EM 1110-2-3200
30 November 2016

US Army Corps of Engineers®
ENGINEERING AND DESIGN

Wire Rope for Civil Works Structures

ENGINEER MANUAL

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CECW-CE

DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
Washington, DC 20314-1000

EM 1110-2-3200

Manual
No. 1110-2-3200

30 November 2016

Engineering and Design
WIRE ROPE FOR CIVIL WORKS STRUCTURES

1. Purpose. This manual provides guidance and information to engineering, operations, maintenance, and construction personnel and to other individuals responsible for the U.S. Army Corps of Engineers (USACE) civil works equipment. The manual provides information and criteria important to the selection, installation, inspection, and maintenance of wire rope and fittings. It applies primarily to gate-operating devices and other civil works structures within the Corps of Engineers' responsibility.

2. Applicability. This manual applies to all HQUSACE elements, major subordinate commands, districts, laboratories, and field operating activities having responsibilities for the design and construction of civil works projects.

3. Distribution Statement. This manual is approved for public release with unlimited distribution.

4. References. References are listed in Appendix A.

5. Background. The manual is intended for designers and operators of civil works navigation structures and hydropower facilities. A unique problem facing the Corps is the wide variety of wire rope service conditions, which are determined by rope and hoisting equipment design, frequency of use, and the operating environments that exist at Corps installations. This manual covers many of these conditions and presents the latest technology from commercial and industrial sources and information from existing Corps projects. Its purpose is to optimize the service life of wire rope and to reduce the likelihood of future failures. Operation and maintenance considerations are also addressed.

FOR THE COMMANDER:

6 Appendices
(See Table of Contents)

PAUL E. OWEN
COL, EN
Chief of Staff

This manual supersedes EM 1110-2-3200, dated 30 September 1998.

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CHAPTER 1

Introduction

1-1. Purpose. This manual provides engineering and operational personnel with guidance on how to select, specify, inspect, install, and maintain wire rope and fittings. It applies primarily to gate operating devices and civil work structures within the Corps of Engineers' responsibility.

1-2. Applicability. This manual applies to all HQUSACE elements, major subordinate commands, districts, laboratories, and field operating activities having responsibilities for the design and construction of civil works projects.

1-3. References. References to this manual, which include technical papers, engineering guidance, engineering manuals, industry standards, and text books, are provided in Appendix A.

1-4. General. The document is a revision and update of the information presented in the 30 September 1998 version of EM 1110-2-3200.

a. Relationship to Other Manuals. This manual supersedes all previous versions of EM 1110-2-3200. It should be used in conjunction with EM 1110-2-2610, Mechanical and Electrical Design for Lock and Dam Operating Equipment, and EM 1110-2-1424, Lubricants and Hydraulic Fluids, and all other referenced engineering manuals for the design, selection, inspection, maintenance, and operation of wire rope. Other applicable manuals are listed in Appendix A.

b. Wire Rope Construction and Materials. Chapter 2 is dedicated to wire rope construction. This includes the different classifications and the different types of wire rope materials.

c. Applications. Chapter 3 is new chapter not provided in the old version of EM 3200. It covers wire rope applications including applications for various types of gates.

d. Design Considerations. Chapter 4 includes design considerations for wire rope including factor of safety, wire rope failure modes, and tensioning devices.

e. Sockets and End Terminations. Chapter 5 provides discussion of sockets and end terminations for wire rope.

f. Specifying Wire Rope. Chapter 6 includes discussion of applicable guide specifications for wire rope and guidelines for purchasing wire rope.

g. Field Acceptance and Installation and Testing. Chapter 7 includes field installation, testing, and tensioning requirements.

h. Inspection, Operation and Maintenance, and Retirement of Wire Rope. Chapter 8 is dedicated to inspection requirements for wire rope and guidelines for retirement of wire rope.

i. Engineering Reports and Case Studies. Appendix B includes a discussion of wire rope failures.

j. Sample Calculations. Appendix C provides several wire rope sizing calculations.

k. Load Limiting Devices. Appendix D includes a white paper from Portland District on various means to limit torque into a mechanical drive system.

l. Sample Inspection Checklist. Appendix E includes a wire rope inspection checklist.

m. Glossary. Appendix F includes a glossary of lubrication terms.

1-5. Mandatory Requirements and Deviation from Design Criteria. This manual provides guidance for the protection of U.S. Army Corps of Engineers (USACE) structures and equipment. In certain cases, guidance requirements, because of their criticality to project safety and performance, are considered to be mandatory as discussed in Engineer Regulation (ER) 1110-2-1150. Those cases will be identified as "mandatory," or the word "shall" or "must" will be used in place of "should."

1-6. Wire Rope Failures. The Corps has recently experienced wire rope failures at several projects. Appendix B discusses these further. These failures helped prompt the development of this manual. Wire rope failures typically render gates inoperable causing delays to navigation and flooding potential, including possible overtopping of a flood risk management dam, equipment damage, and possibly even personnel injury. A unique problem facing the Corps is the wide variety of wire rope service conditions, which are determined by rope and hoisting equipment design, frequency of use, and the operating environments that exist at Corps installations. This manual covers many of these conditions and presents the latest information and guidance from commercial and industrial sources and information from existing Corps projects. Its purpose is to optimize the service life of wire rope, and to reduce the likelihood of future failures.

CHAPTER 2

Wire Rope Construction and Materials

2-1. Wire Rope Basic Concepts. Wire ropes used in gate operating devices act as a machine element. They are a dynamic part of any hoisting or moving system and act quite differently from static applications of rope such as guy wires or anchorage lines. When the rope passes over a sheave or is wound on a drum there is some amount of readjustment of the rope elements. Each of the wires and strands slide over each other and experience a certain and varied amount of bending and abrasion. This movement can lead to wear and fatigue of the wires and strands and should be considered in design, rope selection, and maintenance practices. The following sections discuss rope properties in regard to construction and materials. They do not cover all the available types of wire rope, but they do attempt to cover the types applicable to gate-operating devices. Chapter 4 discusses specifics on rope selection for various design considerations.

2-2. Classification and Construction. Wire rope consists of multi-wire strands laid helically around a core (Figure 2-1). The way the wires are laid to form the strands, the way the strands are laid about the core, the core construction, and the materials and coatings used for the components contribute to the overall properties and performance of the rope.

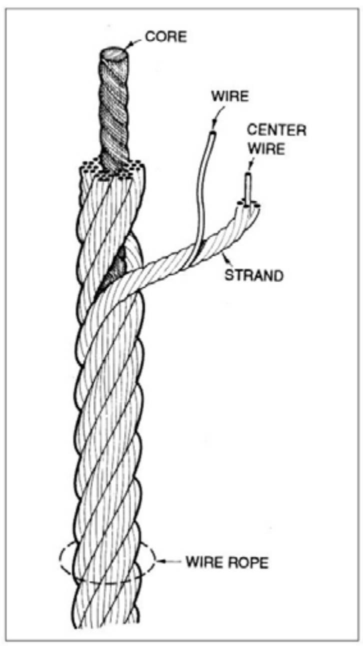

Figure 2-1. Wire Rope Construction.

a. Rope classification. Wire rope classification is designated by the construction of the rope as seen in cross section. The number of strands and the number of wires in each strand are respectively given in its label, for example: 6x19, 6x36, 7x19, etc. Note that the classifications are nominal and may not reflect the actual construction. Classifications group different rope constructions having similar characteristics. For example, the 6x19 classification includes ropes having 6x19, 6x21, 6x25, and 6x26 constructions (Figure 2-2).

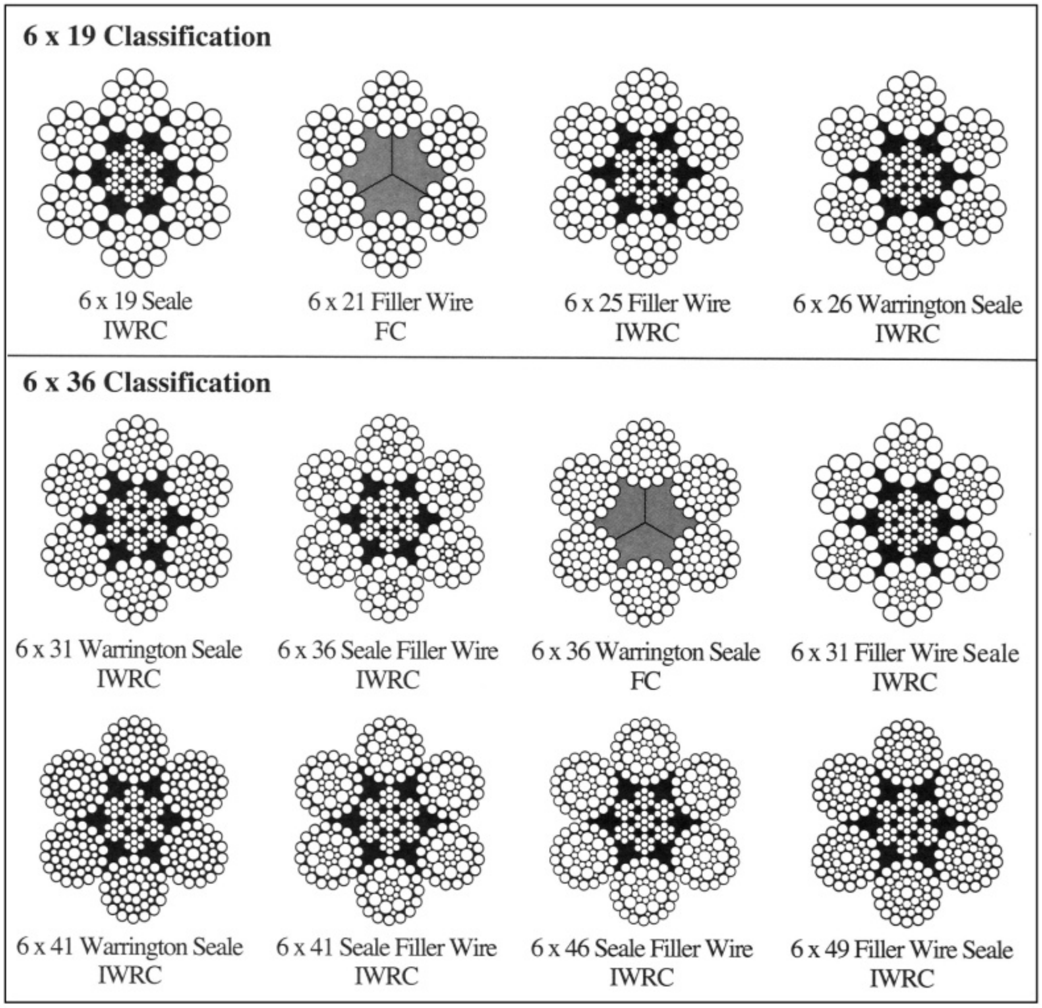

Figure 2-2. Wire Rope Cross Sections.

b. Strand configuration. The individual wires that make up the strands within a rope can vary in orientation and size to provide varying characteristics of different rope constructions. The terms 7-Wire, Filler Wire, Seale, Warrington, and Warrington Seale refer to the different rope strand patterns (Figure 2-3). Note that for the Seale configuration, the wires in any layer of the strand are of equal diameter. For the Warrington configuration, the wires of the outer layer of the strand are of two different diameters. The Warrington Seale configuration is a blend of the Seale and Warrington configurations. The outer layer has equal diameter wires and the next layer inward has wires of two different diameters. For the Filler Wire configuration, all the main wires of each strand are of equal diameter like the 7-Wire configuration. However, extra wires of a small diameter have been added between the main wires. Compared to the 7-Wire configuration, the more complicated configurations result in strands that are more stable, flexible, and less likely to collapse under load. The central core of the rope is typically designated with the particular rope construction. Wire rope cores are typically made up of three types of construction: an independent wire rope core (IWRC), a wire strand core (WSC), and a fiber core (FC). The 6X19 and 6X36 classifications are the most common for Corps gate-lifting applications. The 6X36 Warrington Seal is preferred because it offers high resistance to bending fatigue, which is common in service as wire rope bends over sheaves and drums. Designers should check availability of their specified rope to ensure that construction schedules can be met. Typical time to manufacture larger ropes may run from 4-6 months. Also reference Section 4-8 for more detailed wire rope selection criteria.

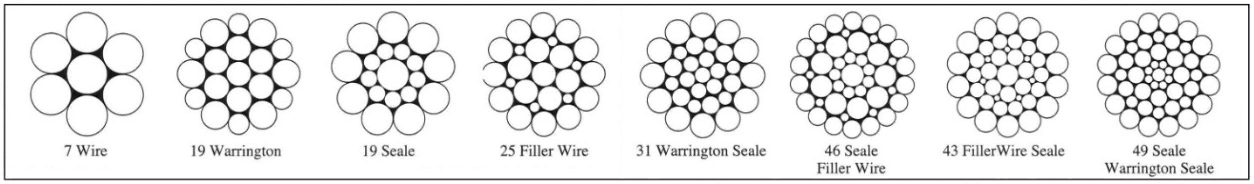

Figure 2-3. Strand Patterns.

c. Rope properties. Important characteristics of wire rope relate to the number and size of the outer wires, and to a lesser extent, the inner wires. A small number of large outer wires results in better resistance to wear and corrosion. A large number of small wires results in better flexibility and resistance to fatigue. There is an inverse relationship between abrasion resistance and resistance to bending fatigue for some widely used wire rope constructions. For many installations, both wear and fatigue may be a concern, which would require a compromise or modifications to the rope lay as discussed below. Engineering judgment in considering the application is needed to determine the trade-off between fatigue resistance and wear resistance. Strength also varies somewhat with classification as shown in any manufacturer product literature or the Wire Rope User's Manual (WRTB 2005). Chapter 4 gives more detail on rope selection for service life, and on other design considerations.

2-3. Rope Lay.

a. Designation method. The construction of a wire rope is designated by the way the wires have been laid to form strands and by the way the strands are laid around the rope core. The lay of a rope is designated by direction and type. Direction is right or left according to how the strands have been laid around the core. The lay type is either regular or lang, depending on whether the wires in the strands are laid in the opposite direction of the strands or the same direction as the strands respectively. The lay length of a wire rope is the distance measured parallel to the center line in which a strand makes one complete spiral or turn around the rope.

b. Right versus left lay. The lay direction refers to how the rope strands are configured about the longitudinal axis of the rope. Right lay means that the strands pass from left to right across the rope, or clockwise along the axis. Left lay means strands pass from right to left. Right lay rope is standard. If lay is not designated, it is presumed to be right regular lay. In hoisting systems that have a group of wire ropes it is advantageous to stagger the type of rope lays within the group with both right and left lay ropes to help counteract the inherent twisting tendencies the rope can impart on free-hanging items, a counterweight for example.

c. Regular lay versus lang lay. The lay type refers to how the individual wires are laid within a strand as compared to how the strands are laid around the core. In regular lay rope, the wires in the strands are wound opposite directions as the strands around the core. Having this construction, the wires in regular lay wire rope line up with the axis of the rope. In contrast, the wires in lang lay wire rope are wound in the same direction as the strands around the core and appear to form an angle with the axis of the rope. There are also alternating configurations in which the strands within a rope have wires wound in opposite directions as compared to one another (Figure 2-4). Regular lay wire rope is used for the widest range of applications. It has a somewhat better resistance to crushing than lang lay wire rope and does not rotate as severely under load when used in an application where either end of the rope is not fixed. However, lang lay wire rope has two important advantages. It has better resistance to both fatigue and abrasive wear. Lang lay rope has a longer exposed length of exterior wires. Bending of lang lay rope results in less axial bending of the outer wires, but greater torsional flexure. Overall, lang lay wire rope displays a 15 to 20% superiority in service life over regular lay when bending is the principal factor affecting service life. Also, because of the longer exposed length of the exterior wires, the ropes are exposed to less pressure, which decreases the rate of abrasive wear on wires, drums, and sheaves. There is no difference in breaking strength between lang and regular lay rope.

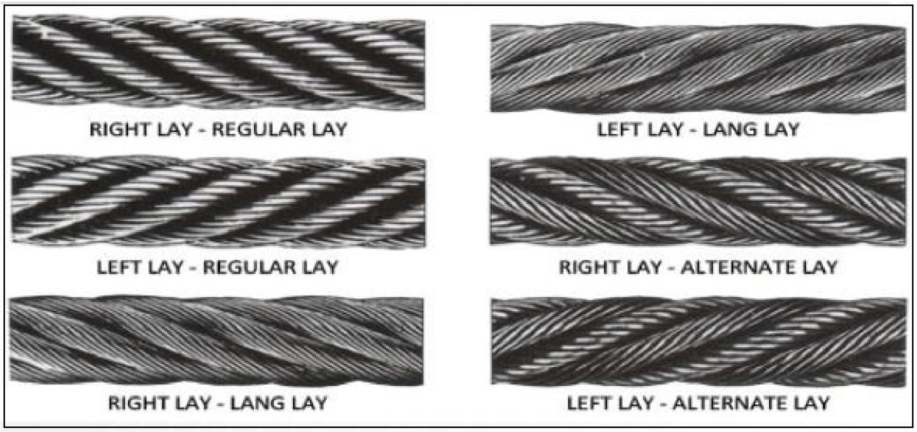

Figure 2-4. Different Rope Lays.

d. Rope lay in Corps applications. The majority of the wire rope used for Corps gate-operating applications is of the regular lay type. However, many installations would be better served with lang lay ropes. A lang lay replacement should be considered for any regular lay wire rope that has failed due to wear or fatigue. Lang lay wire rope is potentially more prone to kinking and unlaying or opening up, which is an unwinding of the rope or strands. Therefore, care must be taken when handling lang lay rope while unwinding. However, a couple of considerations are in order for Lang lay rope. Lang lay wire rope will rotate and twist if the ends are not fixed. Lang lay rope also does not withstand crushing action on a sheave or drum. Also, consideration of a rope tensioning device such as a turnbuckle may be appropriate on gates where lang lay ropes are used. In applications where there are multiple ropes on a counter-weighted lift gate system, it is advantageous to use equal numbers of right and left hand lays in the rope groups. This helps prevent the free-hanging counterweight from trying to twist or spin in the shaft creating interference problems.

2-4. Special Shaping of Ropes and Strands.

a. General. Manufacturers vary rope from the standard round wire and round strand configurations to enhance some of its properties. The variations covered in this section are (1) compacted strand wire rope, (2) swaged (compacted) wire rope, and (3) flattened strand (triangular) wire rope (Figure 2-5). Manufacturers should be consulted when considering specially shaped rope to verify that all the characteristics of the special shape are consistent with the needs of the application and to ensure that the specialty rope is available. In a number of cases, the lack of availability has made the use of some of these specialty ropes cost prohibitive.

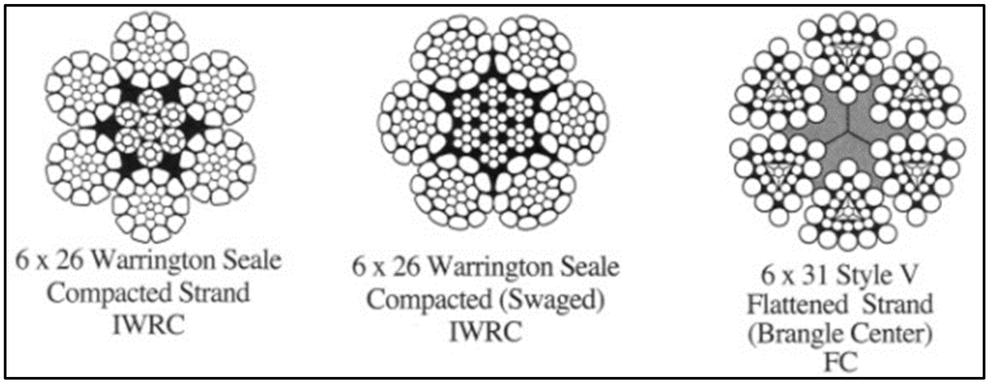

Figure 2-5. Special Wire Rope Shapes.

b. Compacted strand wire rope. Compacted strand wire rope is manufactured from strands that have been reduced in diameter by one of several swaging processes. The outer surfaces of the outer strand wires are flattened and the internal wires are no longer round. Compared to a standard wire rope of the same diameter, a rope of the compacted strand configuration has a greater cross-sectional area of metal. This results in higher strength, but less resistance to fatigue. It has a smoother surface, which makes it more abrasion resistant, but it is less corrosion resistant for two reasons. First, its smoother surface is less able to hold lubrication. Second, the swaging process used to form the strands is not compatible with stainless steel, which is the material of choice for corrosion resistance.

c. Swaged (compacted) wire rope. A standard IWRC wire rope is used to form compacted wire rope. Its entire cross section is reduced in diameter, usually by rotary swaging. Compared to a standard wire rope of the same diameter, it has a greater cross-sectional area of metal and flatter wires on the outer surface. The smooth outer surface provides good wear resistance. It is also stronger and more resistant to crushing, but fatigue life is reduced by the compacting process. Like compacted strand rope, it is less corrosion resistant for the same reasons.

d. Flattened (triangular) strand wire rope. Flattened strand wire rope features strands that are triangular in shape. The center of the strands consist of either a triangular-shaped wire or of wires laid in a triangular configuration. Compared to a standard wire rope of the same diameter, it has a greater cross-sectional area of metal and an increased bearing surface. Strength, abrasion resistance, and resistance to crushing are enhanced with the flattened strand configuration. Fatigue resistance is unaffected. Flattened strand wire rope can be obtained with either FC or IWRC and is usually furnished in lang lay. This variation is compatible with stainless steel, which makes it the most useful of the special shapes for gate-operating devices.

2-5. <u>Flat (Braided) Rope</u>. A number of older Corps installations use flat wire rope for gate-operating devices. Flat rope is always layered over its drum and has generally provided satisfactory service. However, it is expensive to manufacture and requires a long lead time. Expertise in fabricating flat rope is limited. However, in many cases an application using flat wire rope is cost prohibitive or physically impossible to modify to suit more available common type rope constructions so flat wire rope continues to be specified and used. Flat wire rope installations exist and are maintained at the Port Allen and Old River Locks on their bulkhead carriage units (see Chapter 3 of this manual) and McNary Fishway Exit Gate Hoists to name a few (Figures 2-6 and 2-7).

