the 100-year flood elevation of 400 feet identified by the historical highwater marks was realistic. The results were very interesting. If one excluded the log jams in the HEC-II model, the 100-year flood level was much below elevation 400. With the log jams modeled, the flood level rose. The elevation of 400 feet was used as the design and regulatory standard.

The Main Cables – Catenary Cables

Thus far, the main cables have been referred to as catenary cables. For a cable to assume the shape of a catenary, the load on the cable must be uniformly distributed. Under the spaced suspender loading, the shape is closer to a parabola. The difference between the two is very slight. Since the equation for a parabola is easier to work with, most engineers use the parabola equation in the design of simple suspension bridges. Since this case study is presented as a planning document, not an engineering text, the author has refrained from including design equations. However presenting some basic wire rope equations for a single-span suspension bridge at this point has some value (see Figure 9).

- e = sag of catenary cable.
- ℓ = the span or horizontal distance from center of each cable saddle to opposite cable saddle. In the case of the Pochuck Quagmire Bridge, the as-built distance is 110.20 feet.
- W = the total live and dead load of the bridge expressed as load per unit length of span. Assumes backstays have no suspender loads.

  Length of a uniformly loaded cable between two supports at equal elevation:

  $$L = \ell\left(1+\left[\frac{8}{3}\right]\frac{e^2}{\ell^2}-\left[\frac{32}{5}\right]\frac{e^4}{\ell^4}+\left[\frac{256}{7}\right]\frac{e^6}{\ell^6}\right)$$

  The maximum tension in the cable is immediately before the cable saddle:

  $$T_{saddle} = \left[\frac{w}{8e}\right]\sqrt{l^4+16e^2\ell^2}$$

  The minimum tension in the cable is at the midpoint sag lowpoint of the cable: $T_{Lowpoint} = \frac{w\ell^2}{8e}$

  Tension at a given point B: $T_B = \frac{w}{8e}\sqrt{\ell^4+64e^2-y^2}$

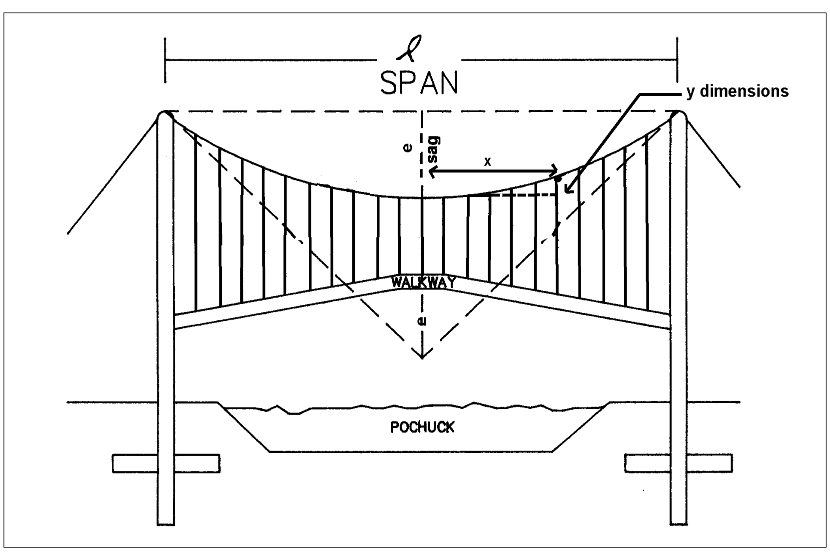
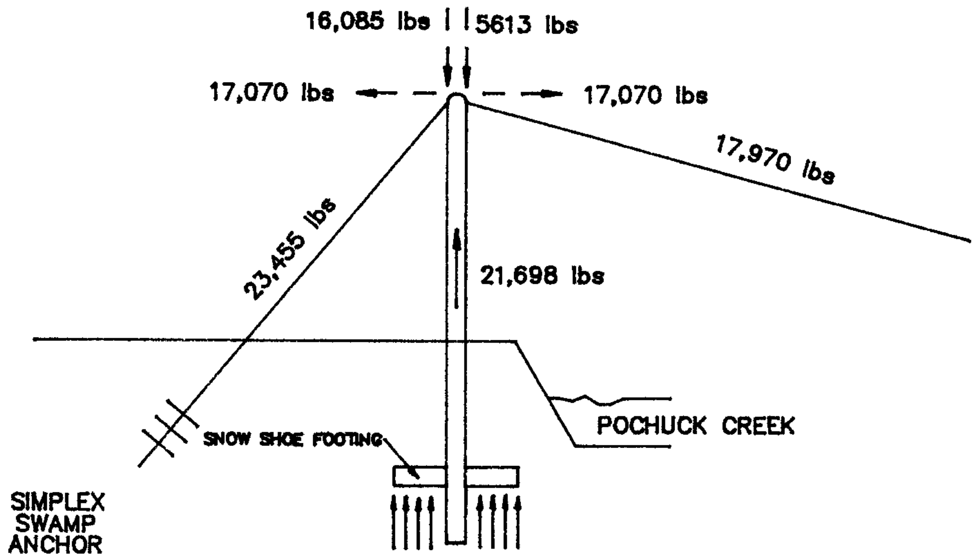
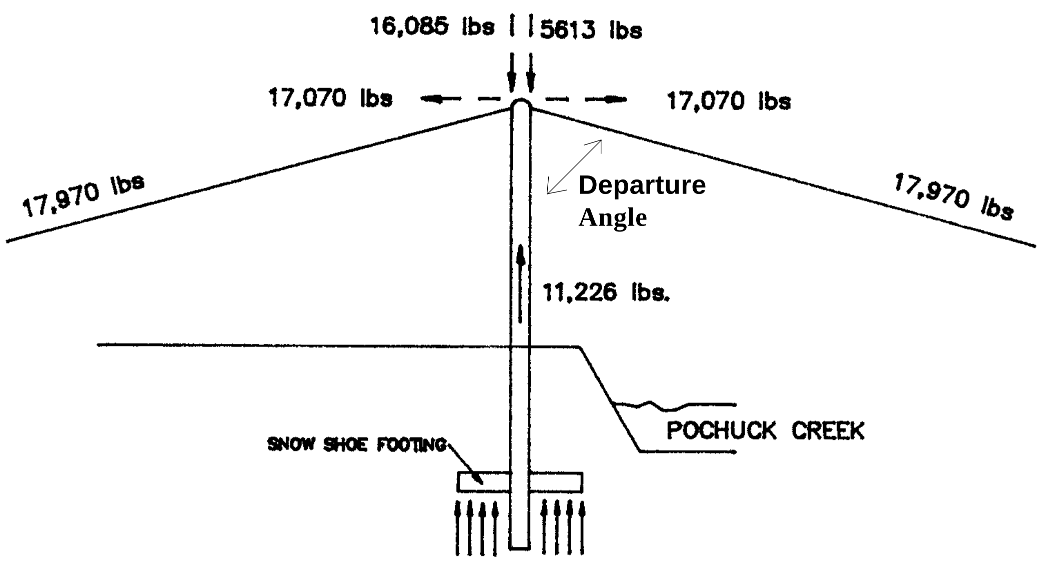


