423	1.008755	1.007425	1.006242	1.005176	1.004038					
0.074	C	1.701381	1.825393	1.975896	2.164110	2.409732	2.752206	3.290653	4.458120					
	X1	0.500	0.518	0.539	0.564	0.596	0.637	0.697	0.811					
	L	1.014456	1.012601	1.0109044	1.009366	1.007985	1.006752	1.005644	1.00454					
0.076	C	1.657251	1.774489	1.915959	2.091523	2.318133	2.628639	3.100801	4.019415					
	X1	0.500	0.518	0.538	0.562	0.592	0.631	0.685	0.780					
	L	1.01524	1.013334	1.011587	1.009998	1.008565	1.007283	1.00613	1.005022					
0.078	C	1.615399	1.726400	1.859626	2.023780	2.233535	2.516493	2.934697	3.687669					
	X1	0.500	0.517	0.537	0.560	0.589	0.625	0.675	0.757					
	L	1.016044	1.014088	1.0122898	1.01065	1.009166	1.007834	1.006635	1.005506					
0.080	C	1.575656	1.680903	1.806582	1.960407	2.155144	2.414174	2.787710	3.421600	6.263285				
	X1	0.500	0.517	0.536	0.558	0.585	0.620	0.666	0.738	1.000				
	L	1.016868	1.014862	1.013013	1.011322	1.009788	1.008405	1.007159	1.006001	1.004254				
0.081	C	1.556526	1.659061	1.781205	1.930228	2.118062	2.366283	2.720283	3.306291	5.012115				
	X1	0.500	0.516	0.535	0.557	0.584	0.617	0.662	0.730	0.900				
	L	1.017287	1.015256	1.0133821	1.011666	1.010106	1.008698	1.007429	1.006254	1.0048491				
0.082	C	1.537866	1.637792	1.756548	1.900991	2.082287	2.320381	2.656424	3.200419	4.573334				
	X1	0.500	0.516	0.535	0.556	0.582	0.615	0.658	0.723	0.865				
	L	1.017711	1.015655	1.0137563	1.012015	1.010429	1.008996	1.007703	1.00651	1.0051819				

		0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.10	0.11	0.12
0.097	C	1.304513	1.374787	1.455923	1.551057	1.664820	1.804445	1.982138	2.220960	2.573389	3.215654			
	X1	0.500	0.513	0.529	0.546	0.566	0.589	0.618	0.654	0.704	0.788			
	L	1.024665	1.022241	1.0199691	1.017852	1.015889	1.014079	1.012419	1.010895	1.0094787	1.00806			
0.098	C	1.291521	1.360303	1.439592	1.532379	1.643061	1.778457	1.949969	2.178835	2.512218	3.099317			
	X1	0.500	0.513	0.528	0.545	0.565	0.588	0.616	0.651	0.699	0.777			
	L	1.025167	1.022719	1.0204229	1.018281	1.016293	1.014459	1.012773	1.011226	1.009789	1.00837			
0.099	C	1.278794	1.346131	1.423635	1.514161	1.621885	1.753244	1.918900	2.138451	2.454428	2.994445			
	X1	0.500	0.513	0.528	0.545	0.564	0.586	0.614	0.648	0.695	0.768			
	L	1.025675	1.023202	1.0208816	1.018715	1.016702	1.014843	1.013132	1.011561	1.0101039	1.00868			
0.100	C	1.266324	1.332261	1.408039	1.496386	1.601270	1.728772	1.888874	2.099695	2.399709	2.899028	5.016576		
	X1	0.500	0.513	0.528	0.544	0.563	0.585	0.612	0.645	0.690	0.759	1.000		
	L	1.026187	1.02369	1.0213452	1.019154	1.017116	1.015232	1.013497	1.011902	1.0104232	1.00899	1.00664		
0.102	C	1.242127	1.305391	1.377884	1.462100	1.561632	1.681918	1.831740	2.026658	2.298438	2.730861	3.786563		
	X1	0.500	0.513	0.527	0.543	0.561	0.583	0.608	0.640	0.682	0.744	0.877		
	L	1.027225	1.02468	1.022287	1.020047	1.01796	1.016025	1.014241	1.012598	1.0110758	1.00962	1.00788		
0.104	C	1.218873	1.279620	1.349036	1.429404	1.523984	1.637655	1.778177	1.958997	2.206615	2.586316	3.374878		
	X1	0.500	0.512	0.526	0.542	0.560	0.581	0.605	0.636	0.675	0.731	0.836		
	L	1.028283	1.02569	1.0232483	1.020959	1.018823	1.016839	1.015005	1.013313	1.0117471	1.01026	1.00863		
0.106	C	1.196506	1.254883	1.321413	1.398190	1.488179	1.595771	1.727850	1.896102	2.122842	2.459931	3.092434		
	X1	0.500	0.512	0.526	0.541	0.558	0.578	0.602	0.631	0.668	0.720	0.807		
	L	1.02936	1.026719	1.024229	1.021891	1.019705	1.017672	1.015789	1.014049	1.0124373	1.01091	1.00933		
0.108	C	1.174979	1.231120	1.294939	1.368358	1.454083	1.556076	1.680465	1.837460	2.046006	2.347967	2.874910		
	X1	0.500	0.512	0.525	0.540	0.557	0.576	0.599	0.627	0.662	0.709	0.786		
	L	1.030455	1.027767	1.0252289	1.022842	1.020608	1.018525	1.016592	1.014804	1.0131467	1.01159	1.01001		
0.110	C	1.154245	1.208276	1.269543	1.339820	1.421577	1.518399	1.635761	1.782628	1.975202	2.247742	2.697700	4.563669	
	X1	0.500	0.512	0.525	0.539	0.556	0.575	0.597	0.623	0.656	0.700	0.768	1.000	
	L	1.031569	1.028834	1.0262481	1.023813	1.021529	1.019398	1.017416	1.015579	1.0138753	1.01228	1.01069	1.00802	
0.112	C	1.134262	1.186297	1.245163	1.312494	1.390552	1.482589	1.593513	1.731229	1.909689	2.157257	2.548338	3.490201	
	X1	0.500	0.512	0.524	0.538	0.554	0.573	0.594	0.619	0.651	0.692	0.753	0.882	
	L	1.032702	1.02992	1.0272865	1.024803	1.022471	1.02029	1.018259	1.016374	1.0146232	1.01298	1.01138	1.00944	