Figure 2-6. Flat Wire Rope on McNary Fishway Exit Gate Hoist.

Figure 2-7. Flat Wire Rope at East Branch Lake Dam – PA.

2-6. Wire Materials.

a. Steels.

(1) Carbon steels. The grades of carbon steel wire rope are Traction Steel (TS), Plow Steel (PS), Improved Plow Steel (IPS), Extra Improved Plow Steel (EIPS), and Extra Extra Improved Plow Steel (EEIPS). EEIPS carbon steel rope is strongest of the carbon steel ropes exceeding the strength of stainless steels and has better resistance to abrasive wear. American Society for Testing and Materials (ASTM) A1023 provides the wire tensile strength grade or level for given grades of rope as well as minimum breaking force of the carbon steel wire rope classifications.

(2) Stainless steels. Wire rope is available in a variety of sizes and types of stainless steel. Although highly corrosion resistant, the use of stainless steel rope requires good engineering judgment depending on application. Of the stainless steels available, Types 302 and 304 are most commonly used regularly on gate-operating devices.

b. Brass/bronze/Monel. The non-ferrous metals are more corrosion resistant in salt water than the steels, but are susceptible to rapid abrasion. They would rarely be applicable for Corps of Engineers gate-operating devices.

c. Kevlar. Kevlar rope is a high strength synthetic fiber rope. Kevlar is one-fifth the weight of steel, but has comparable strengths for similar diameters as steel, and exhibits favorable fatigue characteristics. At Corps installations where water has proven to be very corrosive to the submerged portions of wire ropes, Kevlar replacement ropes have given satisfactory results. Kevlar's properties are very different from steel for abrasion resistance, crushing resistance, and elasticity. Kevlar strands are very susceptible to abrasion damage and they must be protected with a jacket. Any visible damage to the Kevlar strands gives reason to retire the rope from service. Protective jacket material can be a heavy duty braided polyester jacket or an extruded plastic type jacket, usually of a polyethylene material. Polyurethane jacket material is not advised as the material is rubbery and folds on itself causing permanent jacket distortion ultimately degrading the Kevlar fibers. The jacket reduces the usable cross section of the rope, but a jacketed Kevlar rope has about the same breaking strength as a stainless steel rope of the same diameter. This strength makes it possible to attain normal factors of safety with Kevlar replacement ropes. However, due to wide range of possible rope applications, it is not possible to make a blanket recommendation for safe working load. Ropes wear out with use; the more severe the usage, the greater the wear. Because of the jacket, inspection is difficult compared to bare metal wire rope. However, a change in appearance does occur before failure. For example, broken strands can show signs of bulging in the jacket. It is recommended that the rope user determine a retirement criteria for synthetic ropes in their application based on age, cycles, or some other controlling factor. Kevlar rope, when used with multiple layered type drums soon crushes from a round shape to an almost square shape, but does not lose its integrity. Kevlar rope stretches about two times as much as steel under a full load. Therefore, it stores more energy and a rope breakage will release more energy. A higher degree of personnel protection should be considered where Kevlar rope is used. Kevlar rope has been used in a number of Corps installations due it its ease of handling, corrosion free properties, environmentally friendliness (as no lubrication is required), and fatigue resistance. A discussion of past experience with Kevlar rope follows.

(1) Huntington District. The Huntington District (April 1997) uses Kevlar rope for Stoney (roller slide type) gates at three lock and dam projects. In each case the ¾-in. diameter Kevlar rope was a replacement for steel wire rope. The hoisting machinery and sockets were not changed. Overall, their experience with Kevlar rope is positive and they recommend its continued use.

(2) London Locks. The Kevlar rope has been in service since 1992 on their Stoney gate valves. They found that the original specified flattened strand rope is only available by special order and therefore cost prohibitive. Stainless steel ropes fatigue and break quickly in this application offering very limited service life. The Kevlar rope is replaced every 2 to 3 years and they have had success with no failures since Kevlar rope was put into service.

(3) Marmet Locks. The Kevlar rope has been in service since 1992. The ropes on one of the Stoney gate valves failed during November 1995 after approximately 20,000 operations. The valve was not damaged. The ropes' appearance changed before failure. The cause of failure was judged to be fatigue. Knowing this has helped develop a preventative maintenance schedule on rope replacement. The project continues to use the rope because it has a greater service life and is easier to change than stainless steel.

(4) Winfield Locks. The Kevlar rope has been in service since 1993. The ropes on one of the Stoney gate valves failed in January 1997. The valve was not damaged. However, the failure was considered serious as repositioning of the valve was judged to be effort that could be dangerous to the personnel involved. The failure appeared to be initiated as the result of a rope's

sheath becoming misshaped and getting tangled with a previous wrap on its spiral drum. During unwinding, the rope began winding in a reverse direction. They continue to use the Kevlar rope for their Stoney gate valves.

(5) Walla Walla District. The Walla Walla District used Kevlar rope for the radial lock gate at the Lower Granite project from the early 1990s to 2015. The gate is operated 1,000 to 1,500 times per year in fresh, yet turbid, water. The gate hoist was previously fitted with 1-in. diameter stainless steel wire rope that had failed relatively quickly, after only 6 months of service. The apparent mode of failure was fatigue from bending as the portion of the rope making the tightest bend on the spiral drum was the first to fail. Note that the spiral hoist drums were modified slightly to reduce abrasion to the rope when converting to Kevlar. They had adopted a practice to replace the rope on an 8-year cycle, primarily based on having successfully gone 10 years in the past, which perhaps provided a 20% factor of safety on future installations. The project has experienced two failures of the Kevlar rope over the 25 years of use. Although the project has had satisfactory service from the Kevlar rope they have elected to change the rope to plastic filled steel wire rope for the following reasons:

- One failure occurred in the service of Kevlar, thought to be from non-specified jacketing material (polyurethane). Another failure was simply a complete rope failure of all five ropes on one side of the navigation lock Tainter gate after being in service for approximately 11 years.
- There is no way to inspect the condition of the Kevlar strands inside the jacket material.
- There is no real guidance on service life.
- Socket potting compound has a limited shelf life. Any spare ropes must be made up, load tested, and potted ahead of time.
- Non-standard and slightly delicate rigging procedures are required to prevent damage to the jacket while replacing rope.

2-7. Core Materials.

a. General. As previously stated, wire rope consists of multi-wire strands laid helically around a central core. The core contributes very significantly to the overall properties of the rope. There are three basic types of cores, Fiber Core (FC), Independent Wire Rope Core (IWRC), and wire strand core (WSC).

b. Fiber Core (FC). The core in FC wire rope provides no real strength for either crushing or tension. The fiber tends to dampen out vibration, an advantage for some applications, such as elevators. FC is more flexible than IWRC, but flattens under load, inhibiting the free internal adjustment of the wires, which increases stresses. In the past, it was thought that its core had a significant lubricant holding ability. That is not presently considered a real advantage. FC wire rope is not suited for gate-lifting devices.

c. Independent Wire Rope Core (IWRC). The advantages of IWRC are its strength in tension and its resistance to crushing. Its only disadvantage is decreased flexibility. Generally, IWRC wire rope is preferred for gate-operating applications.

d. Wire Strand Core (WSC). WSC ropes are typically used in stationary applications such as guys and suspension bridge cables. WSC ropes are rarely used in gate-operating applications.

2-8. Coating/Filling/Plating.

a. General. In general, galvanized carbon steel rope and plastic-filled rope are the only plated, filled, or coated metal rope suitable for gate-operating devices at Corps installations. The plastic-filled and plastic-coated ropes have certain disadvantages in regards to corrosion and inspection. However plastic-filled rope is being used successfully in a few applications in the Walla Walla District.

b. Plastic-filled. Plastic-filled rope offers some advantages over plain carbon or stainless steel rope. The fully impregnated thermoplastic material serves as a lubricant, or to seal in lubricant on the wire rope, and makes for a smooth outer surface that sheds water and debris (Figure 2-8). This is beneficial in wet applications as it keeps typical wire rope lubricant out of the water. Having a round cross section allows the rope to pass through sheaves with more even contact. The plastic fill also helps prevent abrasion as the individual wires move relative to each other. However, concentrated corrosion cells can form at the exposed wires in a wet environment making plastic-filled rope a potential maintenance concern. The rope is also difficult to visually inspect although it can be non-destructive tested using magnaflux testing to verify the rope's integrity. For submerged applications, the socketed connection requires special attention. At these connections, the thermoplastic material must be removed to properly spelter the socket on the rope. This leaves an area at the rope/socket interface vulnerable to corrosion of the wires. This area must be protected with some sort of coating after the socket is made up. Alternatively, it needs to use some sort of modified socket that allows the intact plastic-filled rope to be extended into the potting compound creating a water tight seal.

c. Plastic-coated. Plastic-coated rope is also difficult to inspect. The coating can soon wear off allowing concentrated corrosion cells to set up similar to the plastic-filled rope. Plastic coated ropes are not recommended for gate-operating installations. Figure 2-9 shows a failure of the plastic coated wire rope at Dillon Dam.

Figure 2-8. Plastic-Filled Wire Rope.

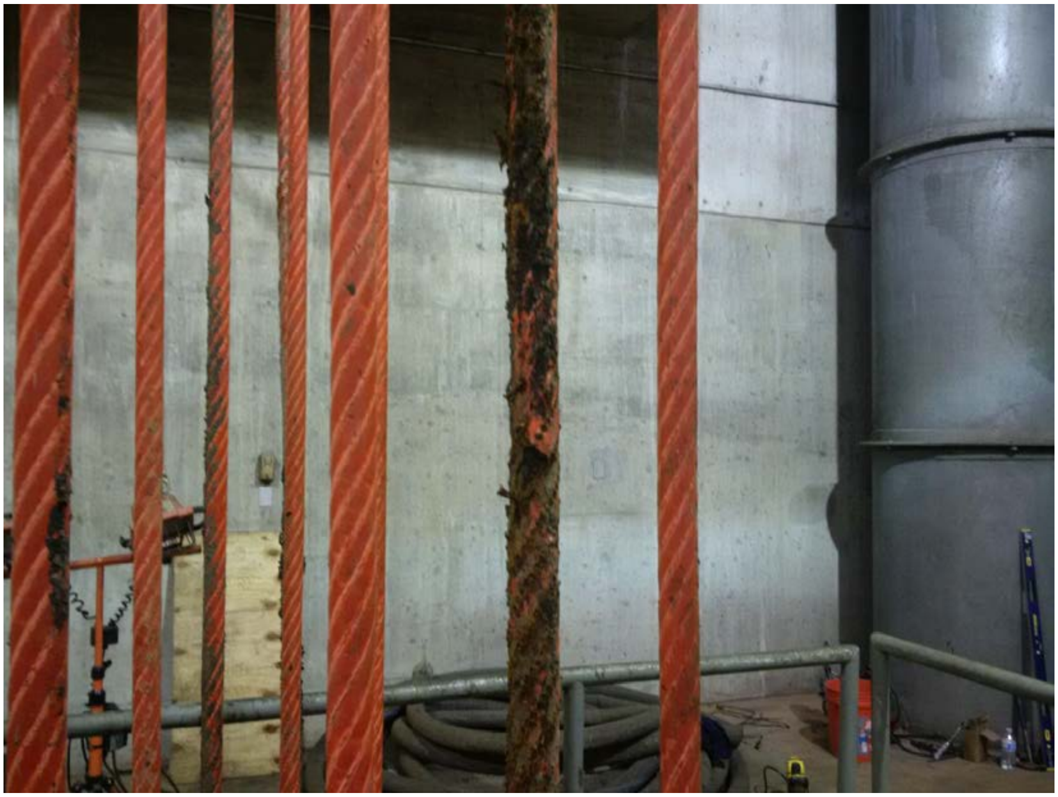

Figure 2-9. Dillon Dam Plastic Coated Wire Rope Failure.

d. Galvanized steel. Galvanized carbon steel rope can be manufactured in several ways. It can be woven from either galvanized rope wire or from drawn galvanized rope wire. Galvanized rope wire is zinc-coated to the finished diameter by either the hot dip process or by the electro-deposition process. Since the diameter of the steel wire is reduced, and the zinc has little strength, a wire rope galvanized in this manner has about a 10% reduction in strength compared to one of bare steel. Drawn galvanized rope wire is zinc-coated, by either the hot dip process or by the electro-deposition process, before its last drawing operation. A wire rope galvanized in this manner has the same strength as one of bare steel. It is also possible to zinc-coat a rope after weaving. A rope galvanized in this manner would have no reduction in strength compared to one of bare steel. Either of the last two galvanizing methods would be preferable to the first for gate-operating devices. Galvanized carbon steel rope is generally very corrosion resistant compared to bare carbon steel rope, at least until the zinc coating disappears. Rate of zinc loss can be very high in industrial areas because of airborne pollution and water pollution. Galvanized rope is much lower in cost than stainless steel (see Section 6-4, “Availability/Cost”). It is also stronger than stainless steel if manufactured from drawn galvanized rope wire. In addition, it is less susceptible to damage from nicks and does not have the galling problems or galvanic corrosion potential of stainless steel. However, if the coating is damaged in submerged applications, local corrosion cells may occur between the exposed wire rope and the galvanized coating. Galvanized wire rope may be difficult to obtain domestically. If specifying galvanized rope is preferred, it is recommended that a thorough market search be performed before advertising the project.

2-9. Manufacturing.

a. Manufacturing Process. The general process of manufacturing wire rope will be discussed here with other specific considerations following. First, wire rods are formed from steel billets in a hot rolling process. After the rolling process, the surface of the rods are cleaned to facilitate the drawing process. In the first drawing process these rods are drawn to a specific diameter in such a way to introduce desired mechanical properties. After the first drawing, the wires are heat treated to achieve the desired micro structure of the material. The wire then goes through a second drawing process to attain the final desired diameter of the wire. The next step is to lay the wires into strands based on the type of wire specified using alike or varied diameters of wire. The final step is then to lay the completed strands around the core, which produces the required finished wire diameter; this process is normally referred to as “closing.”

b. Stress Relief. Newly woven wire rope is normally run through molten lead to relieve stresses in the wires resulting from the various drawing, preforming, and swaging processes. If not stress relieved, the fatigue life of the rope is shortened.

c. Pre-stretching. Wire rope normally stretches more rapidly when new than it does as it ages. Pre-stretching is an operation that takes most of the initial stretching out of the rope. It can be accomplished economically if performed in conjunction with socketing. Pre-stretching is recommended for installations with multi-rope drums, where the ropes need adjustment for equal tension. If pre-stretching is not performed, the ropes may tend to stretch unequally in use and may need to be periodically re-adjusted. See Section 4-5, “Rope Stretch.” The normally accepted procedure for pre-stretching wire rope is as follows. The rope is subjected to three cycles of tensile loading to 40% of its nominal strength. The 40% loads are held for 5 minutes with 5% loads between cycles. There is no standard yet established for dynamic pre-stretching, but there may be in the future. This has been performed by tensioning a rope at 20% of its nominal strength while operating over pulleys. This process appears to be difficult to specify, but it may be an option to consider.

d. Weaving. The whole weaving process is somewhat of an art as far as wire shaping, preforming, determining the exact wire sizes and spool rotation, and performing welding methods. Including weaving criteria in specifications may be very difficult.

e. Blending wires. Manufacturers occasionally mix stronger wires in with weaker wires (in the same rope) to meet minimum acceptance strength requirements. This is common and usually does not present a problem to the buyer. Although the resulting blend meets the required strength criteria, the stronger wires may be less fatigue resistant than the weaker ones and may potentially cause the rope to degrade faster if its prime failure mode is fatigue. If the wire properties are more uniform, that is, if they are of the same strength and meet a minimum ductility requirement, the potential of a fatigue failure may be postponed, increasing service life. ASTM A1007 includes standard procedures for strength testing rope wires for ductility (torsion). Note that the cost of a rope may increase if the wires are required to have both a minimum strength and a minimum ductility.

f. Preforming. Almost all wire rope sold in the United States have preformed wires. Preforming methods differ with different manufacturers. Preforming is normally performed, even if not specified by the buyer. However, it should be included as a requirement in the rope specifications. Wire rope without preformed wires has a tendency to unravel, especially if any individual wires break. Rope with preformed wires has greater flexibility, and it spools more uniformly on a drum. Preforming also provides a better distribution of the load to every wire, which improves fatigue resistance and flexibility.

2-10. Considerations for Selection of Wire Rope. This chapter's discussion is limited to the various rope constructions and materials for gate-operating devices. For proper size and rope type consult Chapter 4, "Design Considerations." For general rules for selection of wire rope see the Wire Rope User's Manual (WRTB 2005). In general, for a properly designed hoisting system, the two factors that will affect the service life of the wire rope are corrosion and fatigue. Rope material selection for the service environment is important to limit the corrosion rates. Also, the relationship between the rope diameter and sheave and drum diameters is a critical factor in estimating the ropes fatigue resistance, which is also a function of the material selection. Anticipated number of cycles of the rope over the expected service life is also a consideration in fatigue.

a. Carbon Steels. Of the available grades of steel mentioned in Section 0, only EIPS and EEIPS are normally specified for gate-operating devices. TS is normally used for elevators. PS and IPS ropes are nearly obsolete and are seldom stocked or fabricated by manufacturers. EIPS is much stronger than TS and has similar toughness. EIPS carbon steel rope is stronger than the stainless steels and has better resistance to abrasive wear. EIPS carbon steel rope that can be properly lubricated is a very good choice of materials in most gate operating applications. Note that there are presently 247 examples of well-maintained carbon steel wire ropes across about 25 projects within the USACE inventory still in place after more than 50 years of service.

b. Galvanized Steel. Galvanized rope is a good choice in marine environments where fatigue is the primary failure mode. However, galvanized wire rope manufactured domestically may be difficult to obtain. Specifying galvanized rope will likely cause acquisition problems. A diligent market research is recommended before specifying galvanized wire rope.

c. Stainless steels. Of the stainless steels available, Types 302 and 304 are most common and have been used regularly on Corps gate-operating devices. Other types of stainless steel are available in sizes suitable for gate operating systems including Types 305 and 316, but those types are not as common. A 10 to 25% loss of strength is realized when comparing stainless steel to the EIPS and better carbon steels. Therefore, the use of stainless steel rope requires a larger diameter rope than does EIPS for the same application. Stainless steels are not as resistant to abrasive wear and are susceptible to galling and abrasion when layered on disk-layered drums. Stainless steel rope is also prone to fatigue failure so care is required in frequently used equipment using stainless steel wire rope that passes over sheaves or wraps on drums. Since they are only slightly magnetic, inspection by the electromagnetic (non-destructive) method is not possible. The stainless steels are many times more corrosion resistant than the carbon steel rope. However, Stainless steel rope should not be used in saltwater applications because of susceptibility to crevice corrosion. If they are used, they must be inspected regularly. It is also important to note that the stainless steels have a different galvanic potential than the carbon steels. When using stainless steel rope, it is possible to set up a galvanic corrosion cell in which carbon steel sockets, rope fittings, gate structure, or other equipment rapidly corrode. Special care must be taken to isolate it from plain carbon steel structures used in most gate applications to limit galvanic corrosion. Stainless steel rope is also very susceptible to fatigue; if considering stainless steel rope, a lang lay rope should help with the fatigue life of the application. Stainless steel is likely best suited for continually submerged applications that will see minimal cycles as long as galvanic isolation from the plain carbon steel components is properly designed for those areas below the water line. Note that there are presently over 240 examples of stainless steel wire ropes across about 11 operating projects within the USACE inventory still in place after more than 50 years of service.

d. Specialty ropes. In the past, flattened strand wire ropes were specified in applications where the wire rope wrapped on a disk-layered drum. This was done primarily because it has a smoother surface, which makes it more abrasion resistant to a normal configuration. Also, strength and resistance to crushing are enhanced with the flattened strand configuration. Fatigue resistance is unaffected. However, this type of rope does not appear to be highly available, which drives the cost up. Extensive market research should be conducted before deciding to specify flattened strand wire rope.

CHAPTER 3

Applications

3-1. Applications within USACE.

a. The purpose of this chapter is to briefly show some of the wide applications of wire rope usage within USACE (and examples outside USACE in the case of rolling gates). Some of the applications are very common such as Tainter gates or vertical lift gates. Other applications are more limited such as ship arrestors and tow haulage units and bulkhead lowering systems. The following applications will be discussed and summarized in this chapter:

(1) Tainter gates.

(2) Culvert valves (tainter valves).

(3) Vertical lift gates for navigation dams.

(4) Vertical lift gates for navigation locks.

(5) Sector gates.

(6) Rolling gates for sea locks.

(7) Ship arrestors.

(8) Tow haulage units.

(9) Bulkhead lowering systems.

b. This list is not intended to be all inclusive of every application of wire rope. A discussion on rolling gates at sea locks is provided to make the reader aware of a significant application of wire rope that is used in other countries including the new Panama Canal Third Lane locks. This chapter does not provide a detailed design discussion for these applications. Instead, refer to Chapter 4 of this manual, Engineering Manual 1110-2-2610, and Permanent International Association of Navigation Congresses (PIANC) Reports 138 and 173.

3-2. Tainter Gates. Wire ropes used for opening and closing Tainter gates (Figures 3-1 to 3-4) are one of the more common applications within USACE. Wire rope systems provide an economical and efficient way of lifting these gates. Tainter gates are used on dams to regulate the pool level and are probably the most common gate type within USACE. Wire rope lifting systems have become widely used for these gates and are generally preferred over lifting chain for new construction. EM 1110-2-2610 discusses this and provides design guidance for the mechanical and electrical drive system. Many large Tainter gates within USACE use multi-part wire rope systems. It is imperative on multi-part wire rope systems that all the wire ropes have equal tension. This is necessary to ensure all the wire ropes are loaded equally and to prevent racking of the gate. EM 1110-2-2610 provides details for accomplishing this. Refer to Chapters 4 and 7 of this manual for additional discussion wire rope tensioning. The wire rope is typically attached to lifting lugs near the bottom of the skinplate, on the upstream side. The wire rope then contacts the Tainter gate skinplate over a portion of the gate height and eventually separates tangentially to the skinplate arc. The hoist drums should be located so that the wire ropes remain in contact with gate skinplate when the gate is closed.