Figure 9. Nomenclature for wire rope equations.

Figure 10 provides freebody vector diagram for the Pochuck Quagmire Bridge cable saddles and tower tops. The identified loads were calculated utilizing the previous equations, bridge loads, and bridge dimensions. The freebody vector diagram illustrate the important design element, that where practical, the cable departure angle on either side of the cable saddle should be equal. Equilibrium is easier to obtain if the angles are equal. If the departure angles are not equal, additional loads are transferred to the backstay and tower. In the Pochuck Quagmire



As-built Freebody Diagram. Departure Angle of Catenary and Backstay angles differ.



Ideal configuration: Departure angle for Catenary and Backstay cables are equal.

Figure 10. The freebody diagram for the Pochuck Quagmire Bridge tower poles.

Bridge, the difference in the departure angle almost doubled the axial load on the poles. The unbalanced tension loads at the cable saddle times the friction coefficient of the saddles result in an overturning load on the towers. This overturning is counteracted by the tower foundation and guylines. Equal departure angles were not utilized on the Pochuck Quagmire Bridge because the poor subsurface soil conditions dictated that the six helix helical anchor be installed at 46°. An installation angle as shallow as 18.2° would have led to difficult installation problems with the helical anchors. Having equal departure angles is easier to attain when the riverbank topography rises up steeply as in a river gorge or when the sag-span ratio is high.

So far, the discussion has concerned the geometry of the wire rope in the vertical plane. The horizontal plane must also be considered. As defined on page 14, cradle and flare must also be considered. As shown by Figure 2 on page 15, the flare is the horizontal offset distance (or angle) between the straight line established by the cable saddles and the connection to the anchorages. A 1.5°-2.0° angle is recommended. The Pochuck Quagmire Bridge backstays have a 2° flare.

The backstay anchorage locations were originally staked out in advance by the survey crew of Conklin Associates. As often happens, the survey stakeout and offset stakes were knocked out during excavation. The only way to ensure the correct flare on short notice was to set up a transit on top of the east poles and to turn angles; this is shown in photo 3 (page 20). Not too often is a transit set up on top of a 34-foot tall transmission pole. The Pochuck Quagmire Bridge cable and suspenders do not have cradle. While it would be easy to vary the offset distance of the bore holes in the 6-inch by 6-inch cross-stringer to achieve cradle in the horizontal plane, this would conflict with the 3.5 percent (or 2 degrees) bevel cut that set the walkway slope. The Lincoln Woods Trail Bridge in WMNF, New Hampshire, is a good example of a suspension bridge with cradle.