		0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.10	0.11	0.12
0.114	C	1.114990	1.165137	1.221738	1.286303	1.360907	1.448508	1.553517	1.682935	1.848849	2.074987	2.419508	3.127184	
	X1	0.500	0.511	0.524	0.538	0.553	0.571	0.592	0.616	0.646	0.685	0.740	0.842	
	L	1.033854	1.031025	1.0283439	1.025812	1.023432	1.021202	1.019122	1.017188	1.0153906	1.01371	1.01209	1.01027	
0.116	C	1.096392	1.144751	1.199215	1.261180	1.332554	1.416032	1.515593	1.637460	1.792163	1.999733	2.306506	2.876781	
	X1	0.500	0.511	0.523	0.537	0.552	0.569	0.589	0.613	0.641	0.678	0.728	0.814	
	L	1.035025	1.032149	1.0294203	1.026841	1.024412	1.022133	1.020005	1.018022	1.0161773	1.01445	1.0128	1.01104	
0.118	C	1.078434	1.125098	1.177542	1.237060	1.305409	1.385050	1.479582	1.594556	1.739192	1.930538	2.206104	2.683093	
	X1	0.500	0.511	0.523	0.536	0.551	0.568	0.587	0.610	0.637	0.672	0.718	0.793	
	L	1.036213	1.033291	1.0305156	1.027889	1.025411	1.023084	1.020907	1.018876	1.0169836	1.01521	1.01353	1.0118	
0.120	C	1.061085	1.106140	1.156673	1.213885	1.279397	1.355460	1.445338	1.554000	1.689558	1.866627	2.115982	2.524712	4.186514
	X1	0.500	0.511	0.522	0.535	0.550	0.566	0.585	0.607	0.633	0.666	0.709	0.775	1.000
	L	1.03742	1.034452	1.0316297	1.028955	1.02643	1.024055	1.021828	1.019749	1.0178092	1.016	1.01427	1.01254	1.00954
0.122	C	1.044313	1.087840	1.136564	1.191601	1.254447	1.327169	1.412732	1.515599	1.642937	1.807360	2.034412	2.390775	3.238686
	X1	0.500	0.511	0.522	0.535	0.549	0.565	0.583	0.604	0.629	0.660	0.701	0.761	0.886
	L	1.038646	1.035631	1.0327626	1.030041	1.027468	1.025044	1.02277	1.020642	1.0186543	1.0168	1.01504	1.01329	1.01112
0.124	C	1.028091	1.070165	1.117174	1.170157	1.230497	1.300094	1.381648	1.479179	1.599048	1.752205	1.960068	2.274904	2.915273
	X1	0.500	0.510	0.522	0.534	0.548	0.563	0.581	0.602	0.626	0.655	0.694	0.748	0.847
	L	1.03989	1.036829	1.0339141	1.031145	1.028525	1.026053	1.02373	1.021554	1.0195189	1.01761	1.01581	1.01405	1.01205
0.126	C	1.012393	1.053085	1.098467	1.149507	1.207488	1.274156	1.351979	1.444587	1.557645	1.700712	1.891910	2.172988	2.691137
	X1	0.500	0.510	0.521	0.533	0.547	0.562	0.579	0.599	0.622	0.651	0.687	0.736	0.820
	L	1.041151	1.038046	1.0350841	1.032269	1.029601	1.027081	1.02471	1.022485	1.0204028	1.01845	1.01661	1.01483	1.0129
0.128	C	0.997194	1.036571	1.080408	1.129609	1.185364	1.249286	1.323629	1.411684	1.518512	1.652501	1.829107	2.082205	2.517112
	X1	0.500	0.510	0.521	0.533	0.546	0.561	0.578	0.597	0.619	0.646	0.680	0.726	0.799
	L	1.042431	1.03928	1.0362727	1.033411	1.030696	1.028128	1.025709	1.023436	1.021306	1.01931	1.01743	1.01561	1.01372
0.130	C	0.982472	1.020594	1.062963	1.110422	1.164078	1.225418	1.296512	1.380345	1.481459	1.607245	1.770981	2.000525	2.374343
	X1	0.500	0.510	0.520	0.532	0.545	0.560	0.576	0.594	0.616	0.642	0.674	0.717	0.782
	L	1.043729	1.040533	1.0374797	1.034571	1.031809	1.029194	1.026727	1.024407	1.0222286	1.02019	1.01826	1.01641	1.01453

Appendix D: Critical Axial Loads for Steel Tubes of Various Effective Heights.