Figure 3-1. Tainter Gate Structure Lifted with Wire Rope.

Figure 3-2. Multi Part Wire Rope for Lifting Tainter Gate.

Figure 3-3. Tainter Gate Wire Rope Detail – Disc Layered Drum.

Figure 3-4. Tainter Gate – Multi Part Wire Disc Layered Drum Detail.

a. A typical wire rope hoist consists of dual drum units with (or without) speed-reduction gearing, connected to a center drive unit via drive shafts. Simpler hoists will not have drum unit reduction gearing, and the drums may be mounted on a common drive shaft spanning the gate bay walls, with the motor-operator located at one end. See Chapter 4 of this manual for additional discussion of wire rope drums. Refer to EM 1110-2-2610 for a detailed discussion of operating machinery for Tainter gates.

b. This paragraph falls under the Tainter gate discussion, but applies to all wire rope applications. Wire rope material selection will depend on the specific application. Stainless steel, galvanized steel, and plain steel have all been used. It is recommended per EM 1110-2-2610 and EM 1110-2-1424 that all wire rope be lubricated regardless of the material. Chapter 4 of this manual provides guidance for the specific type of wire rope selection. EM 1110-2-1424 provides further guidance on the type of wire rope lubricant for all types of wire rope applications. Also, see Chapter 8 of this manual for further discussion of wire rope lubrication.

3-3. <u>Tainter Valves</u>. Tainter valves are commonly used as culvert valves in locks and are operated with wire rope on many USACE navigation locks. Wire rope provides an economical and efficient way of lifting these valves (very similar to Tainter gates) especially at low head locks (Figures 3-5 to 3-8). This includes all the Upper Mississippi River locks. One disadvantage of a wire rope system is that it cannot “force” the tainter valve down into the culvert. The valve has to drop by gravity under its own weight. This type of system is thus typically used on low head locks. On higher head locks, there is usually too much uplift force to allow the tainter valve to lower under its own weight. Also on higher head locks, the tainter valves are typically reversed and hence called “reverse tainter valves.” Because of the higher head, reverse tainter valves are commonly operated with hydraulic cylinders instead of wire rope. EM 1110-2-2610 provides further discussion on this issue.

a. The hoist system on the Upper Mississippi River Locks uses two stainless steel round wire ropes (6x37 construction), one at each end of the tainter valve. This system has worked well with few issues. Stainless steel was used primarily for corrosion resistance. The wire rope is connected to the convex side of the tainter valve at the lower main girder near the side strut location. The cables are connected to two grooved drum assemblies, which are flanked by spherical roller-bearing pillow blocks. The drum assemblies are connected to a quadruple reduction parallel shaft reducer by geared flexible couplings. A slack cable limit switch assembly is provided to prevent unspooling of the cable when the gate is not moving.

b. The wire rope design criteria for tainter valves is essentially the same as for Tainter gates, and is discussed in more detail in Chapter 4 of this manual and also EM 1110-2-2610. One primary difference is that tainter valves are typically smaller and usually only require one wire rope per side. Corrosion can be an issue and the wire rope to valve connection is typically underwater for a majority of its service life. The gate connection is also difficult to maintain and will typically require dewatering of the valve chamber or lock to access and repair.

Figure 3-5. Tainter Valve Drive System with Wire Rope Drums on Each End.

Figure 3-6. Tainter Valve Lifting Cable and Drum.

Figure 3-7. Wire Rope Connection to Tainter Valve.

Figure 3-8. Wire Rope Connection to Tainter Valve.

3-4. Vertical Lift Gates for Navigation Dams and Storm Barriers. Vertical lift gates for navigation dams are another common application for wire rope. A number of dams on the Columbia River use vertical lift gates and wire rope including Bonneville dam (Figure 3-9). Bonneville dam uses 1¼-in. wire rope with eight ropes per side and 16 wire ropes total. Ice Harbor dam and Lower Monumental dam on the Snake River use vertical lift gates and wire rope systems also. The storm surge barrier in New Orleans uses a vertical lift gate and wire rope drive system. The EM 1110-2-2610, Chapter 7, provides specific design guidance for vertical lift gate machinery. Vertical lift gates often use counterweights to reduce the operating load and the loads on the wire rope and hoist. The wire rope reeving requirements for vertical lift gates can be complicated and typically require multiple sheaves. EM 1110-2-2610, Appendix B, provides a typical reeving diagram.

Figure 3-9. Bonneville Dam Wire Rope Lifting System.

a. Vertical lift gate machinery is typically located on a structural deck above the gate. Wire rope hoist systems are often used because of the large size of the gates that often eliminate hydraulic drive systems. Multiple part wire rope systems can be used to limit the loads on each wire rope. Wire rope hoists are more suitable for gates that have deep submergence requirements, where installations that do not allow portions of the hydraulic cylinders above the deck (shallow settings), or where hoisting loads are too large and economics makes hydraulic cylinders impractical. Wire rope hoists consist of drums and a system of upper and lower sheave blocks that are driven through a motor and arrangement of shafts, speed reducers, and spur or helical gears (Figure 3-10). Again, Chapter 4 of this manual provides discussion on hoist drums. Motors may be electric or hydraulic driven. It is common to provide two speeds to permit lowering at approximately twice the raising rate. Controls are typically located at the machinery level and also in a control room. Corrosion, which can be an issue on wire rope hoists for vertical lift gates, must be a consideration. The bottom portion of the wire rope is typically submerged.

Figure 3-10. Bonneville Dam Vertical Lift Gate and Lifting Sheave.

b. New Orleans Bayou Bienvenue Vertical Lift Gate. This vertical lift gate, which is part of the New Orleans Inner Harbor Navigation surge barrier, was installed after Hurricane Katrina (Figures 3-11 and 3-12). The lift gate is 60 ft wide. The mechanical system that is used to raise and lower the Bayou Bienvenue lift gate consists of sheaves (pulleys), four-part wire rope rigging, and two electrically powered winches. Two 1.125-in. diameter (6x37 IWRC) wire ropes are used. The winches are connected together by a shaft, and are powered by a 30 horsepower electric motor. Double wire rope cables are used on each winch. In the event one cable fails, the other will keep the gate from falling. The gate can be supported by the multi-part reeving for extended periods. For maintenance, the gate is provided with a single cable that can support the gate while the multi-part cable is slack. The design does not use counterweights.

c. Because of the large number of wire ropes typically necessary on vertical lift gates, it is even more imperative to ensure equal tension in all the wire rope cables. For large vertical gates, it is recommended to use counterweights if possible. Counterweight cables will typically require wire rope with a larger diameter then that of the main drive wire ropes. Lifting applications for vertical lift gates are very similar to the design and application for vertical lift bridges using wire rope and counterweights. The reeving requirements are nearly the same. Again, reference EM 110-2-2610 or the American Association of State and Highway Transportation Officials (AASHTO) Standard on Movable Bridges for a typical reeving diagram. There are dedicated chapters in this AASHTO standard on mechanical and electrical drive systems for vertical lift bridges. This AASHTO document can be used in conjunction with EM 1110-2-2610.

Figure 3-11. New Orleans Surge Barrier – Bayou Bienvenue – Vertical Lift Gate Hoisting System and Lifting Towers.

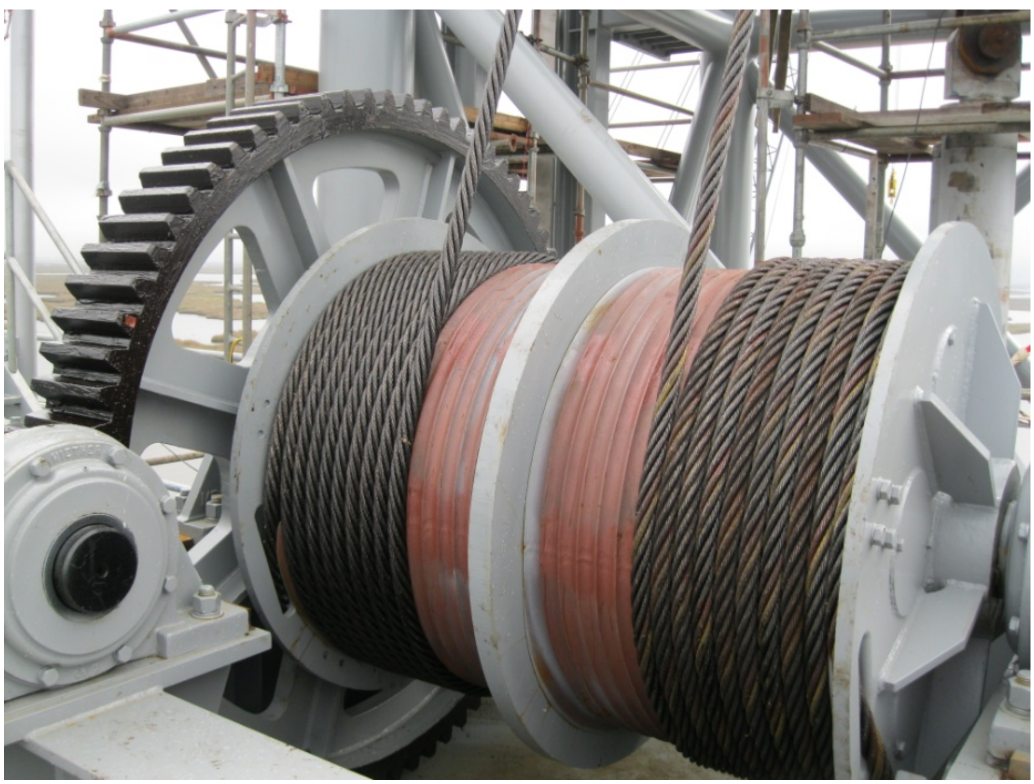

Figure 3-12. Vertical Lift Gate Bayou Bienvenue – Double Cable System – Grooved Drum.

d. Another vertical lift gate wire rope application that has yielded valuable lessons learned is in Walla Walla District. The District has installed equal numbers of right and left hand lays on lift gates with counter weights. The counterweights used to twist and rub the guides throughout the gate travel. This was problematic as there was an opening in a gallery approximately in the middle of the counterweight travel. The counterweight guides would also randomly catch on the stationary guides. The ropes were pre-stretched before end terminations being installed, but some residual twist still resided. The District switched to right and left hand lays in the hopes that the residual twist would cancel each other. This has proved successful. Refer to Chapter 2 of this manual for further discussion.

3-5. Vertical Lift Gates for Navigation Locks. A number of locks within USACE use vertical lift gates in lieu of miter gates for letting vessel traffic into and out of the lock chamber. This includes Lockport Lock on the Illinois River and Lock 19 and Mel Price Lock on the Mississippi River and John Day dam on the Columbia River. Cannelton, McApline, and Markland Locks all use a wire rope driven vertical lift gate for emergency closure or to pass ice if needed. The vertical lift gates typically use multiple gate leafs. Mel Price and Lockport lock use wire rope for lifting the vertical lift gate leafs. Lock 27 on the Mississippi River also uses a vertical lift gate, but uses chain to lift the gate. John Day dam uses wire rope on the navigation lock vertical lift gates. Appendix B discusses some recent wire rope failures at John Day Dam. Similar to vertical lift gates for navigation dams, counterweights should be used if possible to reduce the lifting loads on the machinery. Reeving diagrams are provided in EM 1110-2-2610. Also, the sections of the AASHTO movable bridge standard pertaining to vertical lift bridges can be used for design guidance.

a. Mel Price. Appendix B discusses a recent failure of the wire rope drive at Mel Price. There are three (3) lift gate leaves at the Melvin Price Main Lock (see Figures 3-13 and 3-14). The three leaves overlap each other to close the upstream end of the lock chamber from the gate sill. These gate leaves comprise the normal upstream lock operating gate for the main lock. Under normal operating conditions all of the gate leaves are lowered behind the concrete sill to permit river traffic to pass above them. The two upstream gate leaves are nearly identical. The upstream leaf is designed as a movable sill for use during high river levels, while the middle leaf is used with every lockage during normal pool conditions. The approximate weight of the upstream leaf is 274,000 lb. The approximate weight of the middle leaf is 280,000 lb. The approximate weight of the downstream leaf is 264,000 lb. Counterweights are used to reduce the operating load.

(1) Hoist. Each lift gate hoist consists of: (1) a lift gate cable connection bracket assembly, (2) 12 round wire rope assemblies, (3) a segmented, spiral-wrap steel drum assembly, (4) a drum/gear shaft, (5) a spur bull gear, (6) a spur pinion gear, (7) a pinion shaft, (8) a flexible coupling, (9) a parallel shaft reducer, (10) drum/gear shaft pillow block bearings, (11) pinion shaft pillow block bearings. (12) an electric motor, (13) a shoe-type electric holding brake, (14) a rotary cam limit switch, (15) a manual position indicator, and (16) a structural steel support frame. The wire rope assemblies have stainless steel sockets at each end. Each socket is connected to the counterweight assembly, the gate hoist or the gate leaf.

Figure 3-13. Mel Price Vertical Lift Gate – Showing Three Gate Leafs and the Wire Rope Drums in Background.

Figure 3-14. Mel Price Vertical Lift Gate Machinery and Hoist Drums.

(2) Wire Rope. The wire rope for both the counterweight and the hoist both have diameters of 1½ in., and a 6x30, flattened strand. The gate hoist connects to the gate leaf with 12 parallel wire rope assemblies. The gate hoist wire rope assemblies have adjustable gate sockets, which are bolted to the end of the gate leaf at one end, and drum sockets, which are enclosed in grooves in the hoisting drum at the other end. The counterweight connects to the gate leaf with six parallel wire rope assemblies. The counterweight assemblies have adjustable sockets, located at the counterweight, and gate sockets, which are pinned to the gate leaf. Since each assembly is adjustable, they can be tensioned to share the total load.

b. Lockport. Lockport Lock and Dam is 291.0 miles above the confluence of the Illinois River with the Mississippi river at Grafton, IL (see Figures 3-15 to 3-17). The lock is 110 ft wide by 600 ft long. Maximum vertical lift is 42.0 ft and the average lift is 39 ft. Two submersible-type vertical lift gates, a service gate, and a guard gate are provided at the upstream end of the lock. Appendix B further discusses a failure of the wire rope that occurred in 2012. The wire rope that failed was carbon steel. After the wire rope failure, the wire rope material was switched back to stainless steel. Wire rope used for the lift gate is now 304 stainless steel, 1½ in. diameter, 6x37 construction (IWRC). There are seven wire ropes per side for the vertical lift gate.

Figure 3-15. Lockport Vertical Lift Gate.

Figure 3-16. Lockport Lock – Wire Rope Sheave and Turnbuckles.

Figure 3-17. Lockport Wire Rope Cables.

c. John Day Dam. Appendix B further discusses the wire rope failures of the upstream vertical lift gate at this site. There are vertical lift gates at the upstream and downstream ends of the lock chamber. The downstream vertical lift gate (Figure 3-18) was replaced in 2010. The upstream vertical lift gate is raised and lowered by a total of eight, 1½ in. diameter wire ropes, four on each side. The downstream gate of the John Day Navigation Lock is lifted by 32 wire rope assemblies, 16 on each side, which wrap around friction drums and attach to counterweights located in the towers on the North and South sides of the gate (Figure 3-19). The downstream gate weighs approximately 2 million lb and is 86 ft wide and 112 ft tall. Each counterweight weighs approximately 1 million lb. The downstream wire ropes have a diameter of 2¼ in. and are approximately 200 ft long, weighing approximately 1 ton each.

Figure 3-18. John Day Lock – Downstream Vertical Lift Gate.

Figure 3-19. Downstream Drum and Sheave – John Day Dam.

3-6. Sector Gates. Wire rope can be used to drive sector gates and provides some advantages over a rack and pinion system. However, the reeving system can be complicated. EM 1110-2-2610, Appendix B, includes a diagram of a typical reeving system; Figure 3-20 shows an excerpt. A sector gate is a lock or navigable flood gate typically consisting of two gate leafs each made of a curved skin plate with a framed structure linking the skin plate back to a point of rotation located at the skin plate's center of curvature. Sector gates are primarily used because they can be operated against reverse head. EM 1110-2-2610 provides more discussion and details on sector gates. Sector gates have traditionally been driven by a wire rope and drum mechanism, but newer designs have used a rack and pinion drive. The wire rope and drum mechanism was designed to be an inexpensive method of operating infrequently used gates, such as floodgates. Wire rope systems, or similar winch or capstan systems may also be employed as a backup to rack and pinion systems. A disadvantage of the wire rope and drum mechanism is that the wire ropes tend to lose tension with use, thereby requiring periodic re-tensioning and replacement. Also, because the wire rope drum position does not accurately correlate to the gate position, limit switches must be located on the gate or in the gate recess, potentially exposing them to damage. A number of sector gates in New Orleans District (Figure 3-22) use wire rope drives, including the sector gates at Bayou St John and Bayou Bienvenue.

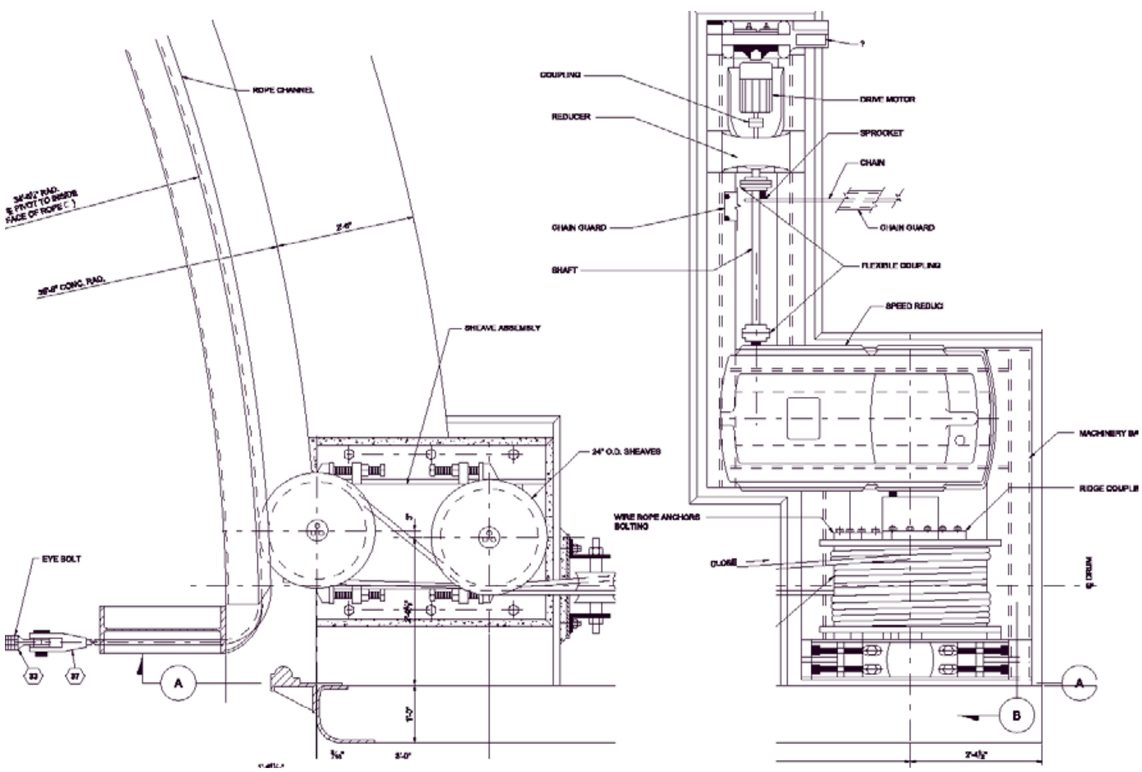

Figure 3-20. Sector Gate Wire Rope Reeving Diagram.

Figure 3-21. Sheaves for Sector Gate Wire Rope Reeving.

Figure 3-22. New Orleans Bayou Bienvenue Sector Gate – Wire Rope Driven.

3-7. Navigation Rolling Gates. Wire rope drives are commonly used to move rolling gates on large sea locks. This includes the new locks and rolling gates at the Panama Canal (55 m [180 ft] wide), the Kaiser Lock in Bremerhaven, Germany (55m [180 ft] wide) and the new Deurganck Dok Lock in Antwerp, Belgium (68m [223 ft] wide). Although USACE does not have these types of gates, there are lessons learned and best practices that can be applied to other wire rope drive systems. This includes the use of automatic wire rope tension systems and the use of alternate lay of wire rope on the winch drums to reduce torsion. PIANC Report 173 provides further discussion of rolling gates.

a. Rolling gates on navigation locks are steel structures that serve to open or close the upstream and/or downstream ends of the lock. They move perpendicularly to the lock axis to open or close. In the closed position, they are stored in a recess in the lock wall. A rolling gate typically is supported on carriages or wagons that roll on tracks as the gate moves. In the closed position, the end of the gate fits into a small recess so that the gate bears on the walls and properly seals. A wire rope winch and drive system is commonly used to move the rolling gate back and forth across the lock chamber (Figure 3-23). Wire rope drives are used because they are economical and simple in design, and because they do not require a significant amount of maintenance. Rolling gates are nearly always buoyant to reduce the operating loads on the winch and drive system. The drive system for rolling gates is similar to Tainter gates and vertical lift gates except that the winch is pulling horizontally instead of vertically.