The wire rope industry, as well as the Occupational Safety and Health Act (OSHA), recommend that a safety factor of 5 be utilized for wire rope installations. A more formal way of stating this is that the working load should not exceed 1/5 of the ultimate breaking strength. While this may seem high compared to other structural system safety factors, it is prudent. This large safety factor takes into consideration misuse, poor maintenance, and public safety. From a historical perspective, John Roebling specified a safety factor of 6 for the Brooklyn Bridge main cables. However, it was reduced to a safety factor 5. The Brooklyn Bridge, an American icon, carries traffic loads never envisioned by its designer 113 years later.

As shown by Figures 11 and 12, wire rope has a number of components. Individual wires are laid together to form a strand. A number of strands

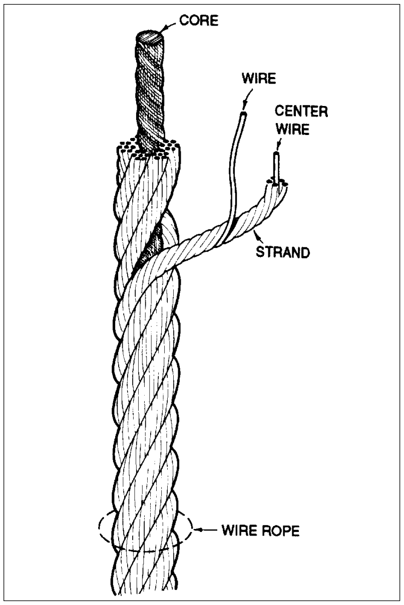


Figure 11. Typical wire rope components. *Courtesy of the Wire Rope Technical Board, Granbury, Texas.*

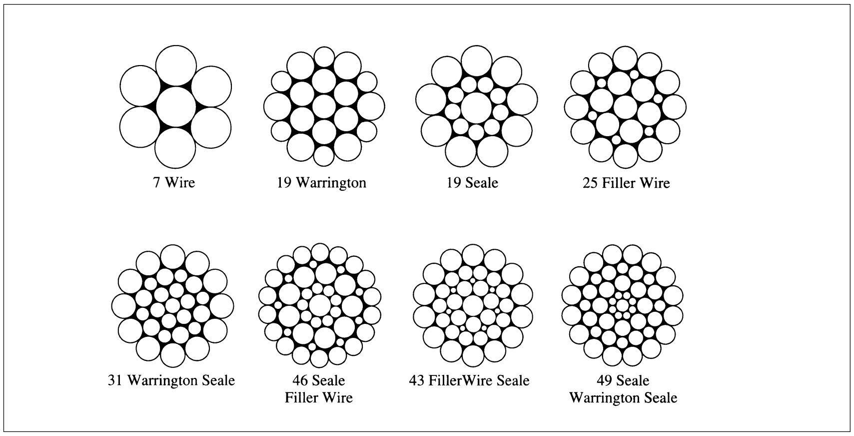


Figure 12. Strand patterns. *Courtesy of the Wire Rope Technical Board, Granbury, Texas.*

are laid in a helical path around a center core to form the wire rope. It is important to remember that the wires and strands all move in relation to one another. A wire rope must be lubricated! The purpose of the wire rope core is to position the strands properly and to allow them to slide freely so each strand picks up an equal portion of the load. The core can be a fiber or an independent wire rope core (IWRC) when additional strength is required. In classifying wire rope, the first number is the number of strands in the rope, and the second number is the number of wires in a strand. For example: 6 x 19 = 6 strands of 19 wires; 6 x 37 = 6 strands of 37 wires; 7 x 7 = 7 strands of 7 wires.

Another primary characteristic is the “lay” of the wire rope. The lay of a wire rope is determined by the direction in which the strands are laid into the rope and by the direction in which the wires are laid into the strands. Each type of lay gives specific characteristics to a wire rope.

- Right lay = Strands form a right hand helix.
- Left lay = Strands form a left hand helix.
- Regular lay = Lay of strands is opposite the wire lay.
- Lang lay = Lay of strands and wires are common.

Different grades of steel, finishes, cores, number of strands, number of wires in a strand, and lay allows a manufacturer to produce a wire rope that has specific characteristics. For example, a 19 x 7 is a spin resistant wire rope good for hoisting applications. The wire rope that is specifically made for suspension bridges is galvanized structural bridge rope. It is made in a right and regular lay. It is commonly a 7 x 7 IWRC, 6 x 7 IWRC, 6 x 25 IWRC, or 6 x 43 IWRC construction depending on diameter. The distinguishing feature of structural bridge rope is that it has a high Modulus of Elasticity (E). The Modulus of Elasticity of a material in tension is the ratio of unit stress to unit strain. The Modulus of Elasticity determines the stretch of a wire rope under load over a period of time. The E for structural bridge rope is 20 million PSI.