Nominal Tube Size	Specification	Effective Height in Feet								
		3	3.5	4	4.5	5	5.5	6	6.5	7
1/2	5S	2162	1523	1017	644	386	219	118	60	29
	10S	2586	1795	1178	731	429	238	125	62	29
	40-Std-40S	3082	2092	1338	806	457	245	123	58	26
	80-XS-80S	3583	2350	1445	832	449	227	108	48	20
	160	3877	2450	1443	792	405	193	86	35	14
	XXS	3954	2280	1208	588	263	108	41	14	5
3/4	5S	4418	3246	2485	1871	1362	959	653	430	274
	10S	5354	3933	3003	2238	1612	1121	753	489	307
	40-Std-40S	6679	4907	3717	2724	1925	1311	861	545	333
	80-XS-80S	8076	5944	4423	3165	2177	1439	915	559	328
	160	9501	6977	5015	3450	2271	1430	862	497	274
	XXS	10445	7509	5143	3350	2074	1221	684	364	184
1	5S	9014	6623	5071	4006	3251	2613	2058	1587	1199
	10S	13650	10028	7678	6066	4898	3879	3005	2276	1687
	40-Std-40S	15750	11572	8859	7000	5625	4418	3390	2543	1864
	80-XS-80S	19044	13991	10712	8484	6715	5185	3906	2872	2059
	160	22563	16577	12692	10003	7725	5805	4245	3021	2092
	XXS	25329	18609	14282	10956	8146	5871	4102	2777	1823
1 1/4	5S	11725	11725	10523	8315	6735	5566	4677	3983	3352
	10S	19120	19120	16280	12863	10419	8611	7249	6126	5107
	40-Std-40S	24067	24067	19750	15605	12640	10446	8799	7388	6118
	80-XS-80S	31733	31733	24526	19378	15696	12972	10902	9056	7412
	160	39867	37607	28793	22750	18427	15254	12708	10420	8409
	XXS	55214	45190	34599	27337	22143	18246	14783	11760	9185
1 1/2	5S	13490	13490	13490	12656	10251	8472	7119	6066	5235
	10S	22079	22079	22079	19781	16023	13242	11127	9481	8194
	40-Std-40S	28780	28780	28780	24836	20118	16626	13970	11904	10284
	80-XS-80S	38453	38453	38453	31353	25396	20989	17636	15027	12940
	160	51452	51452	48930	38661	31315	25880	21747	18571	15781
	XXS	67858	67858	57598	45510	36863	30465	25651	21665	18052
2	5S	16982	16982	16982	16982	16982	16894	14196	12096	10429
	10S	27934	27934	27934	27934	27934	26782	22504	19175	16534
	40-Std-40S	38683	38683	38683	38683	38683	35718	30013	25573	22050
	80-XS-80S	53181	53181	53181	53181	53181	46565	39127	33339	28746
	160	78826	78826	78826	78826	75455	62359	52399	44648	38497
	XXS	95613	95613	95613	95613	85126	70352	59115	50370	43432
2 1/2	5S	26209	26209	26209	26209	26209	26209	26209	26209	23516
	10S	37390	37390	37390	37390	37390	37390	37390	37390	32699
	40-Std-40S	61346	61346	61346	61346	61346	61346	61346	58754	50660
	80-XS-80S	81127	81127	81127	81127	81127	81127	81127	73915	63733
	160	106029	106029	106029	106029	106029	106029	106029	90375	77925
	XXS	145024	145024	145024	145024	145024	145024	129420	110275	95084
3	5S	32076	32076	32076	32076	32076	32076	32076	32076	32076
	10S	45872	45872	45872	45872	45872	45872	45872	45872	45872
	40-Std-40S	80225	80225	80225	80225	80225	80225	80225	80225	80225
	80-XS-80S	108573	108573	108573	108573	108573	108573	108573	108573	108573
	160	151384	151384	151384	151384	151384	151384	151384	151384	151384
	XXS	196789	196789	196789	196789	196789	196789	196789	196789	196789
4	5S	41463	41463	41463	41463	41463	41463	41463	41463	41463
	10S	59444	59444	59444	59444	59444	59444	59444	59444	59444
	40-Std-40S	114266	114266	114266	114266	114266	114266	114266	114266	114266
	80-XS-80S	158668	158668	158668	158668	158668	158668	158668	158668	158668
	120	200808	200808	200808	200808	200808	200808	200808	200808	200808
	160	238357	238357	238357	238357	238357	238357	238357	238357	238357
	XXS	291647	291647	291647	291647	291647	291647	291647	291647	291647