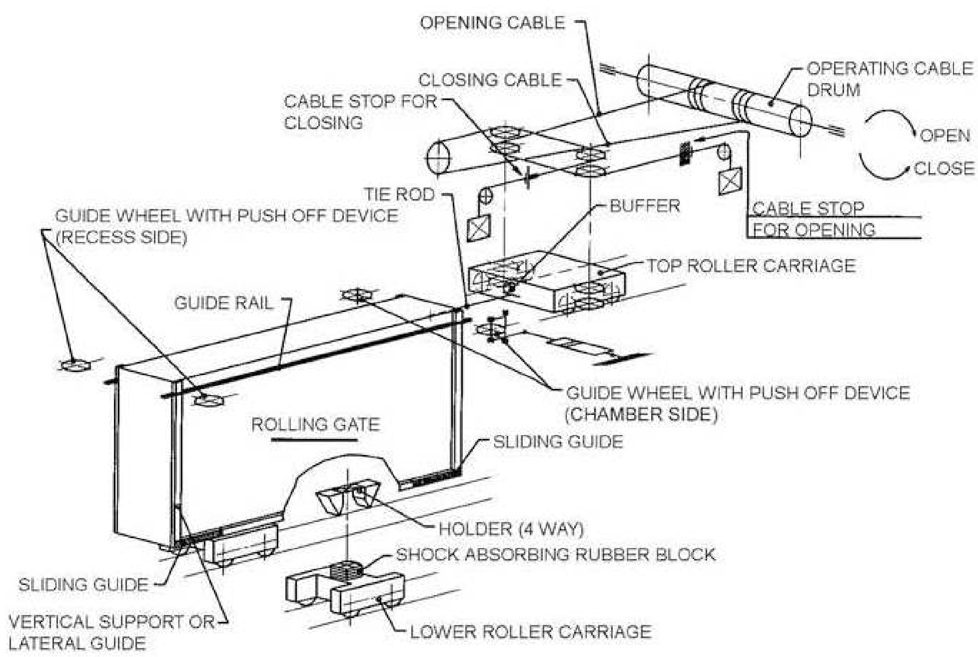

Figure 3-23. Wire Rope Reeving Diagram for a Rolling Gate.

b. Panama Canal Gates. The new Panama Canal locks will use rolling gates as opposed to miter gates. There are redundant rolling gates at each end of the lock (Figures 3-24 and 3-25). Wire rope winch drums will be used to move the gates. Each gate will have a width of 57m (187 ft) and height varying between 29 and 32m (95 and 105 ft) and a structural weight varying between 2200 and 4000 metric tons (2425and 4409 tons). All the rolling gates are operated with a mechanical drive system that uses wire rope drums at each end of the gate. The system essentially acts like a winch to either open or close the rolling gates. The drive system includes a motor, brake, gear box, torque tubes (drive shafts), tensioning system, and the wire rope drums (Figures 3-26 and 3-27). The wire rope is a continuous loop that spools off both the bottom and top of the drum. The wire ropes attach to the upper carriage: one directly at one side, the other via a turning wheel at the far end of the gate chamber. The wire rope diameter for the Panama rolling gates is 45mm (1.77 in.) in diameter. Although the more traditional connection between steel wire ropes and gates is directly at the gate, a different rope reeving lay-out was selected to minimize the gate drive forces further. The chosen layout, which is more commonly applied for the drive system of container crane hoists, has the advantage that the drive force always acts at the center of the gate. With this lay out, skid forces are practically zero. The winch system for the Panama rolling gates uses an automatic tensioning system that is operated with nitrogen gas.

Figure 3-24. Redundant Rolling Gates – Panama Canal Third Lane (Courtesy ACP).

Figure 3-25. Installation of New Panama Canal Rolling Gates.

Figure 3-26. Panama Canal – Wire Rope Tensioning System with Nitrogen Tanks in Background.

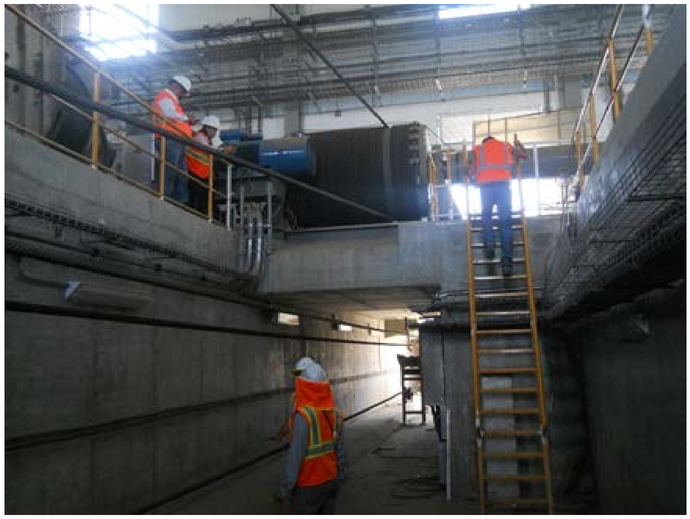

Figure 3-27. Panama Canal – Wire Rope Drum and Guide Rollers.

c. Antwerp Sea Locks. All the locks in the Port of Antwerp use rolling gates and wire rope winch systems (Figures 3-28 to 3-32). These are mechanical drive systems using an electric motor, gearbox, and wire rope winch drums very similar to the Panama Canal rolling gates. The wire rope is a continuous loop that spools off both the bottom and top of the drum. The wire ropes attach to the upper carriage: one directly at one side, the other via a turning wheel at the far end of the gate chamber. The variable speed motor is operated either forward or reverse depending on whether the gate is opening or closing. The winch design uses an alternate lay of wire rope to prevent torsion of the wire rope as it spools on and off the drum. There is a guide system for the wire rope at each lock. Some locks use rollers and some use guide pads. There have been issues with the rollers seizing. Once this happens, the wire rope will cut into the roller.

Figure 3-28. Rolling Gate Berendrecht Lock.

Figure 3-29. Berendrecht Rolling Gate Recess – Note Wire Rope Drives on Each End.

Figure 3-30. Wire Rope Drum – Berendrecht Lock.

Figure 3-31. Wire Rope Winch Drive – Van Cauwelaert Lock.

Figure 3-32. Winch Drum and Cables – Van Cauwelaert Lock.

d. Bremerhaven Germany Kaiser Lock. The new Kaiser Lock was recently completed in 2011. The rolling gates are also operated with a mechanical drive system that uses wire rope drums at each end of the gate (Figures 3-33 and 3-34). Very similar to the gates in Antwerp, the system essentially acts like a winch (pulling in the horizontal direction) to either open or close the rolling gates. The drive system is electric and includes a motor, brake, gear box, torque tubes (drive shafts), and the wire rope drums. One primary difference from the Antwerp gates is that the drive shaft to the hoist drum is vertical (Figure 3-35). The control system is a programmable logic controller (PLC), which is typical for newer rolling gate machinery installations. The wire rope is also a continuous loop that spools off both the bottom and top of the drum. The wire ropes attach to a cross beam spanning across the width of the gate. The wire rope connections to the gate include a hydraulic tension unit. This automatically tensions the wire rope (Figure 3-36). The rolling gates can be operated with a limited unequal head. This is restricted to around 10cm (4 in.). There is over torque protection on the drive system that prohibits movement of the gate when the water levels on both sides of the gate differ too much.

Figure 3-33. Rolling Gate Recess and Wire Rope Cables – Note the Guide Rollers.

Figure 3-34. Wire Rope Connection to Gate.

Figure 3-35. Kaiser Lock – Wire Rope Drum and Drive Gear.

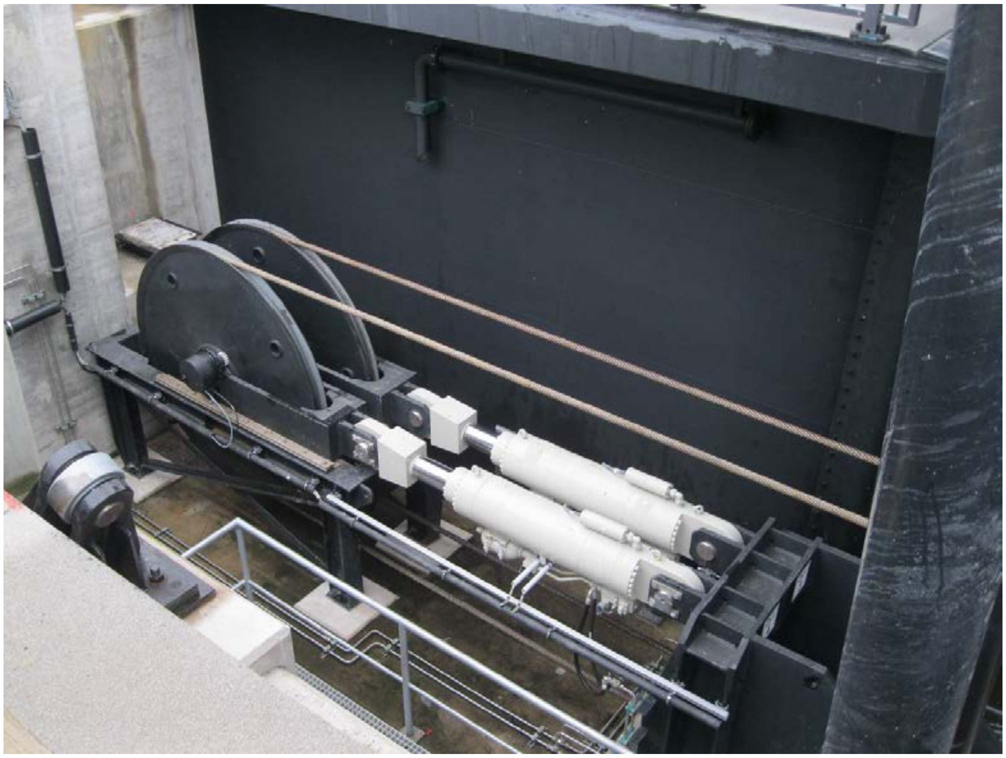

Figure 3-36. Automatic Wire Rope Tensioners – Kaiser Lock.

3-8. Ship Arrestors. Ship arrestors are collision protection systems and devices that prevent barges and ships from impacting lock operating gates. Ship arrestors are located throughout the world in particular in Europe and on the Welland Canal, St. Lawrence Seaway, and the Soo Locks. Ship arrestors that use wire rope are the most common type and are used extensively. Ship arrestors using wire rope are comprised of three main sections: the arresting mechanism, the barrier (boom cable), and the drive. The barrier consists of a boom that transfers a steel wire rope across the lock and locks onto the opposite side of the lock. The wire rope configuration can have as few as one pass across the channel or several passes, depending on the design and force required to stop the vessel. The energy absorption portion can be a hydraulic sealed cylinder that increases the restrictive force on the cable as the speed of impact increases. The Poe Lock at the Soo Locks uses this system. A mechanical braking system and clutch that engage at specific points as the wire rope cable unwinds can also be used. The retarding force is applied to a drum that has either the clutches or the brakes applied to it. The MacArthur lock (Soo Locks, see Figure 3-37) and the Welland Canal systems use this type of design.

a. Soo Locks. The two primary locks at the Soo Locks are the Poe Lock and the MacArthur Lock. Both use ship arrestors for all the lockages. The ship arrestors at the Soo Locks are composed of a steel boom and the arresting steel cable has a diameter of 3½ in. The ship arrestors are similar between the Poe and MacArthur locks in that the boom is driven with a hydraulic cylinder and drops down across the lock chamber. The wire rope is carried by the boom and attaches to (connects to) a second wire rope on the opposite side of the lock. The wire rope is the primary means of arresting or stopping the ships although the boom can also slow down a ship.

Figure 3-37. Macarthur Ship Arrestor – Side View.

(1) The MacArthur Lock uses a boom, cable, and friction drum system for the ship arrestor. The wire ropes, which are of carbon steel with a fiber core, have a diameter of 3½ in. (see Figures 3-38 and 3-39). The boom brings one half of the arresting cable across the lock chamber and the separate wire rope sections are then coupled together with a pin. Swaged connections on the wire ropes are used to couple the sections. Essentially there are two separate wire ropes that are connected together once the boom is placed across the lock chamber. The pin connecting the two wire ropes is driven by an electric motor. The wire rope cable (on both sides of the lock chamber) goes around a sheave/pulley and then a drum and uses friction brakes to slow down a ship (Figure 3-40).

Figure 3-38. Macarthur Lock – 3½-in. Wire Rope Swaged End.

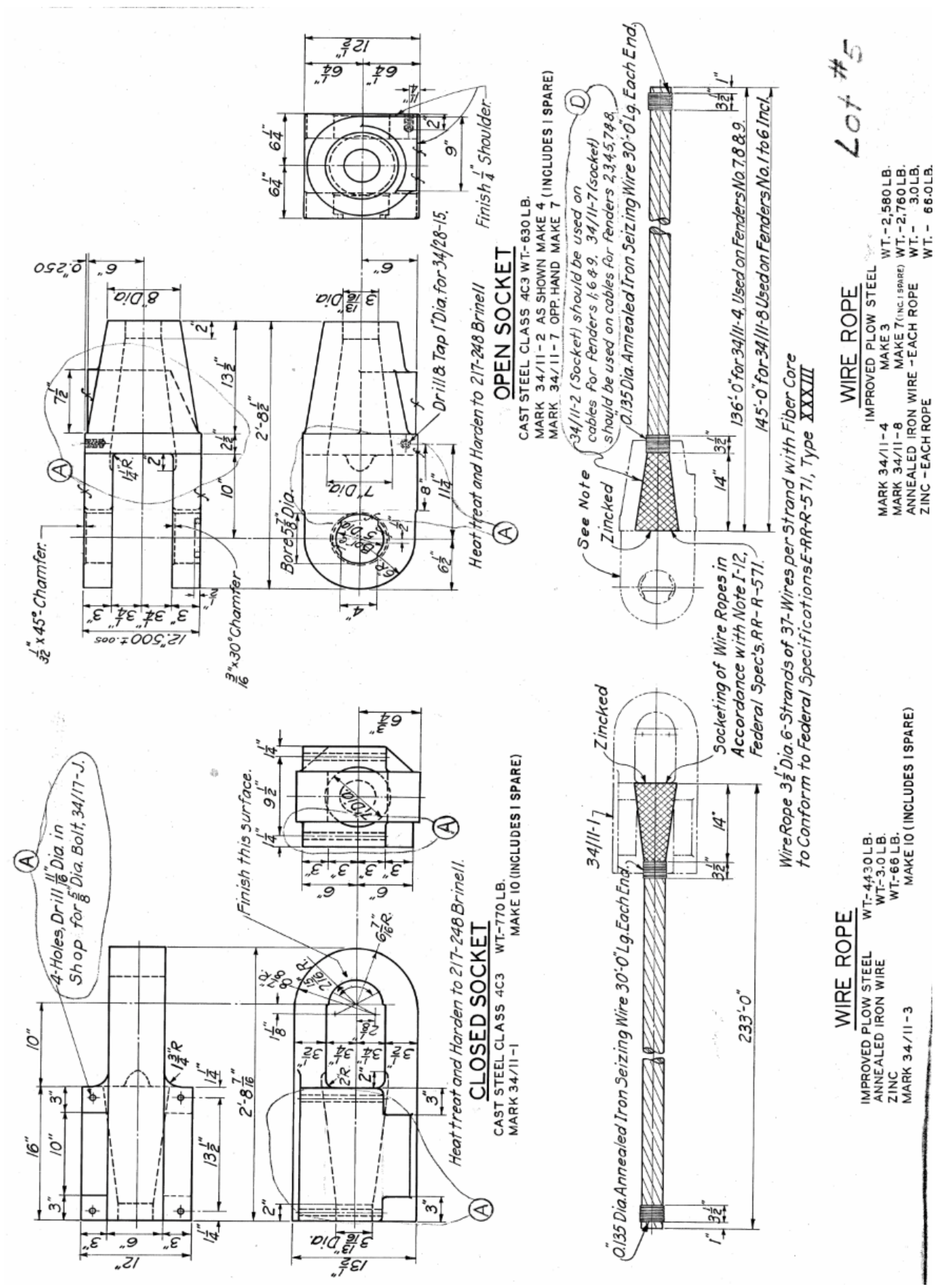

Figure 3-39. Macarthur Lock Wire Rope Detail.

Figure 3-40. Macarthur Lock – Friction Drum and Wire Rope.

(2) The Poe Lock uses a hydraulic cylinder and cross head (Figure 3-41) to “arrest” the cable (after a ship impact) rather than a friction brake (Figure 3-42). The cylinder extends if the ship arrestor is hit by a ship and acts as the arresting mechanism.

Figure 3-41. Poe Lock – Closer View of Bottom of Sheave and Top Cylinder.

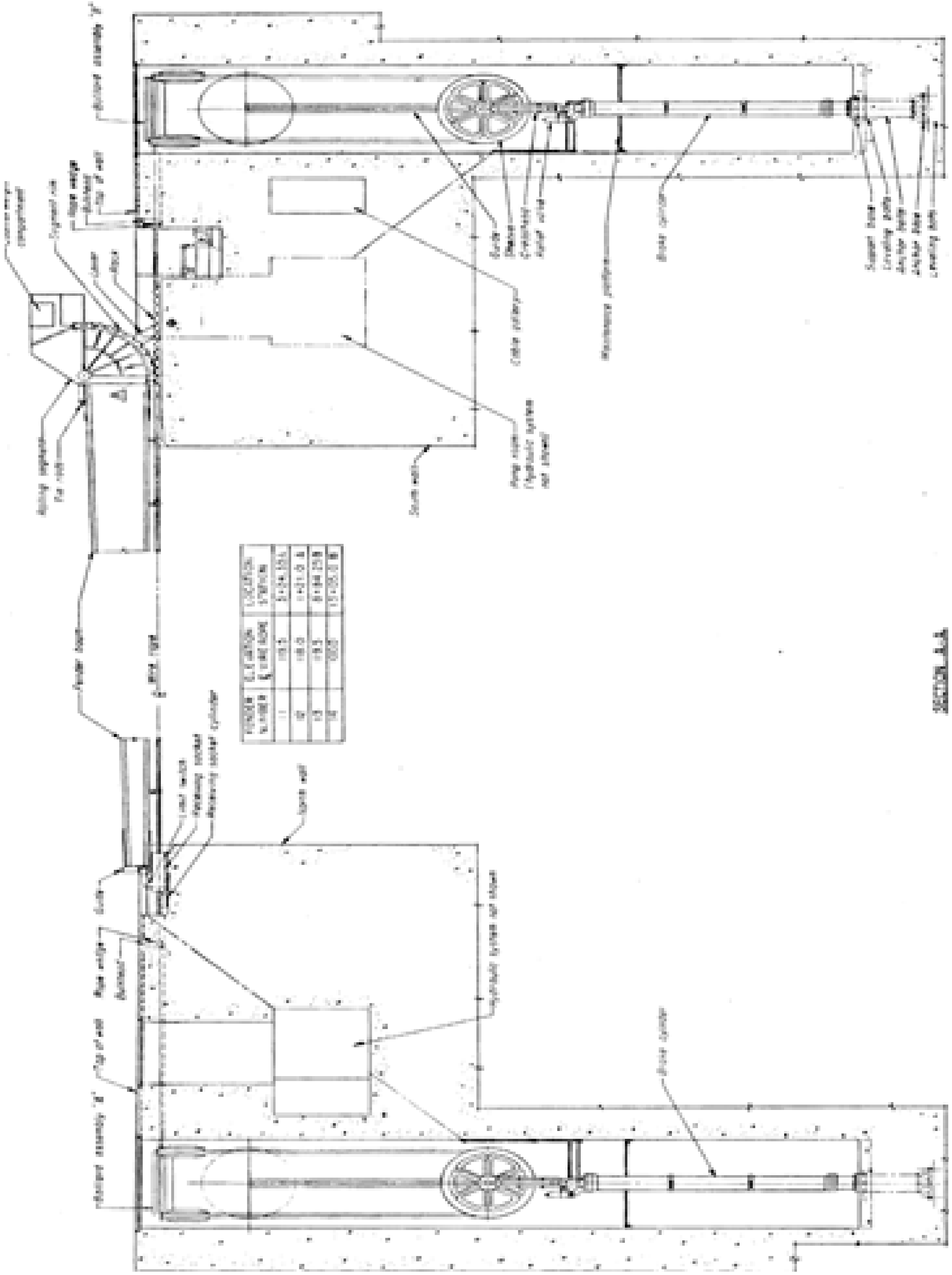

Figure 3-42. Poe Lock Ship Arrestor Section View.

b. Welland Canal. The Welland Canal is part of the St. Lawrence Seaway system. Ship arrestors are also used extensively at the Welland Canal. The ship arrestors are similar to the Soo Lock design (Figure 3-42). The Welland Canal has two (2) types of arrestors (Figure 3-43). This includes a fixed boom and a free boom type. The fixed boom structure (Figure 3-44) spans the lock with a wire rope attached to a braking bollard system and remains in that position when the vessel is in the lock. The free boom drops the wire rope into position, and is then lifted out of the channel until it is time to remove the wire rope to allow for the vessel to continue its transit. The booms on the Welland ship arrestors are operated with a hydraulic cylinder like the Soo Locks. The braking system for the arrestor is of a different design than the Soo Locks. Figure 3-45 shows a drum and brake system.

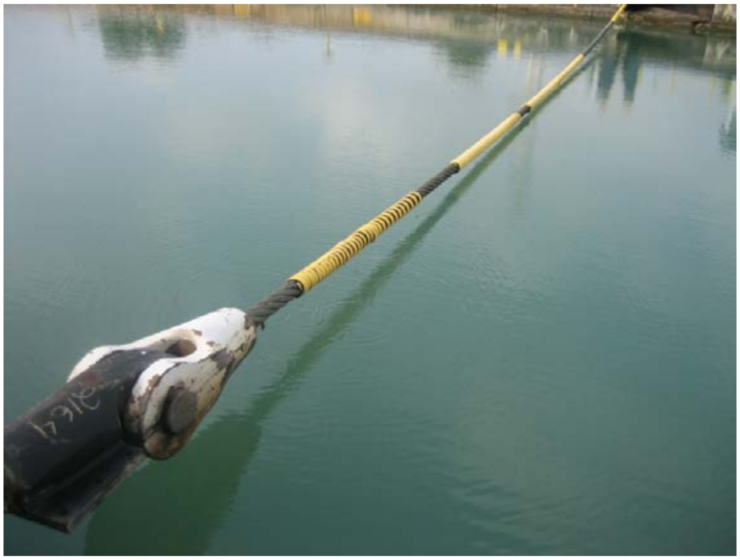

Figure 3-43. Welland Canal Ship Arrestor – Free Boom Type in Place.