The only difficulty with structural bridge rope for small scale projects is that it is not a common item. It is difficult to obtain in short lengths, and it needs to be ordered far in advance. A normal minimum order of structural bridge rope is 5,000 feet. Needing only 404 feet, the project engineer performed a search among suppliers for “left over” lengths of 1-inch bridge rope. None were available. This practical problem was compounded by the purchasing responsibilities among the project partners, the accelerated construction schedule, and the six week construction “window” in the Pochuck Quagmire.

The purchase procedures for the project were set up so each project partner provided the material that they were most familiar with. This stretched the public dollars. The State of New Jersey Division of Parks and Forestry purchased the lumber and common components. The NY-NJ Trail Conference was advancing the money to purchase the specialty items, such as the anchors and the wire rope. This money would be reimbursed by a grant issued by the USDA Forest Service, Wood In Transportation program, when the bridge was complete. The Trail Conference could not commit to purchasing specialty items until all the pieces of the Pochuck puzzle were in place. These puzzle pieces included the environmental and construction permits, approved safety plan, rights of vehicular access, cooperative weather, permits, availability of GPU Energy, volunteer support, and other factors. However, once the critical mass of paperwork, machinery, and peoplepower were finally in sync, one could not say “Oh, the cable will be here in six weeks.” The solution was to substitute a more commonly available wire rope that was equal to bridge rope. Upon consultation with manufacturers, 1-inch 6 x 25 EIP IWRC RRL wire rope was specified. A regular lay rope withstands crushing action well. This is important in the cable saddle use. The nominal breaking strength of the 1-inch 6 x 25 EIP IWRC RRL was certified by the manufacturer to be 105,619 pounds of tension. A break test is performed on each run of cable manufactured. This provided a safety factor of 4.5 against the full dead and live design loads of the bridge. Increasing the wire rope diameter to 1 1/8-inch or 1 1/4-inch to achieve a safety factor of 5 would have increased the cost of the piggyback clips and other hardware. The benefits did not justify the additional expense in light of the rare chance that the bridge will ever have 110 people on it during a 30-inch snowstorm. Prior to making the decision, the project engineer calculated the wire rope safety factor of the other five pedestrian suspension bridges on the Appalachian Trail to determine what safety factor is common and customary for trail bridges. This was performed using their as-built span, sag, walkway surface areas, regional snow loads, design live loads, as-built dead loads, and end attachment efficiency factors. The wire rope safety factors for the Appalachian Trail bridges were as follows:

- Great Gulf = 1.3
- Tye River = 1.5
- Clarendon Gorge = 2.1
- Kimberly Creek = 3.1
- Pochuck Quagmire = 4.5
- Big Branch = 4.85

The Pochuck Quagmire Bridge is clearly at the conservative end of the scale.

A brief comparison of the two wire rope alternatives follows.

	1-inch Bridge Rope	1-inch 6 x 25 Wire Rope
Ultimate Strength	91,400 pounds	105,600 pounds
Cross-Section Area	.471 in^2	.404 in^2
Modulus of Elasticity (E)	20,000,000	13,000,000
Stretch in 202 feet	.10 foot	.18 foot
Cost per foot	$3.50/foot	$2.00/foot

The major difference between the two is that the higher E of the bridge rope results in .1 foot (1.2 inches) versus .18 feet (2.2 inches) of stretch under fully loaded conditions in each 202 feet of catenary cable. This may be significant in large size, heavily traveled steel and concrete bridges, but it is not significant in a 110-foot center span timber trail suspension bridge. There is a turnbuckle, as shown in photo 55 (page 55), at the end of each wire rope that provides for 2 feet of adjustment. Steps were taken to minimize the long-term stretch of the 1-inch 6 x 25 EIP IWRC wire rope. The wire rope was proof tested under a load of 36,000 pounds subsequent to cutting and installation of the wire rope sockets. This ensured the integrity of the wire rope sockets. This was 1.5 times the ultimate design load and multiple times the everyday working load. The use of the 6 x 25 wire rope was a sound decision. It was the last construction material ordered. The order was placed when the towers were up and ready to receive them. GPU Energy donated a truck and peoplepower to pick up the cable. The wire rope catenary cables were installed that same evening, and the project moved forward without missing a beat. The suspenders were installed immediately afterwards. By this time, it was October, and the hurricane season was in full stride. The site had begun to deteriorate rapidly, and time was of the essence.