Nominal Tube Size	Specification	Effective Height in Feet								
		7.5	8	8.5	9	9.5	10	10.5	11	11.5
1	5S	887	643	456	317	216	144	94	60	38
	10S	1222	866	601	407	270	175	111	69	42
	40-Std-40S	1335	934	639	427	279	178	111	68	40
	80-XS-80S	1441	984	655	426	270	167	101	59	34
	160	1410	925	590	367	222	130	75	42	23
	XXS	1160	715	427	248	139	76	40	20	10
1 1/4	5S	2785	2284	1850	1479	1168	910	701	532	399
	10S	4201	3410	2730	2157	1681	1293	981	734	542
	40-Std-40S	4996	4023	3194	2501	1931	1471	1104	818	597
	80-XS-80S	5977	4749	3718	2867	2179	1632	1204	875	627
	160	6680	5222	4018	3044	2269	1665	1202	854	598
	XXS	7044	5304	3922	2847	2029	1420	976	658	436
1 1/2	5S	4551	3918	3341	2821	2360	1955	1604	1303	1048
	10S	7076	6050	5120	4289	3557	2921	2374	1910	1521
	40-Std-40S	8832	7505	6311	5252	4325	3524	2841	2267	1790
	80-XS-80S	11014	9271	7718	6354	5173	4165	3316	2611	2034
	160	13249	10990	9007	7293	5835	4612	3602	2779	2119
	XXS	14840	12036	9631	7603	5921	4550	3449	2579	1903
2	5S	9085	7985	7073	6324	5649	5016	4426	3883	3385
	10S	14403	12659	11213	10023	8916	7881	6922	6042	5240
	40-Std-40S	19208	16882	14970	13345	11817	10396	9086	7889	6805
	80-XS-80S	25041	22009	19543	17311	15229	13304	11543	9945	8510
	160	33535	29540	26029	22761	19751	17008	14534	12325	10372
	XXS	37834	33283	29050	25147	21590	18384	15525	13003	10802
2 1/2	5S	20485	18005	15949	14226	12768	11523	10452	9546	8690
	10S	28484	25035	22176	19781	17753	16022	14544	13265	12047
	40-Std-40S	44131	38787	34358	30646	27505	24824	22570	20473	18487
	80-XS-80S	55518	48795	43224	38554	34603	31269	28358	25595	22992
	160	67882	59662	52849	47140	42309	38268	34472	30895	27549
	XXS	82829	72798	64486	57520	51724	46272	41159	36403	32013
3	5S	32076	32076	29228	26070	23398	21117	19154	17452	15967
	10S	45872	45872	40926	36505	32764	29569	26820	24437	22359
	40-Std-40S	80225	76510	67774	60452	54256	48966	44414	40468	37026
	80-XS-80S	108573	98753	87477	78027	70030	63202	57326	52233	47790
	160	145182	127601	113031	100821	90487	81665	74072	67491	61750
	XXS	172897	151960	134608	120067	107761	97254	88213	80376	73703
4	5S	41463	41463	41463	41463	41463	41463	41361	37687	34481
	10S	59444	59444	59444	59444	59444	59444	58333	53150	48629
	40-Std-40S	114266	114266	114266	114266	114266	114266	106467	97008	88756
	80-XS-80S	158668	158668	158668	158668	158668	155972	141471	128902	117937
	120	200808	200808	200808	200808	200808	188963	171395	156168	142883
	160	238357	238357	238357	238357	238357	215379	195355	177999	162857
	XXS	291647	291647	291647	291647	274841	248044	224983	204995	187557

Nominal Tube Size	Specification	Effective Height in Feet								
		12	12.5	13	13.5	14	14.5	15	15.5	16
1 1/4	5S	296	216	156	111	78	54	37	25	17
	10S	395	284	201	141	97	66	45	30	19
	40-Std-40S	430	305	214	148	100	67	45	29	19
	80-XS-80S	442	307	211	142	94	62	40	25	16
	160	412	279	186	122	79	50	31	19	12
	XXS	284	181	114	70	42	25	15	8	5
1 1/2	5S	835	659	515	399	306	232	175	130	96
	10S	1199	936	723	553	419	314	233	171	124
	40-Std-40S	1399	1081	827	626	469	348	255	185	133
	80-XS-80S	1566	1193	899	669	493	359	259	184	130
	160	1596	1188	873	634	455	323	226	157	107
	XXS	1385	995	705	493	340	231	155	103	67
2	5S	2933	2526	2162	1840	1556	1307	1092	907	748
	10S	4516	3868	3291	2783	2339	1953	1620	1336	1095
	40-Std-40S	5832	4965	4199	3528	2945	2442	2012	1647	1339
	80-XS-80S	7231	6102	5114	4256	3518	2888	2354	1906	1532
	160	8661	7178	5903	4818	3902	3136	2501	1979	1555
	XXS	8899	7272	5893	4736	3776	2985	2341	1820	1404
2 1/2	5S	7878	7112	6394	5725	5104	4532	4007	3528	3093
	10S	10893	9808	8794	7850	6978	6177	5444	4777	4174
	40-Std-40S	16618	14871	13247	11747	10370	9113	7972	6942	6018
	80-XS-80S	20555	18290	16196	14274	12520	10930	9496	8211	7066
	160	24440	21572	18943	16550	14386	12442	10705	9165	7806
	XXS	27991	24336	21038	18083	15454	13132	11096	9322	7787
3	5S	14664	13515	12503	11613	10756	9935	9151	8405	7698
	10S	20534	18924	17526	16252	15028	13857	12741	11681	10680
	40-Std-40S	34004	31339	29040	26816	24688	22661	20738	18921	17211
	80-XS-80S	43890	40542	37410	34412	31555	28844	26282	23873	21616
	160	56836	52291	47946	43814	39901	36214	32757	29529	26528
	XXS	67544	61671	56100	50843	45908	41298	37013	33050	29402
4	5S	31667	29185	26983	25021	23266	21689	20267	18981	17813
	10S	44661	41159	38054	35288	32812	30588	28583	26769	25122
	40-Std-40S	81514	75123	69456	64406	59888	55829	52169	48858	45852
	80-XS-80S	108314	99822	92291	85581	79577	74184	69321	64921	61011
	120	131225	120937	111813	103684	96410	89876	83984	78653	73991
	160	149569	137842	127443	118178	109887	102439	95724	89836	84269
	XXS	172253	158748	146771	136101	126553	117976	110458	103424	96628