Figure 3-44. Welland Canal Fixed Boom Type (Similar to Soo Locks).

Figure 3-45. Welland Canal Brake System.

3-9. Tow Haulage Units. EM 1110-2-2610 further discusses tow haulage units. They are used extensively on the Upper Mississippi River locks. The Upper Mississippi River locks are 600 ft in length and require 1200-ft tows to be broken into two parts. The tow haulage unit (Figure 3-46) allows half of the tow to be pulled through the lock chamber. Tow haulage units are also used on the Monongahela River, Upper Ohio River, Cumberland, and the Kanawha River at several locks. Some of the 1200-ft tows are broken into three parts, which puts extra wear on the winch unit and wire rope.

Figure 3-46. Mechanical Tow Haulage Winch Unit.

Winch systems or tow haulage systems at navigation locks provide the capability to move commercial vessels through the lock chamber (Figure 3-47). For 1200-ft tows, the barge sections must be split in half (or sometimes in three parts) to lock through the chamber. Once the barges are split apart, the winch or tow haulage system (Figure 3-48) is used to pull the first barge cut through the chamber while the tow boat remains with the second barge section. The winch and travelling kevel discussed below typically pulls the first barge cut to the end of the guide wall and past the miter gates. This allows the tow boat and second barge section to lock through. The wire rope is reeved through a fairlead on the lock wall and is then attached to the travel kevel to pull the barge section. The tow haulage winch can either be driven mechanically or hydraulically. EM 1110-2-2610 describes the mechanical system for the tow haulage units in more detail.

Figure 3-47. Tow Tied onto Travel Kevel.

Figure 3-48. Tow Haulage Winch Fairlead.

3-10. Bulkhead Lowering Carriages. Bulkhead lowering carriages are used to set bulkheads under head and flow conditions. New Orleans Port Allen Lock and Old River Lock both use lowering carriages for setting bulkheads as does Bonneville Lock on the Columbia River (Figure 3-49). The lowering carriages at Port Allen and Old River use flat wire rope. The Bonneville Lock uses round wire rope. Wire rope provides an efficient means of operating these hoist carriages. EM 1110-2-2610 and PIANC Report 138 further discuss bulkhead lowering devices.

Figure 3-49. View of Two Existing Bulkheads Stacked on the Lowering Carriage.

a. Old River. The construction of the Old River Lock was completed in 1963. Twelve steel bulkheads are used for emergency and/or maintenance situations and are placed near the miter gates. There are slots cut into the wall of the 78-ft high lock chamber for placing the bulkheads. In the event of damage to the miter gates, the slot on the Mississippi River side is used for emergency closure. Lowering machinery and lowering carriages are used to place all of the bulkheads at once under high velocity flows. This system includes a flat braided wire rope on the lowering machinery (Figure 3-50).

Figure 3-50. Picture of Flat Wire Rope Installed at Old River Lock Lowering Carriage.

The existing design consists of bulkhead lowering machinery and a carriage that has been in place since the Old River Lock became operational in 1963 (Figure 3-51). Steel bulkheads are used for emergency and/or maintenance situations. Bulkheads are placed in slots in the walls of the lock (upstream of the upper gates and downstream of the lower miter gates). In the event of an accident or damage to the miter gates, the bulkhead slots on the Mississippi River side (upper end) are used for emergency closure. Bulkheads are equipped with rollers to allow lowering all of the bulkheads at once under high velocity flows and high head conditions. To set the bulkheads, two separate processes and equipment are used. First, a crane is used to lift and set the bulkheads onto a lowering carriage. Second, a winch system is used to lower and raise the bulkheads to the bottom of the lock chamber. This system includes a flat braided wire rope made from 15 ⅝-inch diameter wire ropes held together side by side with hand-stitched seizing wire. The wire rope is wrapped around a sheave on the carriage and is then anchored into the lock wall.

Figure 3-51. View of Existing Bulkhead Lowering Machinery at Old River Lock.

b. Port Allen Lock. The design of the bulkhead lowering system (Figure 3-52) is similar to the Old River system. Figure 3-53 shows the reeving diagram. The Port Allen system also uses braided flat wire rope.

Figure 3-52. Bulkhead Lifting Machinery Port Allen Lock.

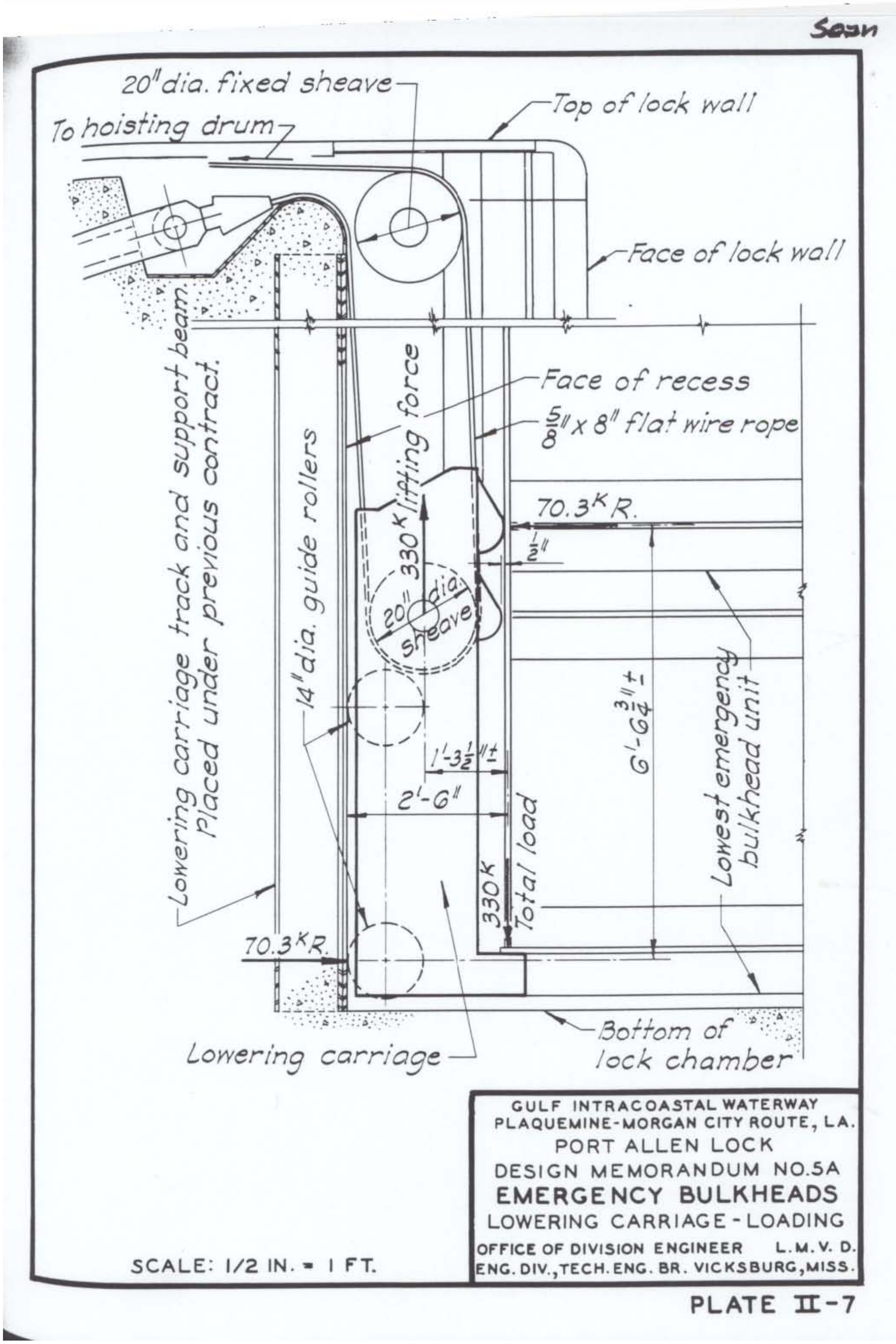

Figure 3-53. Reeving Diagram – Port Allen Bulkhead Lowering Carriage.

c. Bonneville Lock – Columbia River. The Bonneville Lock was completed in 1993 and incorporates a bulkhead lowering system. This allows bulkheads to be placed under head and flow conditions. This system has been used at least once and bulkheads were able to be set under flow conditions. It is a mechanical drive system using an electric motor, gearbox, and winch drums that force the bulkheads down into the slots (Figures 3-54 to 3-56).

Figure 3-54. Bulkhead Winch Cable System – Bonneville Lock.

Figure 3-55. Bonneville Lock – Winch System.

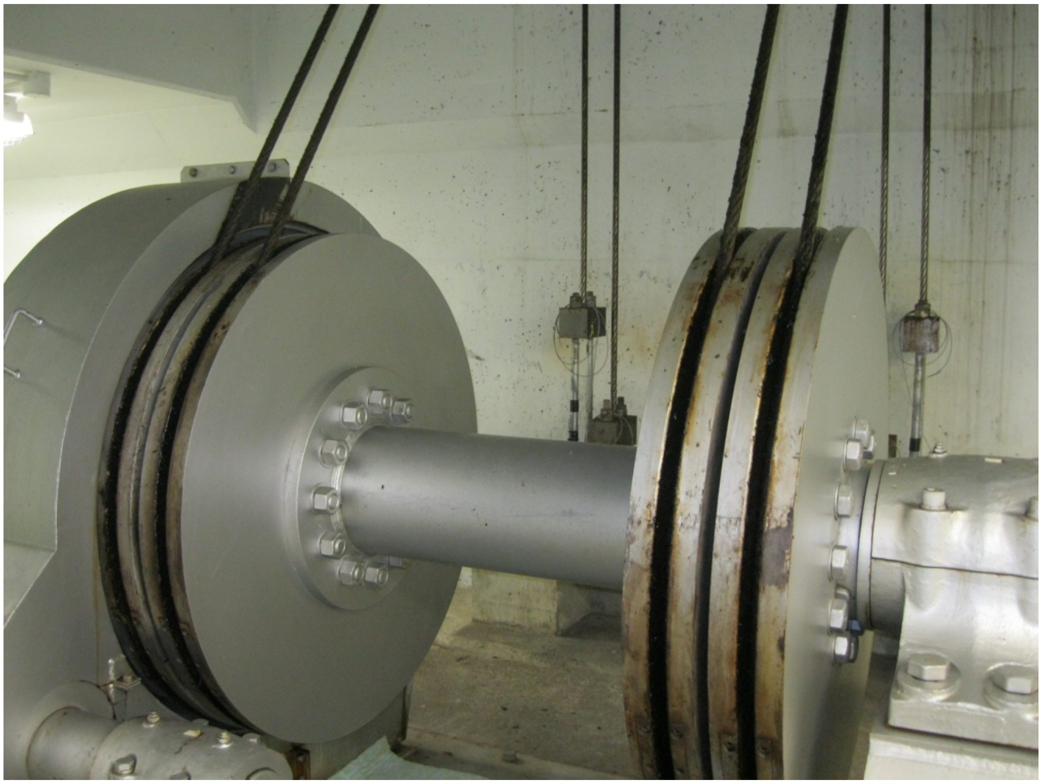

Figure 3-56. Detail of Winch Drums.

CHAPTER 4

Design Considerations

4-1. General. This chapter will cover required design factors of safety, how to calculate rope loads, failure modes, rope selection considerations for civil works structures, and design considerations for devices that interface with ropes.

4-2. Factors of Safety. The following factors of safety (FOSs) must be used for design of wire ropes used for civil works structures. These FOSs are calculated by dividing the minimum breaking strength by the applied tension. The rope strengths used to calculate FOSs must be based on the published minimum breaking strength and shall be reduced by the applicable rope strength reductions, such as those discussed in Section 4-3, before calculating the FOS. The most common sources for published rope strength values are ASTM A1023 and Fed Spec RR-W-410. At a minimum, the applied tensions must be those discussed in Section 4-2 (a and b, or c, as applicable). This criteria shall be used for new installations and retrofits or rehabilitations of existing systems. The same FOS guidelines are recommended for rope replacements (replacements in kind), but are not mandatory if the existing system was designed to different, yet reasonable, design criteria. Wire rope loses strength once in service. Because of this, the wire rope industry also uses the term Design Factor which is defined as the nominal rated strength to the total working load. It can also be defined as the minimum breaking force of a wire rope to the total load it is expected to carry. The term Design Factor is meant to convey that the rated strength of the wire rope is constantly changing over time.

a. Normal Operating Tension FOS. The normal operating tension is the maximum tension a rope will be subjected to under the most conservative normal operating conditions. This tension must account for all applicable operating loads including dynamic loading, inertial effects, increases from sheave bearing friction, etc. The FOS for the normal operating tension must be at least 5.0, based on the rope minimum breaking strength. This FOS has been found to provide a reasonable level of protection against minor unexpected conditions and reasonable service lives for most civil works structures applications. This criteria matches the mechanical normal full load criteria from EM 1110-2-2610. A higher FOS may be justified for an installation where many loading cycles are anticipated and fatigue is a concern. Engineering judgment must be used to determine when it may be necessary to design to a higher FOS.

b. Maximum Tension FOS. The maximum load applied to a rope must not exceed 70% of the minimum breaking strength of the rope (FOS of 1.43). Maximum rope loading for most gate systems occur during gate jammed scenarios. Designers should be aware of design criteria that requires designing the system for uneven load distributions under a maximum loading condition. EM 1110-2-2610 provides an example of this scenario that requires designing for a 70/30 load distribution between sides of a spillway Tainter gate under the maximum overload condition. When applying cases of uneven load distribution, the rope system must be designed so no rope exceeds 70% of the minimum breaking strength. Designers may want to consider load-limiting devices as an option to shut down the motor in case of an overload for protection of the wire rope. See Appendix D – Load-limiting Devices.

c. Static Loading FOS. Some ropes are used for static only applications such as locating or stationing parts. These ropes must have a minimum FOS 3.0 based on the minimum breaking strength.

d. Reserve Strength. As a wire rope is used abrasion and fatigue occur, which reduces its strength, particularly at the ropes outer wires. The term reserve strength defines the combined strength of only a wire rope's inner wires (Table 4-1). Designers should consider ropes with a higher reserve strength for applications with higher potential for abrasion and fatigue. For example, consider a 6x31 classification rope that has 12 outside wires. The inner wires only have a reserve strength of 43%. Such a rope with an original FOS of 5 in a severely worn condition would have a much lower FOS since the outer wires have 57% of the rope's strength.

Table 4-1. Number of Outside Wires vs. Reserve Strength (6 or 8 Strand Rope).

Number of Outside Wires*	Percent of Reserve Strength
3	0
4	5
5	3
6	8
7	22
8	27
9	32
10	36
12	43
14	49
16	54
18	58
*Source: WRTB 4th ed. (2005)	

4-3. <u>Rope Strength Reductions</u>. Certain wire rope loading conditions cause an increase in the local stresses in a rope. The effects of the local stress increases are easiest to measure as breaking strength reductions. The percent of breaking strength decrease is often expressed as an efficiency value. To note, the efficiency is an expression of a reduction in breaking strength only. It is not related to a power loss in a mechanical drive-train. Applicable rope strength reductions must be applied to reduce the rope strength when determining an FOS.

a. Bending over a Curved Surface.

(1) Published rope breaking strength values are based on pulling rope to failure in a straight line. When a rope passes over a curved surface such as a drum, sheave, or pin it causes an uneven loading on the rope and a resulting strength reduction. Figure 4-1 shows the local stress increase from uneven rope loading.

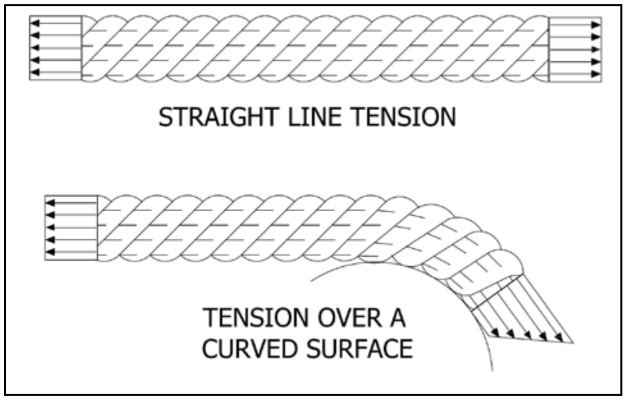

Figure 4-1. Uneven Rope Loading Over a Curved Surface.

(2) The Wire Rope Users Manual (WRTB 2005, Figure 38) shows correction factors for strength reductions caused from a wire rope passing over a curved surface. The curve is based on static loads and applies to 6x19 and 6x37 class ropes but is somewhat representative for other wire rope construction. These values are expressed as strength efficiency vs. the D/d ratio, where D is the radius of the curved surface and d is the diameter of the rope. Bend radius efficiency values must be applied to reduce the breaking strength of rope that passes over a curved surface. For example, a rope pulled in a straight line is 100% efficient. A rope passing over a curved surface 26 times its own diameter would be approximately 93% efficient. If the minimum breaking strength of the rope is 50,000 lbf, the strength of this rope passing over the curved surface 26 times its diameter would be 46,500 lbf. Efficiency reductions from a rope bending over multiple curved surfaces are not cumulative. For ropes that pass over multiple curved surfaces with different radii and the same tension, only the efficiency reduction cause by the minimum D/d ratio must be used. The reader should refer to the Wire Rope Users Manual for additional information.

(3) Designers should also be aware that the service life of a rope is influenced by the bending radii to which it is subjected. Wire rope that operates over sheaves, drums, or other curved surfaces are subjected to cyclic bending stresses. The magnitude of bending stresses are dependent on the D/d ratio. With all other factors being identical, a rope subjected to a larger D/d ratio will have a longer service life than a rope subjected to a smaller D/d ratio. This concept is demonstrated graphically in the Wire Rope Users Manual (WRTB 2005, Figure 34). The figure shows the differences in relative service life (caused by bending stresses) of a rope subjected to different D/d ratios. For example, a rope system with a D/d ratio of 20 has a relative service life of 12. The identical rope system with a D/d ratio of 30 has a relative service life of 24. This means that the rope with the D/d ratio of 30 will have twice the service life of the rope with a D/d ratio of 20.

(4) The data in Table 4-2 from the Wire Rope Users Manual provides general guidance for minimum recommended D/d ratios of various rope constructions below. Many wire rope manufacturers also provide specific minimum bend radius guidelines and recommendations for their wire ropes. These are typically no less than a radius that results in a 93% bend efficiency. Rope manufacturers should be consulted for specific minimum bend radius recommendations. If guidance is not available from the rope manufacturer, designers should try to stay in compliance with the minimum D/d ratios listed in Table 4-2.

Table 4-2. Suggested Minimum Sheave and Drum Ratios.

Construction*	Suggested D/d ratio
6x7	42
19x7 or 18x7 Rotation Resistant	34
6x19S	
6x25 B Flattened Strand	30
6x27 H Flattened Strand	
6x30 G Flattened Strand	
6x31 V Flattened Strand	
6x21 FW	
6x26 WS	
8x19S	26
7x21 FW	
6x25 FW	
6x31 WS	
6x37 FWS	
7x25 FW	23
6x36 WS	
6x43 FWS	
7x31 WS	
6x41 WS	20
6x41 SFW	
6x49 SWS	
7x36 WS	
8x25 FW	
19x19 Rotation Resistant	
35x7 Rotation Resistant	
6x46 SFW	18
6x46 WS	
8x36 WS	
* Source: WRTB 4th ed. (2005)	

b. Termination Efficiencies. Some rope terminations cause uneven load distributions in wire ropes. Similar to bending over a curved surface, these terminations cause effective reductions in the breaking strength of the rope. For civil works structures only terminations with 100% efficiency (swaged sockets, spelter/resin sockets, and drum terminations with an appropriate amount of dead wrap) must be used. Termination types that are less than 100%

efficient are not as permanent, rugged, and resilient and therefore are not appropriate for civil works structures. Chapter 5 covers rope terminations in more detail.

4-4. Calculating Rope Tension. The process to calculate rope loads involves first finding the rope tension that would occur without losses. Next, tension increases due to losses such as sheave bearing efficiencies are added to find the total rope tension. The FOSs provided above are applied to the total rope tension. The process is demonstrated here with some short examples. Appendix C of this manual provides more detailed sample problems.

a. Frictionless Rope Tension.

(1) The frictionless rope tension for single leg wire ropes and for single and multiple part sheave block tackles is calculated by dividing the total load by the parts of wire rope supporting the load. As the title implies, this tension does not include friction losses. Figure 4-2 shows a four part rope system. Figure 4-3 shows a drawing of this system where the rope system is supporting a 100 kip load.

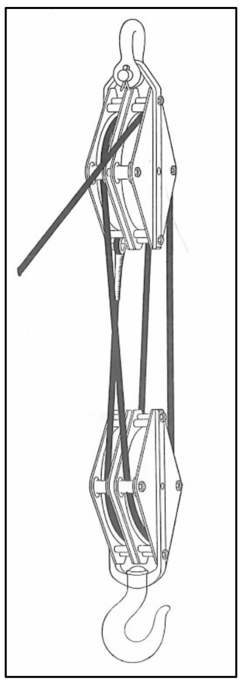

Figure 4-2. Four Part Rope System.

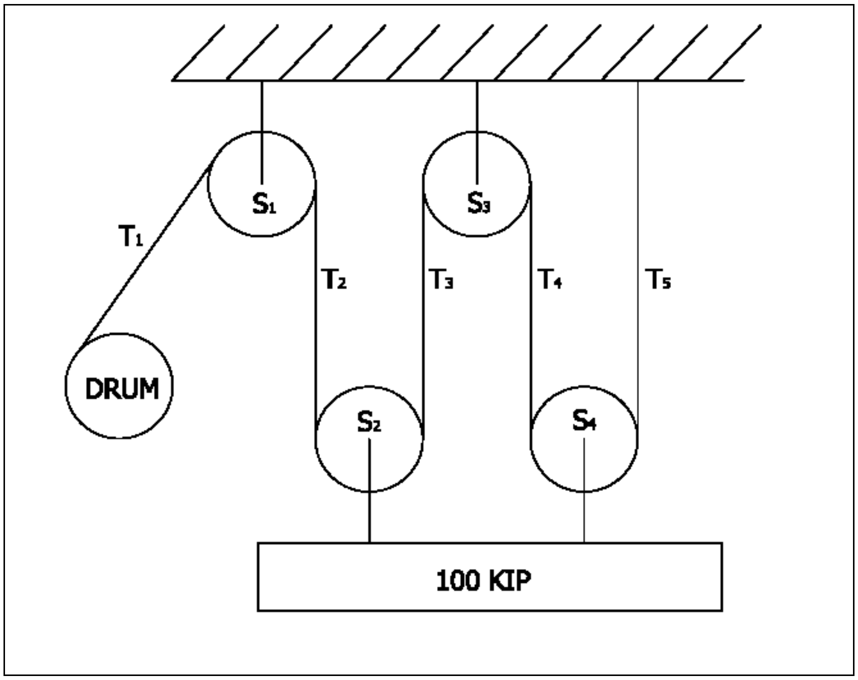

Figure 4-3. Four Part Rope System Diagram.