Nominal Tube Size	Specification	Effective Height in Feet								
		16.5	17	17.5	18	18.5	19	19.5	20	20.5
2	5S	614	500	405	327	261	208	164	129	101
	10S	891	721	580	463	368	290	227	177	137
	40-Std-40S	1081	868	692	548	431	337	262	202	155
	80-XS-80S	1223	970	764	597	464	358	274	208	157
	160	1212	937	719	548	414	311	231	171	125
	XXS	1074	815	613	458	339	249	181	131	94
2 1/2	5S	2701	2348	2033	1753	1506	1288	1096	930	785
	10S	3632	3147	2714	2332	1994	1698	1440	1216	1023
	40-Std-40S	5193	4461	3815	3248	2752	2322	1950	1630	1357
	80-XS-80S	6052	5159	4376	3695	3105	2597	2161	1790	1476
	160	6614	5576	4677	3903	3241	2677	2200	1799	1464
	XXS	6468	5341	4386	3581	2907	2347	1883	1503	1193
3	5S	7032	6405	5818	5270	4760	4287	3851	3450	3081
	10S	9736	8850	8022	7251	6536	5874	5264	4704	4192
	40-Std-40S	15609	14114	12723	11435	10247	9154	8154	7241	6411
	80-XS-80S	19511	17556	15747	14080	12550	11150	9876	8720	7675
	160	23752	21194	18847	16703	14753	12986	11392	9960	8678
	XXS	26060	23012	20245	17745	15496	13482	11686	10092	8683
4	5S	16750	15806	14922	14064	13233	12431	11657	10914	10201
	10S	23622	22302	21035	19805	18617	17469	16365	15305	14289
	40-Std-40S	43202	40692	38260	35909	33643	31463	29372	27371	25461
	80-XS-80S	57420	53939	50575	47332	44214	41225	38366	35639	33044
	120	69447	65055	60823	56755	52856	49128	45575	42196	38992
	160	78887	73699	68712	63933	59365	55012	50875	46953	43246
	XXS	90084	83803	77792	72056	66599	61423	56527	51909	47566

Nominal Tube Size	Specification	Effective Height in Feet								
		21	21.5	22	22.5	23	23.5	24	24.5	25
2 1/2	5S	660	553	461	383	317	261	214	175	142
	10S	856	714	592	490	403	330	269	219	177
	40-Std-40S	1124	927	761	622	506	410	330	265	212
	80-XS-80S	1211	989	804	650	523	419	334	265	210
	160	1185	954	764	609	483	381	299	234	182
	XXS	941	738	576	447	344	264	201	153	115
3	5S	2745	2438	2160	1908	1681	1476	1293	1130	984
	10S	3725	3300	2916	2569	2257	1977	1727	1504	1307
	40-Std-40S	5659	4980	4369	3822	3334	2899	2513	2172	1872
	80-XS-80S	6734	5889	5135	4463	3866	3339	2875	2467	2111
	160	7535	6521	5624	4834	4141	3535	3008	2550	2155
	XXS	7443	6356	5408	4585	3872	3258	2731	2281	1898
4	5S	9518	8867	8246	7656	7096	6566	6066	5595	5151
	10S	13317	12391	11510	10673	9880	9131	8424	7759	7134
	40-Std-40S	23642	21913	20275	18726	17264	15888	14595	13384	12251
	80-XS-80S	30581	28248	26045	23969	22017	20187	18474	16875	15385
	120	35961	33101	30409	27881	25514	23302	21241	19324	17546
	160	39751	36464	33381	30497	27805	25300	22973	20818	18827
	XXS	43492	39681	36126	32819	29750	26910	24289	21876	19660

Nominal Tube Size	Specification	Effective Height in Feet					
		25.5	26	26.5	27	27.5	28
3	5S	855	741	640	551	473	406
	10S	1132	977	842	723	619	528
	40-Std-40S	1608	1377	1176	1002	850	720
	80-XS-80S	1800	1530	1297	1096	923	775
	160	1815	1523	1274	1062	882	731
	XXS	1574	1300	1070	877	716	583
4	5S	4735	4345	3981	3641	3324	3030
	10S	6549	6001	5490	5013	4571	4160
	40-Std-40S	11195	10211	9297	8449	7666	6942
	80-XS-80S	14001	12718	11531	10435	9425	8498
	120	15901	14381	12982	11696	10517	9438
	160	16992	15305	13757	12341	11048	9870
	XXS	17630	15776	14087	12551	11159	9899

Appendix E: Tables for Values of the Hyperbolic Cosine and Hyperbolic Sine.

To use this chart, find the column with the tenths value and the row with the hundredths and thousands value. For example, to find the hyperbolic cosine of 0.346, start with column 0.300 and follow it down to row 0.046. The hyperbolic cosine of 0.346 is 1.060458.

COSH	0.000	0.100	0.200	0.300	0.400	0.500	0.600	0.700	0.800	0.900	1.000
0.000	1.000000	1.005004	1.020067	1.045339	1.081072	1.127626	1.185465	1.255169	1.337435	1.433086	1.543081
0.002	1.000002	1.005207	1.020471	1.045950	1.081896	1.128670	1.186741	1.256689	1.339214	1.435142	1.545434
0.004	1.000008	1.005413	1.020880	1.046565	1.082724	1.129719	1.188021	1.258213	1.340998	1.437204	1.547794
0.006	1.000018	1.005623	1.021293	1.047184	1.083556	1.130773	1.189307	1.259743	1.342788	1.439271	1.550160
0.008	1.000032	1.005838	1.021710	1.047808	1.084393	1.131831	1.190596	1.261278	1.344583	1.441344	1.552532
0.010	1.000050	1.006056	1.022131	1.048436	1.085234	1.132893	1.191891	1.262818	1.346383	1.443423	1.554910
0.012	1.000072	1.006279	1.022556	1.049068	1.086079	1.133960	1.193191	1.264363	1.348189	1.445508	1.557294
0.014	1.000098	1.006505	1.022986	1.049704	1.086929	1.135032	1.194495	1.265913	1.350000	1.447599	1.559685
0.016	1.000128	1.006736	1.023419	1.050345	1.087783	1.136108	1.195804	1.267468	1.351816	1.449695	1.562082
0.018	1.000162	1.006970	1.023856	1.050990	1.088641	1.137189	1.197118	1.269028	1.353638	1.451797	1.564485
0.020	1.000200	1.007209	1.024298	1.051638	1.089504	1.138274	1.198436	1.270593	1.355466	1.453905	1.566895
0.022	1.000242	1.007451	1.024743	1.052291	1.090371	1.139364	1.199760	1.272163	1.357299	1.456018	1.569311
0.024	1.000288	1.007698	1.025193	1.052949	1.091243	1.140458	1.201088	1.273738	1.359137	1.458138	1.571733
0.026	1.000338	1.007949	1.025647	1.053610	1.092119	1.141557	1.202421	1.275319	1.360980	1.460263	1.574161
0.028	1.000392	1.008203	1.026105	1.054276	1.092999	1.142661	1.203759	1.276904	1.362829	1.462394	1.576595
0.030	1.000450	1.008462	1.026567	1.054946	1.093883	1.143769	1.205101	1.278495	1.364684	1.464531	1.579036
0.032	1.000512	1.008725	1.027033	1.055620	1.094772	1.144881	1.206449	1.280091	1.366544	1.466674	1.581484
0.034	1.000578	1.008991	1.027503	1.056298	1.095666	1.145998	1.207801	1.281691	1.368409	1.468823	1.583937
0.036	1.000648	1.009262	1.027977	1.056981	1.096563	1.147120	1.209158	1.283297	1.370280	1.470978	1.586397
0.038	1.000722	1.009537	1.028456	1.057668	1.097465	1.148247	1.210520	1.284908	1.372157	1.473138	1.588863
0.040	1.000800	1.009816	1.028939	1.058359	1.098372	1.149378	1.211887	1.286525	1.374039	1.475305	1.591336
0.042	1.000882	1.010099	1.029425	1.059054	1.099283	1.150513	1.213258	1.288146	1.375926	1.477477	1.593815
0.044	1.000968	1.010386	1.029916	1.059754	1.100198	1.151653	1.214635	1.289773	1.377819	1.479655	1.596300
0.046	1.001058	1.010677	1.030411	1.060458	1.101118	1.152798	1.216016	1.291404	1.379717	1.481839	1.598792
0.048	1.001152	1.010972	1.030910	1.061166	1.102042	1.153947	1.217402	1.293041	1.381621	1.484029	1.601290
0.050	1.001250	1.011271	1.031413	1.061878	1.102970	1.155101	1.218793	1.294683	1.383531	1.486225	1.603794
0.052	1.001352	1.011574	1.031920	1.062594	1.103903	1.156260	1.220189	1.296331	1.385446	1.488427	1.606305
0.054	1.001458	1.011881	1.032432	1.063315	1.104840	1.157423	1.221590	1.297983	1.387366	1.490635	1.608823
0.056	1.001568	1.012193	1.032947	1.064040	1.105782	1.158591	1.222996	1.299641	1.389293	1.492849	1.611346
0.058	1.001682	1.012508	1.033467	1.064769	1.106728	1.159764	1.224406	1.301303	1.391224	1.495069	1.613877
0.060	1.001801	1.012827	1.033991	1.065503	1.107679	1.160941	1.225822	1.302971	1.393161	1.497295	1.616413
0.062	1.001923	1.013151	1.034519	1.066241	1.108634	1.162123	1.227242	1.304645	1.395104	1.499526	1.618957
0.064	1.002049	1.013478	1.035051	1.066983	1.109593	1.163309	1.228668	1.306323	1.397053	1.501764	1.621506
0.066	1.002179	1.013810	1.035587	1.067729	1.110557	1.164500	1.230098	1.308007	1.399006	1.504008	1.624062
0.068	1.002313	1.014145	1.036127	1.068480	1.111525	1.165696	1.231533	1.309696	1.400966	1.506258	1.626625
0.070	1.002451	1.014485	1.036672	1.069234	1.112498	1.166896	1.232973	1.311390	1.402931	1.508514	1.629194
0.072	1.002593	1.014829	1.037221	1.069994	1.113475	1.168101	1.234418	1.313089	1.404902	1.510776	1.631770
0.074	1.002739	1.015176	1.037773	1.070757	1.114457	1.169311	1.235868	1.314794	1.406878	1.513044	1.634352
0.076	1.002889	1.015528	1.038330	1.071525	1.115443	1.170525	1.237323	1.316504	1.408860	1.515318	1.636940
0.078	1.003044	1.015884	1.038892	1.072297	1.116434	1.171745	1.238783	1.318219	1.410848	1.517598	1.639536
0.080	1.003202	1.016244	1.039457	1.073073	1.117429	1.172968	1.240247	1.319939	1.412841	1.519884	1.642138
0.082	1.003364	1.016608	1.040026	1.073854	1.118428	1.174197	1.241717	1.321665	1.414840	1.522176	1.644746
0.084	1.003530	1.016976	1.040600	1.074638	1.119432	1.175430	1.243192	1.323396	1.416845	1.524474	1.647361
0.086	1.003700	1.017348	1.041178	1.075428	1.120441	1.176668	1.244671	1.325132	1.418855	1.526779	1.649982
0.088	1.003874	1.017724	1.041759	1.076221	1.121454	1.177911	1.246156	1.326874	1.420871	1.529089	1.652611
0.090	1.004053	1.018104	1.042346	1.077019	1.122471	1.179158	1.247646	1.328621	1.422893	1.531406	1.655245
0.092	1.004235	1.018489	1.042936	1.077821	1.123493	1.180410	1.249140	1.330373	1.424920	1.533728	1.657887
0.094	1.004421	1.018877	1.043530	1.078627	1.124520	1.181667	1.250640	1.332130	1.426953	1.536057	1.660535
0.096	1.004612	1.019270	1.044129	1.079438	1.125551	1.182928	1.252145	1.333893	1.428992	1.538392	1.663189
0.098	1.004806	1.019666	1.044732	1.080253	1.126586	1.184194	1.253654	1.335661	1.431036	1.540733	1.665851