(2) To find the frictionless tension for the rope system shown in Figure 4-3, the 100 kip load is divided evenly among the four ropes supporting the load:

$$T_2 = T_3 = T_4 = T_5 = \frac{100\ kip}{4} = 25\ kip \qquad \text{Eq 4-1}$$

(3) With no friction losses, the rope between the drum and first sheave (T_1) matches that of the tension between the first and second sheave (T_2).

$$T_1 = T_2 = 25\ kip \qquad \text{Eq 4-2}$$

(4) Therefore, the tension in each section of the rope is equal. Now the friction losses can be accounted for.

b. Friction tension increases.

(1) Load increases are experienced when a rope passes over a sheave. This is due to a portion of the rope tension being applied to overcome the friction in the sheave bearing, as demonstrated in Figure 4-4. In this one-part rope system, it is plain to see that, for the frictionless case, the tension $T_1 = T_2 = 100$ kips. When friction losses are applied, the tension T_2 remains equal to 100 kips. However, the tension T_1 is increased by an amount necessary to overcome the friction in the sheave bearing. The tension between the drum and sheave becomes $T_1 + \mathbf{D}T$.

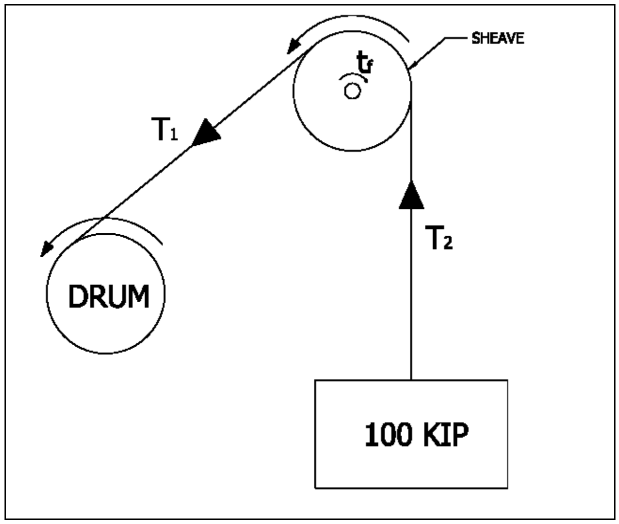

Figure 4-4. One Part Rope System.

(2) There is more than one method commonly used to account for tension increases (ΔT) from sheave bearing friction losses. The method shown here is based on an estimated friction in the sheave bearing. Appendix C shows the derivation of this method. This method uses the following equation to find the tension increase from friction as the rope passes over a sheave:

$$\boldsymbol{T+\Delta T = T\left(\frac{D+\mu(d_b)}{D-\mu(d_b)}\right)} \qquad \text{Eq 4-3}$$

where:

T = Frictionless rope tension
ΔT = Tension increase due to sheave bearing friction
μ = sheave bearing coefficient of friction
D = sheave pitch diameter (centerline diameter of rope running over sheave)
d_b = sheave bearing diameter.

(3) The sheave pitch diameter and bearing diameter should be known values. If a designer is working to size a new system, preliminary values of D = 20d (min D/d ratio for common civil works structure ropes) and d_b = 5d are typically conservative initial guesses. Sheave bearing coefficients of friction have a number of uncertainties that must be estimated. Bearing friction depends on the condition of the bearing, contaminants that enter the bearing, and how well and how often it is maintained. Designers should select a coefficient of friction that accounts for maintenance performed at longer intervals than intended by design and for cases where water, dirt, debris, etc. enter the bearing. Conservative yet reasonable operating conditions that should be accounted for in the design coefficient of friction should include bearing maintenance that is performed at time periods longer than the designed interval, or the intrusion of water, dirt, or debris. Table 4-3 lists recommended coefficients of friction for roller and plain bearings. These are larger than typical manufacturer ratings as they include allowances for extended maintenance intervals and for some water, dirt, or debris entering the bearing. These do not include allowances for more extreme conditions, such as frequent operation at very low temperatures. Engineering judgment must be used to account for these more extreme conditions.

Table 4-3. Sheave Bearing Coefficients of Friction.

Bearing Type	μ
Roller	0.06
Plain	0.30

(4) In the four part rope system example shown in Figure 4-5, there are increased rope tensions due to friction losses. This assumes that the sheaves have plain bearings, that the rope has a 1-in. diameter (d = 1 in.), that the sheave pitch diameter is 26 in. (D = 26 in.), and that the sheave bearing diameter is 3 in. (d_b = 3 in.).

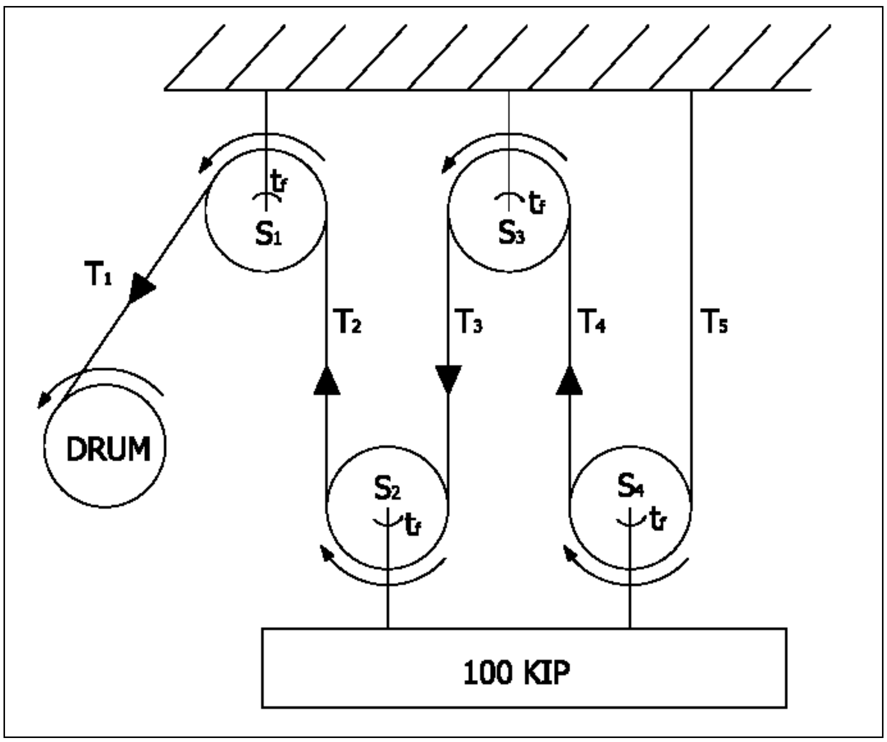

Figure 4-5. Four Part Rope System Dynamic Tension.

(5) Begin by plugging the values into the tension increase equation above:

$$\boldsymbol{T + \Delta T = T\left(\frac{26in + 0.3(3in)}{26in - 0.3(3in)}\right) = 1.072(T)} \qquad \text{Eq 4-4}$$

(6) The tension may now be found at each location:

$$\boldsymbol{T_5 = \frac{100\ kip}{4} = 25\ kip}$$
$$\boldsymbol{T_4 = 1.072(T_5) = 26.80 kip}$$
$$\boldsymbol{T_3 = 1.072(T_4) = 28.73 kip}$$
$$\boldsymbol{T_2 = 1.072(T_3) = 30.79 kip}$$
$$\boldsymbol{T_1 = 1.072(T_2) = 33.02 kip}$$

(7) Note the significant increase in tension compared to the frictionless tension. Tension T_1 with friction losses is 32% higher than the frictionless tension.

4-5. Rope Stretch. This section discusses two types of rope elongation under load including constructional stretch, which occurs during the early life of the rope, and elastic stretch, which is dependent on the tension applied to the rope. Both are pertinent to determining the length of the rope. Designers should consider that wire rope can be measured under tension at the manufacturing facility and socketed for a more accurate length.

a. Constructional stretch. When a load is applied to a new wire rope, the rope elongates as the strands and wires constrict and squeeze the rope core. Constructional stretch can be thought of as “bedding down” of the strands and wire within the rope. The amount of this stretch is influenced by a rope’s core type, rope construction, length of rope lay, and rope material. FC ropes experience more constructional stretch than do IWRC ropes because the fiber core compresses more than a steel core as it is squeezed by the strands and wires. For a six-strand IWRC rope, the constructional stretch will be around ¼ to ½% of the length.

b. Pre-Tensioning. Constructional stretch generally ceases at an early stage in the life of a rope. However, it can still cause large unbalanced tensions if not accounted for. This is especially true with multi-rope drums. Pre-stretching is a method to minimize constructional stretch by stretching the rope before installation. A common pre-stretching procedure is to perform three cycles of pulling a rope to 40% of its tensile load for 5 minutes and reducing the tension to 5% of its tensile load between pull cycles. This example and other pre-stretching requirements can be found in ASTM A1023. Typically, pre-stretching is performed by the wire rope assembler before installing terminations. Overall, pre-stretching is a practical and inexpensive way to minimize or eliminate constructional stretch and should be used for civil works structures.

c. Elastic stretch. Elastic stretch is the recoverable deformation of the rope material that follows Hooke’s law. Elastic stretch is dependent on the rope’s cross section area and the modulus of elasticity. A reasonable approximation can be made using the method from the Wire Rope User’s Manual (WRTB 2005). The method from the Wire Rope User’s Manual is summarized below for rope types that might be used on civil works structures.

d. Elastic Stretch Approximation Method.

(1) Elastic stretch can be approximated with the rope modulus of elasticity and the approximate metallic area using the following relation:

$$\boldsymbol{Change\ in\ length} = \frac{(\boldsymbol{Change\ in\ load})(\boldsymbol{length})}{(\boldsymbol{Metalic\ area})(\boldsymbol{Modulus\ of\ elasticity})} \qquad \text{Eq 4-5}$$

(2) Tables 4-4 and 4-5 show approximate modulus of elasticity values and approximate metallic area cross sections. These values are summarized from the Wire Rope User's Manual (WRTB 2005) for ropes that would be most commonly used on a civil works structure. For a more comprehensive list, see the Wire Rope User's Manual. The metallic areas in Table 4-5 are given for 1-in. diameter rope. The area values can be converted to that of a different rope diameter by squaring the diameter of the rope size of interest and multiplying by the area of a 1-in. rope. It is also noted that the metallic area of ropes vary. The values listed in Table 4-5 are based on a 3% oversize, which is a common target value for manufacturers. Actual area values will vary. However, these are accurate enough for this elastic stretch approximation method.

Table 4-4. Approximate Modulus of Elasticity.

Rope Classification*	Zero through 20% Loading	21% to 65% Loading
6x19 with IWRC	13,500,000	15,000,000
6x36 with IWRC	12,600,000	14,000,000
8x19 with IWRC	12,000,000	13,500,000
8x36 with IWRC	11,500,000	13,000,000
*Applicable to new rope with constructional stretch removed Reprinted from the Wire Rope User's Manual (WRTB 2005)		

Table 4-5. Approximate Metallic Areas of 1-in. Rope.

Construction	IWRC or WSC (in^2)		Construction	IWRC or WSC (in^2)
6x6	0.386		6x31 WS	0.481
6x7	0.451		6x33 FW	0.490
6x19 S	0.470		6x36 WS	0.485
6x19 W	0.482		6x37 FW	0.493
6x21 FW	0.478		6x41 SFW	0.491
6x21 S	0.477		6x41 WS	0.490
6x25 FW	0.483		6x43 FWS	0.458
6x26 WS	0.476		6x46 SFW	0.492
6x29 FW	0.486		6x46 WS	0.492
Reprinted from the Wire Rope User's Manual (WRTB 2005)				

e. Elastic Stretch Example Problem.

(1) Find the elastic stretch of a 100-ft long, 6x36 class, 6x36 WS, IWRC, ⅞-in. diameter rope between the dynamic normal operating tension and maximum tension. To solve this, assume the rope is sized to comply with the criteria in Section 4-2 which requires the normal operating tension to have a minimum FOS of 5 based on the rope breaking strength. It also requires the rope not exceed 70% of the breaking strength under maximum tension. Therefore, the rope will be loaded between 20 and 70% of its rated breaking strength. These breaking strength percentages do not exactly match the percent of breaking strength ranges listed in Table 4-4. However, this analysis will proceed using the 21 to 65% range modulus of elasticity with the understanding that it is only determining a rough order of magnitude elastic stretch. For a more accurate estimate the stretch that occurs in each range should be calculated separately to account for the different modulus. Begin by correcting for the area of a ⅞-in. diameter rope. Now it is possible to find the change in tension that corresponds to the change between 20 and 70% rope tension:

$$A_{7/8-in} = \left(D_{7/8-in}\right)^2 A_{1-in} = \left(\frac{7}{8} in\right)^2 (0.485) = 0.371\ in^2$$

(2) A breaking strength of 39.8 tons for EIPS rope will be used from ASTM A1023:

$$[0.70(39.8\ tons) - 0.20(39.8\ tons)]2{,}000 \frac{lbf}{ton} = 39{,}800\ lbf$$

(3) The elastic stretch may now be calculated by:

$$\boldsymbol{\Delta L} = \frac{(\mathbf{39{,}800}\ \boldsymbol{lbf})(\mathbf{100}\ \boldsymbol{ft})\left(\mathbf{12}\frac{\boldsymbol{in}}{\boldsymbol{ft}}\right)}{(\mathbf{0.371}\ \boldsymbol{in^2})(\mathbf{14{,}000{,}000}\boldsymbol{psi})} \approx \mathbf{9}\boldsymbol{in} \qquad \text{Eq 4-6}$$

(4) The elastic stretch for 100-ft of ⅞-in. diameter, 6x36 class, 6x36 WS, IWRC, EIPS rope has been determined to be approximately 9-in.

4-6. Rope Bearing Pressure. Excessive wear of rope drums and sheaves is most often caused by a combination of rope load that is too high, a drum material that is too soft, or drum and sheave tread diameters that are too small. To minimize wear, the unit radial pressure between the rope and grooves must be maintained below allowable values. Allowable unit radial pressure for drums and sheaves varies with material. Note that the materials listed in Table 4-6 are available in a wide range of hardness so the pressure values will vary. Also note that, if the allowable radial pressure is exceeded, the drum or sheave’s grooves will wear rapidly, eventually causing accelerated wear of the rope. When possible, it is ideal to have a high hardness on the drum or sheave to prevent imprinting the wire rope pattern on the drum. If imprinting occurs, the drum or sheave rope contact surfaces will need to be re-machined when replacing ropes to avoid damaging the new rope with the imprinted pattern. Drum and sheave hardness values of 371-400 Brinell Hardness Number (BHN) are recommended when possible to avoid imprinting. The bearing pressure of wire rope on a drum or sheave can be calculated with the following formula:

$$\boldsymbol{p} = \frac{\mathbf{2}\boldsymbol{T}}{\boldsymbol{Dd}} \qquad \text{Eq 4-7}$$

where:

T = the rope tension
D = the tread diameter of the sheave or drum
d = the nominal diameter of the rope
p = bearing pressure.

Table 4-6. Sheave and Drum Suggested Surface Hardness; Suggested Allowable Bearing Pressure of Ropes on Various Sheave Materials.

	Regular Lay Rope, psi				Lang Lay Rope, psi			Flattened Strand	
Material	6x7	6x19	6x36	8x19	6x7	6x19	6x36	Lang Lay, psi	Remarks
Cast Iron	300	480	585	680	350	550	660	800	Based on minimum Brinell hardness of 125
Carbon Steel Casting	550	900	1075	1260	600	1000	1180	1450	30-40 Carbon. Based on minimum Brinell hardness of 160
Chilled Cast Iron	650	1100	1325	1550	715	1210	1450	1780	Not advised unless surface is uniform in hardness
Manganese Steel, Induction Hardened or Flame Hardened	1470	2400	3000	3500	1650	2750	3300	4000	Grooves must be ground and sheaves balanced for high speed service
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4-7. Failure Modes. Failure of a wire rope is typically caused by any one or a combination of corrosion, fatigue, abrasive wear, and excessive stress. The following paragraphs comment on each condition.

a. Corrosion. Ropes for civil works structures are often exposed to submerged or marine environments for the duration of their operating life. Because of this, corrosion is typically either predicted to be the primary failure mode or is a major consideration when selecting a rope type. The primary corrosive threat is water, which acts as an electrolyte that allows corrosion to take place. Submerged and marine environments can contain damaging substances such as chlorides, nitrates, calcium carbonates, bacteria, or galvanic currents. The main methods to combat corrosion are proper material selection and lubricating ropes on regular intervals.

b. Fatigue. Fatigue usually results from moving over sheaves, drums, or rollers. A rope moving over drums, sheaves, or rollers is subjected to cyclic bending stresses. To bend around a sheave, the strands and wires of a rope must move relative to one another. This movement compensates for the difference in diameter between the underside and top side of the rope. Stress magnitude depends on the ratio of the diameters of the drums and sheaves to the diameter of the rope and the applied load. Fatigue is also affected by lubrication and the condition of the surface over which the rope is bending. Lack of rope lubrication or excessive pressure caused by too small of groove diameter limits wire slip. This increases bending and fatigue. Some devices require rope to change bending direction from drum to sheave, or from one sheave to another. Reverse bending further accelerates wire fatigue. Effects of fatigue can be minimized by selecting ropes with lang lay construction and small wires, performing regular lubrication, and minimizing reverse bending of ropes with the design of the rope system.

c. Abrasive wear. Similar to fatigue, wear from abrasion normally results from contact with sheaves and drums. Wire rope, when loaded, stretches much like a coil spring. When bent over a sheave, its load-induced stretch causes it to rub against the groove. As a result, both the rope and groove are subject to abrasion. Within the rope, wires and strands move relative to each other causing additional abrasion. Excessive abrasion can be caused by the sheave or drum being of too soft a material; or by having too much rope pressure, debris on the rope contact surfaces, an improper groove diameter, or an improper fleet angle. Movement of rope against roller guides can cause excessive abrasion. Improper tensioning can allow the rope to rub against metal or concrete structures. Wire rope featuring lang lay construction and large wires tends to be effective in reducing abrasive wear.

d. Excessive stress. Excessive stress in Corps applications has generally resulted from attempted operation when a gate is inoperable because of ice and debris or gate misalignment. Excessive stress can also result from improper tensioning in a device using multiple ropes. The main methods to prevent excessive stress is to properly design for conditions involving overload, jamming, or misalignment. In addition, load limiting devices can be incorporated into the mechanical system to limit the amount of overload the system can produce, which can minimize the potential for excessive stress.

4-8. Selection of Rope for Civil Works Structures. Despite the large range of wire rope classes, constructions, and materials available there are relatively few types that are best suited for civil works structures. This section will discuss rope selection considerations specific to civil works structures. In addition, each common type and its main advantages and disadvantages are discussed.

a. Rope Core. IWRC is the only type of rope core that shall be utilized for civil works structures. FC has been used for some gate systems in the past, but is not a suitable core material for civil works structures due to its tendency to flatten and crush under high loads.

b. Rope Lay. Regular lay ropes are the most commonly used and are suitable for most applications. The primary advantage of lang lay ropes is the improved bending fatigue performance (typically 15-20% better performance than regular lay). They are also believed to have better abrasion resistance. Lang lay should be evaluated for use when fatigue is one of the top expected failure modes. However, designers should be aware of the limitations of lang lay, which include the occurrence of severe rotation when an end is not fixed and the fact that they should not be used with swage sockets.

c. Rope Material. There are no specific material limitations for ropes used for a civil works structure. However, most USACE gates operate in corrosive (marine or fully submerged environments) so galvanized and stainless steel ropes are often the best and most common choices. Uncoated (bright) ropes are also acceptable for use in less corrosive applications. It is most common to select a rope material based on its ability to resist the expected predominant failure mode. If corrosion is the primary failure mode stainless ropes should be selected. For example, a gate with submerged ropes that experiences very few operating cycles would be best suited for stainless steel ropes. If fatigue is the primary failure mode, galvanized or bright ropes should be selected. For example, a navigation lock gate that experiences many operating cycles per day would be best suited for galvanized ropes.

d. Wire Size. When considering preliminary rope selection, it is a best practice to keep wires in a manageable size. If a device uses a very small diameter rope, say ⅝-in., initially consider a construction such as 6x7. If a device uses a medium diameter rope, say 1¼ in., initially consider a construction such as 6x19. If a device uses a large diameter rope, say 2½ in., initially consider a construction such as 6x37. In this way, a small rope would have relatively large wires and large rope would have relatively small wires. The wires tend to be relatively constant in size through a large range of rope diameter. This causes abrasion and corrosion characteristics of the wires over a large range of rope diameters to be similar.

e. Rope Diameter. When possible, choosing standard rope sizes can provide greater availability of ropes, terminations, fittings, and other rope accessories. Rope size in ¼-in. increments, for example ½-in., ¾-in., 1-in., 1¼-in., 1½-in., 1¾-in., 2-in., 2¼, 2½-in., etc. tend to be the most available.

f. Rope Types. The following rope types are some of the most common choices for civil works structures.