SINH	0.000	0.100	0.200	0.300	0.400	0.500	0.600	0.700	0.800	0.900	1.000
0.000	0.000000	0.100167	0.201336	0.304520	0.410752	0.521095	0.636654	0.758584	0.888106	1.026517	1.175201
0.002	0.002000	0.102177	0.203377	0.306612	0.412915	0.523352	0.639026	0.761096	0.890783	1.029385	1.178290
0.004	0.004000	0.104188	0.205418	0.308704	0.415080	0.525610	0.641401	0.763610	0.893463	1.032257	1.181383
0.006	0.006000	0.106199	0.207460	0.310798	0.417246	0.527870	0.643778	0.766128	0.896147	1.035134	1.184481
0.008	0.008000	0.108210	0.209503	0.312893	0.419414	0.530133	0.646158	0.768649	0.898834	1.038014	1.187584
0.010	0.010000	0.110222	0.211547	0.314989	0.421584	0.532398	0.648540	0.771174	0.901525	1.040899	1.190691
0.012	0.012000	0.112234	0.213592	0.317087	0.423755	0.534665	0.650925	0.773701	0.904220	1.043788	1.193803
0.014	0.014000	0.114247	0.215637	0.319185	0.425928	0.536934	0.653313	0.776231	0.906918	1.046681	1.196920
0.016	0.016001	0.116260	0.217684	0.321285	0.428103	0.539205	0.655703	0.778764	0.909620	1.049578	1.200042
0.018	0.018001	0.118274	0.219731	0.323387	0.430279	0.541478	0.658096	0.781301	0.912325	1.052480	1.203169
0.020	0.020001	0.120288	0.221779	0.325489	0.432457	0.543754	0.660492	0.783840	0.915034	1.055386	1.206300
0.022	0.022002	0.122303	0.223828	0.327593	0.434637	0.546031	0.662890	0.786383	0.917747	1.058296	1.209436
0.024	0.024002	0.124318	0.225878	0.329699	0.436819	0.548311	0.665291	0.788929	0.920463	1.061210	1.212577
0.026	0.026003	0.126334	0.227929	0.331805	0.439002	0.550593	0.667694	0.791478	0.923183	1.064128	1.215723
0.028	0.028004	0.128350	0.229981	0.333913	0.441187	0.552877	0.670101	0.794030	0.925907	1.067051	1.218874
0.030	0.030005	0.130366	0.232033	0.336022	0.443374	0.555164	0.672509	0.796586	0.928635	1.069978	1.222029
0.032	0.032005	0.132384	0.234087	0.338133	0.445563	0.557452	0.674921	0.799144	0.931366	1.072909	1.225190
0.034	0.034007	0.134401	0.236141	0.340245	0.447753	0.559743	0.677335	0.801706	0.934101	1.075844	1.228355
0.036	0.036008	0.136420	0.238197	0.342358	0.449946	0.562036	0.679752	0.804271	0.936840	1.078784	1.231526
0.038	0.038009	0.138438	0.240253	0.344473	0.452140	0.564332	0.682172	0.806839	0.939582	1.081728	1.234701
0.040	0.040011	0.140458	0.242311	0.346589	0.454335	0.566629	0.684594	0.809411	0.942328	1.084677	1.237881
0.042	0.042012	0.142478	0.244369	0.348706	0.456533	0.568929	0.687019	0.811985	0.945078	1.087630	1.241066
0.044	0.044014	0.144498	0.246428	0.350825	0.458733	0.571231	0.689447	0.814563	0.947832	1.090587	1.244256
0.046	0.046016	0.146519	0.248489	0.352945	0.460934	0.573536	0.691878	0.817145	0.950589	1.093548	1.247452
0.048	0.048018	0.148541	0.250550	0.355067	0.463137	0.575843	0.694311	0.819729	0.953351	1.096514	1.250652
0.050	0.050021	0.150563	0.252612	0.357190	0.465342	0.578152	0.696748	0.822317	0.956116	1.099484	1.253857
0.052	0.052023	0.152586	0.254676	0.359314	0.467549	0.580463	0.699187	0.824908	0.958885	1.102459	1.257067
0.054	0.054026	0.154609	0.256740	0.361440	0.469758	0.582777	0.701628	0.827502	0.961658	1.105438	1.260282
0.056	0.056029	0.156634	0.258805	0.363567	0.471968	0.585093	0.704073	0.830100	0.964434	1.108422	1.263502
0.058	0.058033	0.158658	0.260872	0.365696	0.474181	0.587411	0.706520	0.832701	0.967215	1.111409	1.266727
0.060	0.060036	0.160684	0.262939	0.367827	0.476395	0.589732	0.708970	0.835305	0.969999	1.114402	1.269958
0.062	0.062040	0.162710	0.265008	0.369958	0.478611	0.592055	0.711424	0.837913	0.972788	1.117399	1.273193
0.064	0.064044	0.164736	0.267077	0.372092	0.480830	0.594380	0.713879	0.840523	0.975580	1.120400	1.276433
0.066	0.066048	0.166763	0.269148	0.374226	0.483050	0.596708	0.716338	0.843138	0.978376	1.123406	1.279679
0.068	0.068052	0.168791	0.271220	0.376362	0.485272	0.599038	0.718800	0.845756	0.981176	1.126416	1.282930
0.070	0.070057	0.170820	0.273292	0.378500	0.487496	0.601371	0.721264	0.848377	0.983980	1.129431	1.286185
0.072	0.072062	0.172849	0.275366	0.380639	0.489722	0.603706	0.723732	0.851001	0.986787	1.132450	1.289446
0.074	0.074068	0.174879	0.277441	0.382780	0.491950	0.606043	0.726202	0.853629	0.989599	1.135474	1.292713
0.076	0.076073	0.176910	0.279517	0.384922	0.494180	0.608383	0.728675	0.856260	0.992415	1.138502	1.295984
0.078	0.078079	0.178941	0.281595	0.387066	0.496412	0.610725	0.731151	0.858895	0.995235	1.141535	1.299260
0.080	0.080085	0.180974	0.283673	0.389212	0.498646	0.613070	0.733630	0.861533	0.998058	1.144573	1.302542
0.082	0.082092	0.183006	0.285753	0.391359	0.500881	0.615417	0.736112	0.864175	1.000886	1.147615	1.305829
0.084	0.084099	0.185040	0.287833	0.393507	0.503119	0.617767	0.738597	0.866820	1.003718	1.150661	1.309121
0.086	0.086106	0.187074	0.289915	0.395657	0.505359	0.620119	0.741085	0.869468	1.006553	1.153713	1.312418
0.088	0.088114	0.189109	0.291998	0.397809	0.507601	0.622473	0.743576	0.872120	1.009393	1.156768	1.315721
0.090	0.090122	0.191145	0.294082	0.399962	0.509845	0.624831	0.746070	0.874776	1.012237	1.159829	1.319029
0.092	0.092130	0.193182	0.296167	0.402117	0.512091	0.627190	0.748567	0.877435	1.015085	1.162894	1.322342
0.094	0.094138	0.195219	0.298254	0.404273	0.514339	0.629552	0.751066	0.880097	1.017937	1.165964	1.325660
0.096	0.096148	0.197257	0.300341	0.406431	0.516589	0.631917	0.753569	0.882763	1.020793	1.169038	1.328984
0.098	0.098157	0.199296	0.302430	0.408591	0.518841	0.634284	0.756075	0.885433	1.023653	1.172117	1.332313

Appendix F: Notes on Concrete Strength and Curing.

Concrete is a mixture of cement, aggregate, water, and air voids. When cement mixes with water it starts a chemical reaction. This reaction continues until all the water has combined with the cement or the water evaporates. Concrete should not dry; it should cure. If fresh concrete is covered and kept moist (cured) from the first day it continues to gain strength. If it is allowed to dry out, it will stop gaining strength.

The table below represents approximations of concrete strengths, in psi, at various ages and various curing lengths. The strengths are based on concrete mixed at a 3:2:1 (Gravel:Sand:Cement) ratio and mixed by hand in a field engineering situation.

Day	Air Cure	3 Day Cure	7 Day Cure	28 Day Cure
3	554	825	825	825
7	894	1154	1154	1154
14	1047	1475	1603	1603
21	1090	1578	1786	1853
28	1093	1626	1877	2000

These estimates are based on an educated guess from a concrete expert (Dr. Thomas Van Dam, Civil & Environmental Engineering, Michigan Technological University) and a generic curing graph taken from a Kosmatka et al. ("Design/Control of Concrete Mixes,", CPCA, 1991).

Appendix G: Useful Equations and Constants.

Quadratic Equation:

If $ax^2 + bx + c = 0$, then

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

Standard Weights

	pcf	lbs/in^2
Water	62.4	0.0361
Concrete	150	0.0868
Gravel	95	0.0550
Gravel w/sand	125	0.0723
Sand (dry)	100	0.0579
Sand (wet)	120	0.0694
Limestone (solid)	163	0.0943
Limestone (broken)	97	0.0561
Granite (Solid)	168	0.0972
Granite (broken)	103	0.0596
Steel	495	0.2865

Friction Angle of Various Soils

	Φ
Sand and Gravel Mixture	33-36
Well Graded Sand	32-35
Fine to Medium Sand	29-32
Silty Sand	27-32
Silt	26-30