(1) 6x36 Class, 6x37 Warrington Seale, IWRC. This construction has small wire sizes relative to its rope diameter compared to other civil works structure rope constructions. This provides good bending performance, which makes it a common choice for ropes that run through block or sheave assemblies. The tradeoff for the smaller wire size is reduced abrasion resistance and increased susceptibility to corrosion. This construction is best for larger rope sizes (1-in. and larger) due to the smaller wire size. It can often be found with galvanized or bright finish. Availability can vary and can require purchase of a full mill run length of rope.

(2) 6x19 Class, 6x26 Warrington Seale, IWRC. This construction is commonly available in galvanized and bright finish, but can be difficult to find in stainless steel. It has a larger wire size relative to a 6x37 construction, which gives better abrasion resistance and lower bending performance. It is typically available in ¾-in. and larger diameters. The primary advantage compared to the 6x37 construction is availability. This construction is often readily available in smaller lengths than a full mill run.

(3) 6x19 Class, 6x25 Filler Wire, IWRC. This construction is very similar to a 6x26 construction, but tends to be available in stainless steel. Like the 6x26 construction, it tends to be readily available in smaller length quantities. It is typically available in ¾-in. and larger diameters.

(4) 6x7 Class, 6x7 SC. This construction is used for smaller rope sizes typically ranging from ¼- to ⅝-in.

(5) 6x25 B Flattened Strand. Flattened strand has two primary advantages over non-flattened constructions, higher crushing resistance, and larger cross section area that provides slightly higher strength values. The tradeoff for these improved properties is higher cost and lower availability. There some applications where the improvement of these properties justifies the additional cost.

4-9. Rope Component Considerations. This section will discuss general considerations for the design of components that interface with wire rope. Specifically, the recommended dimensions and other general considerations presented in this section should be followed when designing and maintaining rope drums and sheaves. Other components that interface with wire ropes should also follow these considerations, as applicable. Sections 4-10 and 4-11 give additional information on sheaves and drums.

a. Bending Radii. Wire rope operating over sheaves, drums, or other components is subjected to cyclic bending stresses. The magnitude of bending stresses are dependent on the ratio of the diameter of the sheave or drum (D) to the diameter of the rope (d). Specific guidance is covered in Section 4-3.

b. Rope Grooves. Grooves are used on wire rope sheaves and drums to help support the rope from flattening when the rope is under tension. Groove dimensions that are too small pinch the rope and prevent the individual wire from moving. Groove dimensions that are too large will cause the rope to flatten, which again prevents proper movement of individual wires. Table 4-7 lists recommended rope grooves. There are different recommended dimensions for new or re-machined rope grooves compared to grooves that are in service. Both are discussed further below.

(1) New and Re-machined Grooves. New and re-machined grooves are based on the maximum size of new rope, which is 5% over the nominal rope diameter. The recommended groove radius is provided in the “minimum new groove” column in Table 4-7. The “maximum groove” is the largest radius that should be used for new and re-machined grooves.

(2) In Service Grooves. Rope grooves will wear as they are used. In particular, the roots of the grooves tend to experience the most wear. When inspecting in-service drums and sheave grooves, the “minimum worn groove” column should be used. When a groove is smaller than the recommended dimensions a groove should be re-machined. If proper groove dimensions are not re-established, the rope will be pinched and damaged as it runs through the groove.

(3) Groove Surface Considerations. In addition to proper groove radius, rope grooves should also be inspected for surface condition and alignment of the wear pattern. If the surface of rope grooves are imprinted with the rope profile, then re-machining or replacement should be performed. This can also be an indication of a surface that is too soft. The surface hardness criteria listed in Table 4-6 should be checked when rope imprints are found in rope grooves. Grooves that wear off center can be an indication of an alignment problem with the reeving of the rope. If this condition is noticed, the alignment of the sheave or drum should be checked and corrected.

Table 4-7. Rope Groove Radius.

Nominal Rope Diameter		Groove Radius					
		Minimum Worn Groove		Recommended Minimum New Groove		Maximum Groove	
inches	mm	inches	mm	inches	mm	inches	mm
¼	6.5	0.128	3.250	0.134	3.400	0.138	3.510
5/16	8	0.160	4.060	0.167	4.240	0.172	4.370
⅜	9.5	0.192	4.880	0.199	5.050	0.206	5.230
7/16	11	0.224	5.690	0.232	5.890	0.241	6.120
½	13	0.256	6.500	0.265	6.730	0.275	6.990
9/16	14.5	0.288	7.320	0.298	7.570	0.309	7.850
⅝	16	0.320	8.130	0.331	8.410	0.344	8.740
¾	19	0.384	9.750	0.398	10.110	0.413	10.490
⅞	22	0.448	11.380	0.464	11.790	0.481	12.220
1	26	0.513	13.030	0.530	13.460	0.550	13.970
1⅛	29	0.577	14.660	0.596	15.140	0.619	15.720
1¼	32	0.641	16.280	0.663	16.840	0.688	17.480
1⅜	35	0.705	17.910	0.729	18.520	0.756	19.200
1½	38	0.769	19.530	0.795	20.190	0.825	20.960
1⅝	42	0.833	21.160	0.861	21.87	0.894	22.710
1¾	45	0.897	22.780	0.928	23.570	0.963	24.460
1⅞	48	0.961	24.410	0.994	25.250	1.031	26.190
2	52	1.025	26.040	1.060	26.920	1.100	27.940
2⅛	54	1.089	27.660	1.126	28.600	1.169	29.690
2¼	58	1.153	29.290	1.193	30.300	1.238	31.450
2⅜	60	1.217	30.910	1.259	31.980	1.306	33.170
2½	64	1.281	32.540	1.325	33.660	1.375	34.930
2⅝	67	1.345	34.160	1.391	35.330	1.444	36.680
2¾	71	1.409	35.790	1.458	37.030	1.513	38.430
2⅞	74	1.473	37.410	1.524	38.710	1.581	40.160
3	77	1.537	39.040	1.590	40.390	1.650	41.910

Table 4-7. Rope Groove Radius (Continued).

Nominal Rope Diameter		Groove Radius					
		Minimum Worn Groove		Recommended Minimum New Groove		Maximum Groove	
inches	mm	inches	mm	inches	mm	inches	mm
3⅛	80	1.602	40.690	1.656	42.060	1.719	43.660
3¼	83	1.666	42.320	1.723	43.760	1.788	45.420
3⅜	86	1.730	43.940	1.789	45.440	1.856	47.140
3½	90	1.794	45.570	1.855	47.120	1.925	48.900
3¾	96	1.922	48.820	1.988	50.500	2.063	52.400
4	103	2.050	52.070	2.120	53.850	2.200	55.880
4¼	109	2.178	55.320	2.253	57.230	2.338	59.390
4½	115	2.306	58.570	2.385	60.580	2.475	62.870
4¾	122	2.434	61.820	2.518	63.960	2.613	66.370
5	128	2.563	65.100	2.650	67.310	2.750	69.850
5¼	135	2.691	68.350	2.783	70.690	2.888	73.360
5½	141	2.819	71.600	2.915	74.040	3.025	76.840
5¾	148	2.947	74.850	3.048	77.420	3.163	80.340
6	154	3.075	78.110	3.180	80.770	3.300	83.820
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(1) Groove Pitch. The pitch of the grooves should take into consideration the maximum rope diameter allowed. For example, the groove pitch for a 1-in. diameter rope should allow for the fact that Federal standards allow 5% oversize resulting in up to a 1.050-in. diameter rope.

c. Fleet Angle. Fleet angle must be within certain limits to ensure smooth winding on drums and to prevent wire rope from crushing and abrading, either on itself or against drum grooves. The limits are ½ degree minimum to 1½ degrees maximum for smooth drums and ½ degree minimum to 2 degrees maximum for grooved drums. The Wire Rope Users Manual (WRTB 2005, Figure 39) shows a detail.

4-10. Sheaves. Sheaves are used to guide a wire rope into a new direction. They can direct a wire rope around obstacles or locate a changing rope angle to a constant position over a gate. Sheaves are also used in block assemblies to create multi part rope systems. Block assemblies can be used to spread a load over multiple rope legs reducing tension in each leg. Figure 4-6 shows an example of a system of sheaves used in a block assembly. This block is being used to create a multi-part rope system to hoist a vertical lift gate.

Figure 4-6. Gate Hoist Sheave Block System.

a. Design considerations. Sheaves should be selected or designed to comply with the surface hardness (Section 4-6) bend radii (Section 4-9), and groove dimensions (Section 4-9) requirements shown above.

b. Design Criteria. Design criteria for sheaves should comply with the requirements specified in EM 1110-2-2610.

c. Bearings. Plain and roller bearings are both commonly used on sheaves. The main advantage of plain bearings is their simplicity and relatively low cost. The disadvantage is their higher coefficient of friction that results in higher dynamic rope tension. Aside from significantly lower coefficients of friction, roller bearings also have the advantage that they can be purchased with a standard seal designs to help exclude moisture and contaminants. In general, roller bearings are more commonly used on systems that have many sheaves and are frequently used.

4-11. Drums. Wire rope drums are used to transmit power from the drive train of a gate operating or hoist system to the wire ropes. There are three common types of drums used for civil works structures: grooved, smooth, and disk-layered. Each are discussed in more detail below. Drums for civil works structures should be selected or designed to comply with the following criteria.

a. Design considerations. Drums should be selected or designed to comply with the surface hardness (Section 4-6), bend radii (Section 4-9), and groove dimensions (Section 4-9) requirements shown above.

b. Design Criteria. Design criteria for wire rope drums should comply with the requirements specified in EM 1110-2-2610.

c. Dead Wraps.

(1) Wire rope drums for civil works structures shall have a minimum of two dead wraps. When possible three dead wraps are recommended. When a rope is under tension, the dead wraps are pulled against the drum and provide friction that helps to resist the rope slipping on the drum. Many grooved and plain drums use clips or other terminations that do not provide 100% termination efficiency. For these styles of drums, the dead wraps are critical to ensure that the drum termination develops 100% efficiency and that it can support the full rope tension without rope slippage. The resistance to rope slippage provided by the dead wraps can approximated by the following equations.

(2) The normal force of the rope pressure applied to the drum can be found with the following equation:

$$N = P(L_{dead}) \qquad \text{Eq 4-8}$$

(3) In this equation P is the pressure exerted on the drum expressed as force per length. This can be found with the following equation where T is the applied rope tension and r is the radius of the dead wraps:

$$P = \frac{T}{r} \qquad \text{Eq 4-9}$$

(4) L_{dead} is the length of dead wraps, which is expressed in terms of the number of dead wraps (W_{dead}) in the following equation. The number of dead wraps is required to be a minimum of two:

$$L_{dead} = 2\pi r(W_{dead}) \qquad \text{Eq 4-10}$$

(5) The friction force of the dead wraps provides resistance to slippage and should be equal to or greater than the rope tension. This can be represented as:

$$T \leq \mu(N) \qquad \text{Eq 4-11}$$

(6) Where μ is the coefficient of friction of the wire rope on the drum. For example, a grease lubricated steel on steel coefficient of friction (COF) of 0.16 will be used. By combining these equations and simplifying, it is possible to obtain an expression to determine if the dead wrap friction will be greater than the applied rope tension.

$$1 \leq 2\pi(\mu)W_{dead} \qquad \text{Eq 4-12}$$

(7) If the right hand side of this equation is larger than 1, the dead wrap friction will be greater than the applied tension.

d. Drum Rope Terminations. Grooved and plain drums typically use a rope clip that secures the end of the rope from unraveling from the drum. Figure 4-7 shows some common configurations. Disk layered drums typically use a speltered rope socket that is designed to be secured into the drum.

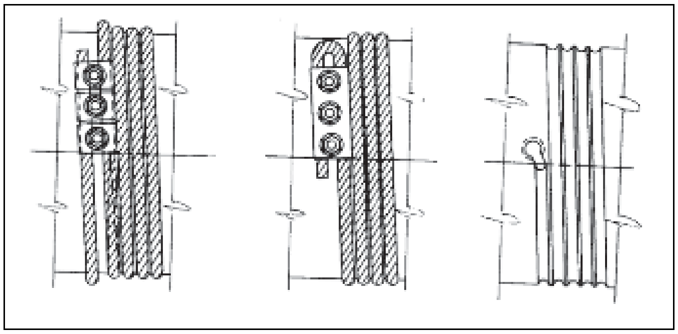

Figure 4-7. Drum Rope Clips.

e. Grooved Drums. Grooved drums are fabricated from a large cylindrical casting or weldment. Rope grooves are machined into the cylinder to support the rope and provide a guide for proper spooling of the rope onto the drum. Figure 4-8 shows a grooved drum.

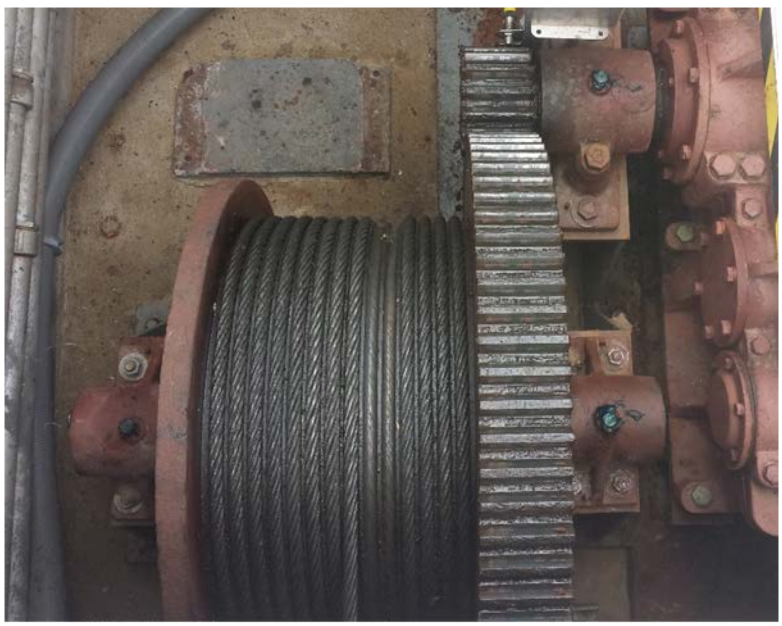

Figure 4-8. Grooved Drum.

(1) Advantages. Grooved drums provide the most favorable conditions for the rope since the grooves provide support for the rope and prevents the rope from rubbing against itself. For good service life, the pitch and diameter of the grooves, the fleet angle, the anchoring system, and the nominal diameter of the drum must all be correct for the size and type of rope.

(2) Disadvantages. The axial length of grooved drums can become long compared to other drum types. This is to allow the rope grooves to accommodate the full length of rope. Some grooved drums are designed for multiple layers, which can minimize the axial length. However, the second rope layer has a higher potential for crushing and wear. In general, grooved drums with multiple layers should not be used for high capacity hoists due to the higher potential for crushing and wear. The movement of the rope along the axial length of these drums often requires a combination of

sheave blocks or idler sheaves, and a lifting beam to connect to the gate. This larger size and complexity of these drums means they have a higher cost.

(3) Typical Applications. Grooved drums are commonly used for bridge and gantry crane hoists and for high capacity gate hoists.

f. Plain Drums. Plain drums are similar to grooved drums but without the rope grooves. Figure 4-9 shows a plain drum for a tow haulage unit.

Figure 4-9. Plain Drum.

(1) Advantages. Plain drums can be more compact than grooved drums as the rope is stacked in layers. They can have a higher rope length capacity and lower fabrication cost than grooved drums.

(2) Disadvantages. Plain drums require the rope to wind tightly against the preceding wrap causing the rope to abrade against itself.

(3) Typical Applications. Plain drums are commonly used on low capacity hoists, mobile or compact cranes, and winches. They are not generally a good choice for high load hoists.

g. Disk Layered Drums. The disk-layered type drums requires the rope to be wrapped over itself in multiple layers. They are typically fabricated in a stacked plate design as shown in Figure 4-10.

(1) Advantages. The advantage of a disk layered drum is that the position where the rope exits off the drum does not move axially along the length of the drum as it does with grooved and plain drums. This can simplify the connection of the ropes to the gate and eliminate the need for a lifting

beam. In addition disk layered drums use multiple ropes, which can reduce rope size. They also have a compact design and are generally less expensive than grooved drums.

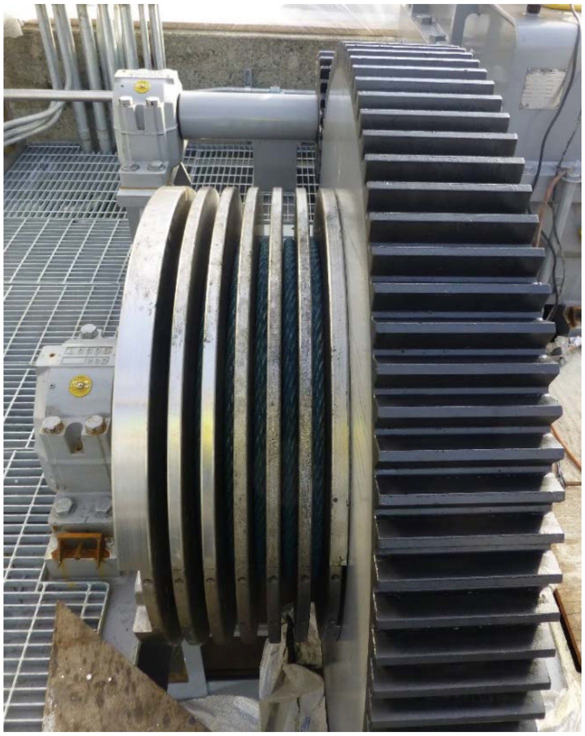

Figure 4-10. Disk Layered Drum.

(2) Disadvantages. Disk layered drums are exposed to a higher level of crushing and abrasion verses a grooved drum. They also have a more limited capacity than do other drum types, and they do not accommodate a fleet angle. Side loading of the drum plates also must be considered in the design. Each layer of rope contacts the previous wrap and the side/separator plate. This causes a load on the side/separator plates in the axial direction that must be supported in the drum design. In addition, the tensioning requirements for multi rope systems, such as those used with disk layered drums, are more complex.

(3) Typical Applications. Disk layered drums are commonly used on gate hoists with relatively small vertical lifts and high loads such as large spillway Tainter gates.

4-12. Tensioning Devices. If multiple ropes share a common load, a method to ensure equal load sharing between each rope in the system must be incorporated. When selecting a tensioning device, the constructional stretch, elastic stretch, and other potential for slack in the system should be considered. This is most often accomplished with an adjustable threaded device such as a turnbuckle or U-bolt. Refer to Chapter 7 of this manual for additional discussion of wire rope tensioning devices.

a. Turnbuckles. Turnbuckles are one of the simplest tensioning devices that can be incorporated into a rope system (Figure 4-11). They can often be procured as a standard manufactured or off-the-shelf component with load ratings that exceed the rope breaking strength. They are also easily incorporated into rope system with standard swage or speltered rope sockets. Turnbuckles must be used in a span of rope that does not pass over a sheave or onto a drum. If turnbuckles are used, it is recommended that a line be painted on the wire rope before installation. This allows tensioning to be performed without twisting the ropes.

b. U-Bolts. U-bolts are commonly used as a rope tensioning device on spillway Tainter gates (Figures 4-12 and 4-13). The primary advantage of U-bolts over other tensioning devices is that they can accommodate a changing rope angle as a gate is lifted.

Figure 4-11. Turnbuckle Rope Tensioning System.

Figure 4-12. U-Bolt Rope Tensioning System on a Spillway Tainter Gate.

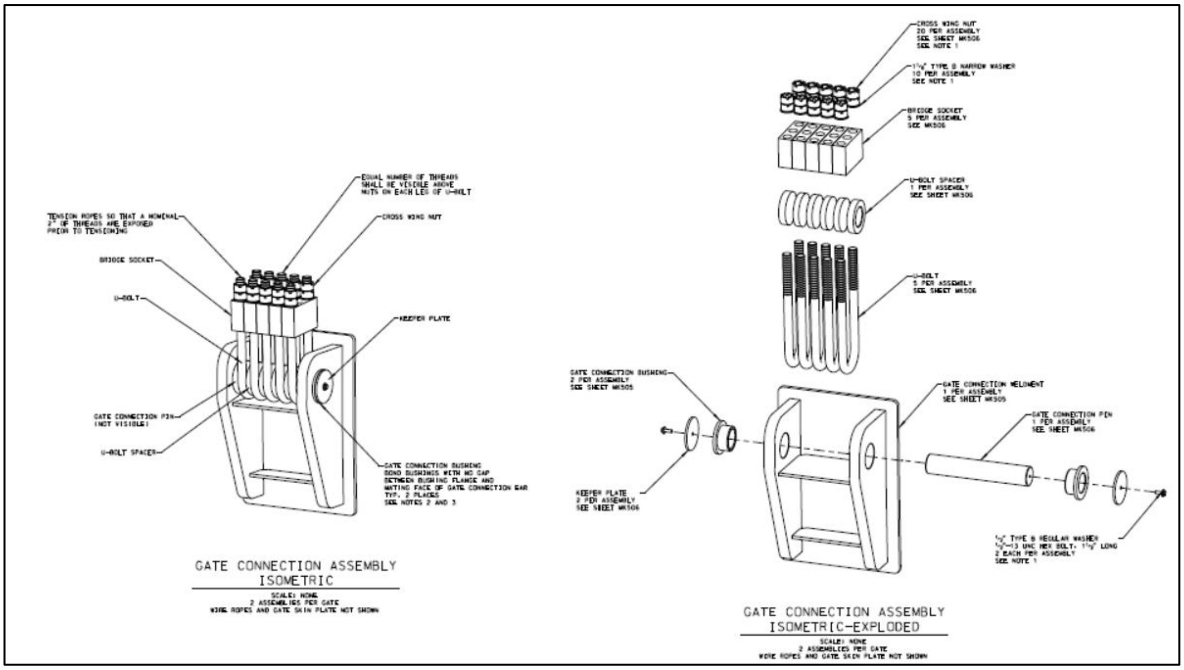

Figure 4-13. U-Bolt Rope Tensioning System on a Spillway Tainter Gate.

4-13. Tension Balance. Unbalanced rope tensions can cause gate misalignment, overload of individual ropes, or other problems such as fouling (binding) of rope through a sheave system. For civil works structures, a rope tension balance for multi-rope system must be determined after considering the following factors.

a. Individual Rope Tension Limits. It is typically reasonable to keep rope tensions within 5% (±2.5%) of the average of tensions within a group. Tension limits of individual ropes should be considered, but are typically not the limiting factor for determining proper tension balance. Allowable rope tension is limited to 70% of the rope breaking strength.

b. Gate Skew Considerations. The balance of rope tension between sides of a gate can cause gate skew, gate deformations, or other gate misalignment. Designers of the rope system should work in coordination with the gate structural engineer to determine the proper rope tension between the sides of the gate that the gate can operate under to prevent any binding against the gate piers.

c. Tainter Gate Recommended Tension Values. As noted, tainter gates are susceptible to skew caused by imbalanced rope tensions between sides of a gate. In many cases, this has resulted in gates contacting the gate piers resulting in binding. The following tension balance requirements are a consideration that has been acceptable for many tainter gate systems.

(1) Individual Ropes. Individual rope tensions should be maintained in a range within 5% (±2.5%) of the average of the rope tensions.

(2) The sum of rope tensions on each side of the gate should be maintained within 0.5% of the average of the sum of rope tension on each side of the gate.

4-14. Wear Plates. Wear plates (Figure 4-14) are recommended where wire ropes come into contact with a surface of the gate. The main reason to install wear plates is to provide a sacrificial surface to prevent the ropes from imprinting on or causing galvanic corrosion on the gate. Steel wear plates have been used successfully, but have the disadvantage that they must be replaced when corrosion becomes severe. More recent wear plate installations have successfully taken advantage of Ultra High Molecular Weight (UHMW) polyethylene (PE) to help isolate dissimilar metals. UHMW polyethylene wear plates are softer and have a large coefficient of thermal expansion relative to steel, which must be accounted for in the design of the wear plate mounting system.

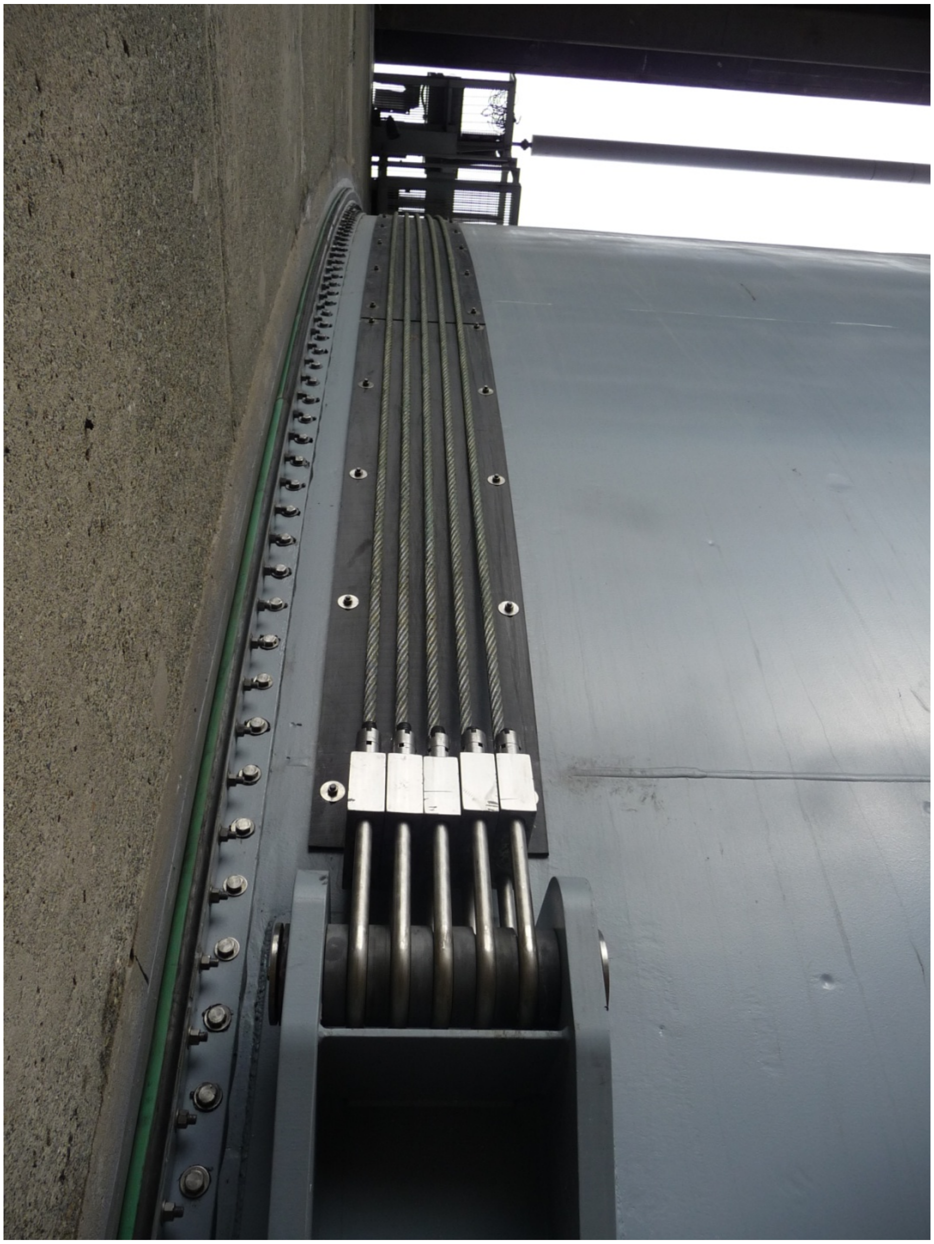

Figure 4-14. UHMW-PE Wire Rope Wear Plates.

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CHAPTER 5

Sockets and End Terminations

5-1. General. Sockets and end terminations are of great importance in regards to efficiently transferring force from the drum, through the wire rope, and to the gate. There are many types of sockets and end terminations with different characteristics, and they should be selected and applied correctly for each installation to maximize rope assembly service life. Since their strength varies, not all will develop the full strength of the rope (see Section 4-2, “Factors of Safety”). This chapter presents various sockets, drum terminations, and miscellaneous terminations for gate hoisting applications along with information on cutting and splicing wire rope. Figure 5-1 shows some of the more common end terminations. This chapter also presents information on the option of using two-piece ropes. The sockets and end terminations shown in Figure 5-1 along with efficiencies listed in Table 5-1 are given for information only. Terminations with less than 100% efficiency shall not be used for gate hoisting applications.

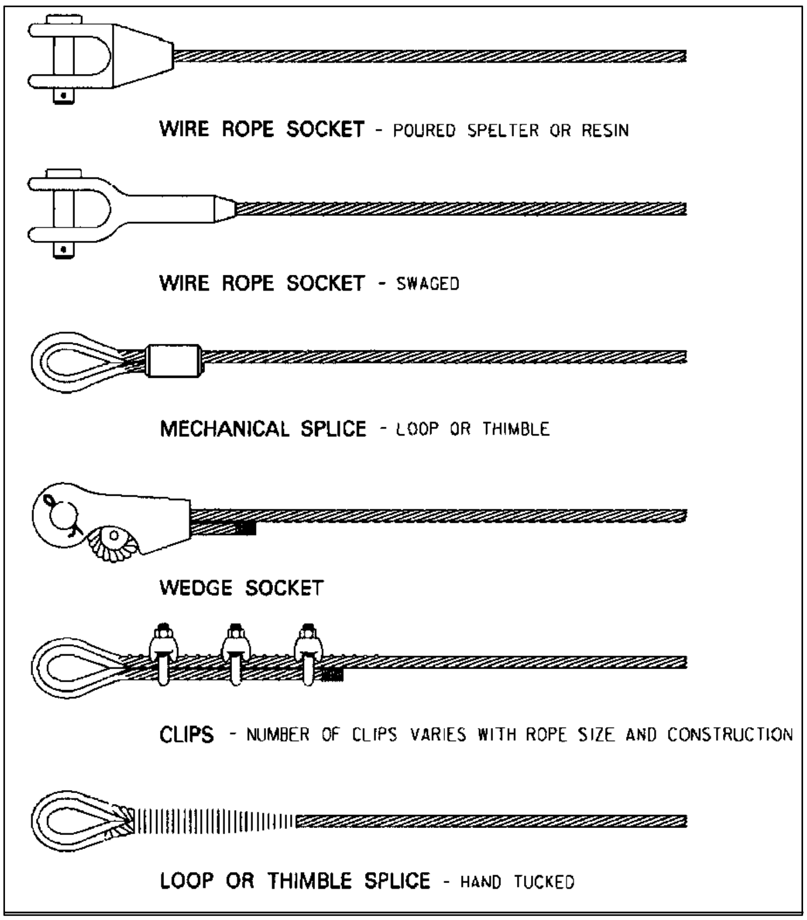

Figure 5-1. Frequently Used Terminations.

Table 5-1. Approximate Efficiencies for Terminations of Wire Rope.

Type of Termination	Efficiency	
	Rope with IWRC	Rope with FC
Wire Rope Socket (Spelter or Resin)	100%	100%
Swaged Socket (Regular Lay Ropes Only)	100%	(Not Recommended)
Mechanical Spliced Sleeve (Flemish Eye)		
1-in. dia. and smaller	95%	92 ½%
Greater than 1-in. dia. through 2-in.	92 ½%	90%
Greater than 2-in. dia. through 3½-in.	90%	(Not established)
Loop or Thimble Splice-Hand Spliced (Tucked) (Carbon Steel Rope)		
½-in.	86%	86%
⅝-in.	84%	84%
¾-in.	82%	82%
⅞- thru 2½-in.	80%	80%
Loop or Thimble Splice-Hand Spliced (Tucked) (Carbon Steel Rope)		
½-in.	76%	
⅝-in.	74%	
¾-in.	72%	
⅞-in.	70%	
Wedge Sockets*	75% to 80%	75% to 80%
Clips**	80%	80%

* These values apply for properly installed wedge sockets. Refer to the Wire Rope User's Manual (WRTB 2005) for Installation.

** These values apply for properly installed clips. Refer to the Wire Rope User's Manual (WRTB 2005) for installation.

a. Industry and Government Standards. The following are some of the relevant industry standards:

- Fed Spec RR-S-550: Sockets, Wire Rope.
- Fed Spec FF-C-450: Clamps, Wire Rope.
- American Society of Mechanical Engineers (ASME) B30.26: Rigging Hardware.
- Mil Std MS51844: Sleeve, Swaging-Wire Rope.
- EN 13411-6: Terminations for Steel Wire Ropes. Safety. Asymmetric Wedge Socket.

- API RP-9B: Application, Care, and Use of Wire Rope for Oil Field Service.
- International Standards Organization (ISO) 17558: Steel Wire Ropes – Socketing Procedures – Molten Metal and Resin Socketing.

b. Manufacturer's Instructions. In addition to industry and government standards, manufacturer's recommendations and instructions for installation and use of end terminations should be followed. Manufacturer's literature for sockets and end fittings and wire rope in general are widely available online. All wire rope users and design and specification engineers should become familiar with the available online literature, terminology, and jargon before attempting to specify their use.

5-2. Sockets.

a. General. Sockets are normally used at the gate end of a wire rope, and they must develop 100% of the strength of the rope. It should be noted that sockets are not normally reused and that new sockets should be provided when replacing rope. It is recommended that swaged and speltered sockets be attached at the rope manufacturer's facilities. For various reasons, this is not always possible, and in those cases, on-site spelter socketing of large diameter ropes can be accomplished without the large presses required for swaged sockets. Swaged sockets are frequently installed by the rope manufacturer as qualified personnel, proper dies, and heavy hydraulic presses are required. A great deal of expertise is needed for attaching both swaged sockets and speltered sockets. The rope must be well aligned with the socket and the rope strands must have uniform tension. A line drawn on the rope before pre-stretching is often used to ensure that any post-stretching twist is accommodated. For longer lengths of wire ropes where the relationship of sockets on opposite ends of the ropes is important, it is recommended to pre-stretch first to ensure that any rotational set is taken out of the rope before socketing. Also, the proof loading with sockets in place before use is more readily accomplished at a rope manufacturer's facilities. Although socketing is best left to experts, note that socketing information is provided in ISO 17558 and API RP-9B. Also, note that some sockets for gate-lifting devices are a custom design.

b. Swaged Sockets. Swaged sockets are mechanically pressed onto wire rope (Figure 5-2). Figure 5-3 shows some of the equipment used for swaging, which range from hand tools for smaller diameter wire rope to large presses for large diameter wire rope.

c. Swaged sockets are used less often for gate-operating devices than are speltered sockets. If properly designed and attached, they can develop 100% of the strength of the rope. Note that swaged sockets are not suitable for lang lay rope, nor are they suitable for ropes with a fiber core. One advantage of swaged sockets is that simple no-go gauges can be used to verify proper installation. There are many types of Military Specification swage fittings, but most are available for only smaller diameter wire ropes with diameters up to ⅝-in.

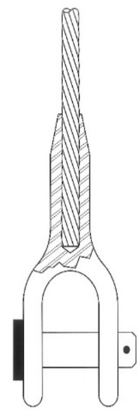

Figure 5-2. Swaged Socket Cross Section.

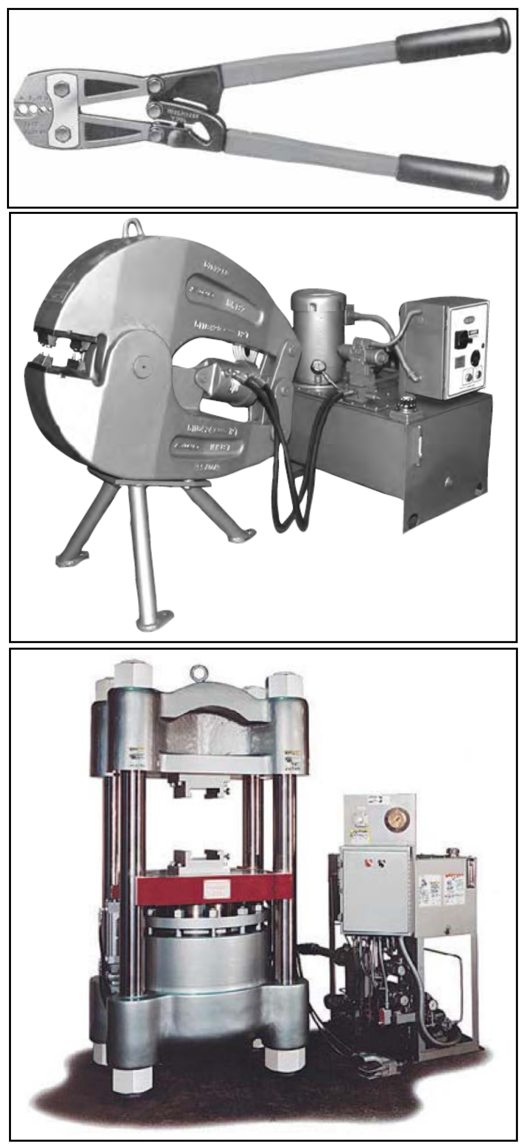

Figure 5-3. Wire Rope Swaging Tools.

d. Speltered Sockets. Speltered (or poured) sockets are attached to wire rope with zinc or resin (Figures 5-4 and 5-5). They are normally specified for the gate end of a rope, but can also be used for the drum socket or anchor. They are best where the rope is in straight tension, that is, where the load does not touch the rope (Figure 5-6). The Wire Rope User's Manual (WRTB 2005) references API RP-9B and ISO standards for socketing procedures. Both zinc-filled and resin-filled sockets develop 100% of the strength of the rope if attached correctly. In fact, speltered sockets are normally used for wire rope strength testing. Zinc fill has a longer history, but resin fill has become common due to the advantages described below. It is recommended that speltered sockets be proof loaded before use. Socketing procedures as detailed in ISO 17558 are divided between preparation for socketing and the actual socketing itself. Steps for preparation are the same for both resin and zinc spelter socketing and are critical to the success of the procedure. They include: serving or seizing; cutting of the rope; preparation of the socket; inserting the rope into the socket; preparation of the brush; cleaning and degreasing the brush; hooking, positioning, and alignment; and sealing. Serving, also commonly referred to as seizing, is either temporary or permanent. Temporary serving is used to hold the strands and wires in position during the cutting operation and is removed before preparation of the brush. Permanent serving is used to hold the strands and wires in place during the socketing operation and usually consists of wire applied to the part of the rope that is immediately adjacent to the base of the socket. It should be removed after socketing is complete.

Figure 5-4. Typical Open Spelter Socket.

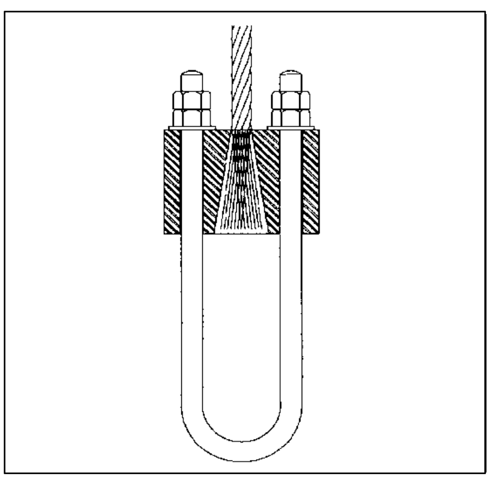

Figure 5-5. Spelter Socket Cross Section.

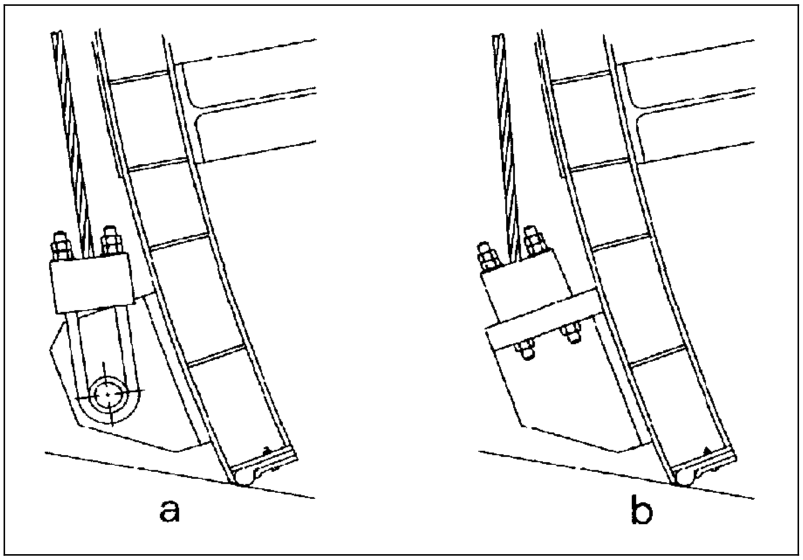

Figure 5-6. Proper Socket Mounting, (a) correct – socket can rotate, and (b) incorrect – rope bends at socket interface because socket does not rotate

(1) Tainter Gate Wire Rope Connections. The spelter type end termination and the gate connection shown in Figure 5-6a are considered good practice for connection to Tainter gates. This ensures that the rope and termination are always loaded only in tension, thus avoiding sharp bending of wires and minimizing fatigue breakage at or near the socket. The success of these type gate connections depend on their continued ability over time to rotate with the gate. Corrosion of the U-bolts, blocks, pins, or gate brackets can inhibit the ability to rotate. Corrosion of the bolts or U-bolts can also hinder the ability to adjust the tension in the individual ropes. Figure 5-7 shows a gate connection assembly where corrosion of the gate wire rope connection bracket prevented the rotation of the wire rope adjusting block, resulting in breakage of one bolt and bending of the other. Regular inspection of these assemblies is important to verify their continued proper function.

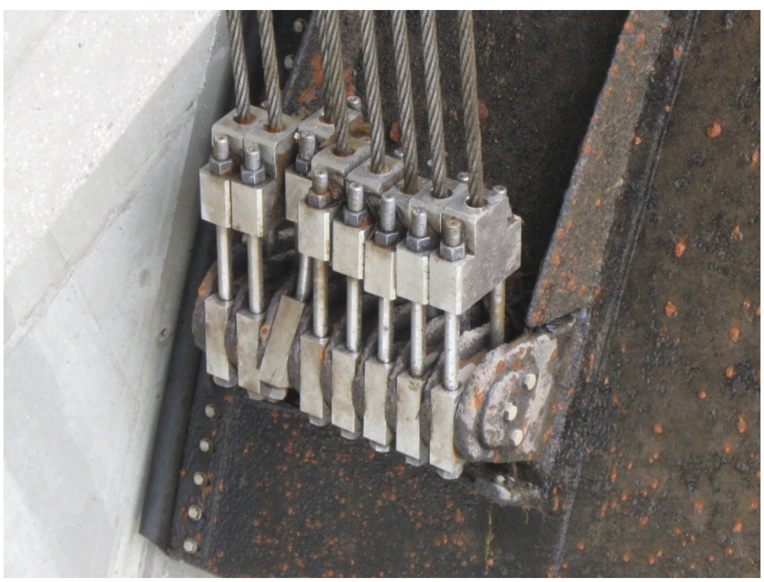

Figure 5-7. Tainter Gate Wire Rope Connection with a Broken Bolt on One Block

(2) Zinc Speltering. To develop 100% of rope strength, it is important to follow all steps of the prescribed socketing procedure and that to ensure that the procedure be performed by qualified personnel. Those steps are described in ISO 17558 and include preheating the socket, melting the metal, pouring, and cooling. Figure 5-8 shows some of these steps. The standard requires that the preheat temperature be at least 50% of the melting temperature of the socketing medium (zinc). Socket manufacturers often limit the preheat temperature to 797-842 °F (425-450 °C). The use of zinc spelter stainless steel sockets on stainless wire rope is not recommended. However, if the use of these sockets is found necessary, care must be taken to follow the proper procedure. Through testing, the following steps for zinc spelter socketing of stainless steel sockets on stainless steel wire rope have been found to be a required addition to the ISO 17558 procedure. Without these additional steps, it has been found that the zinc can solidify prematurely, the result of which are voids and incomplete zinc-to-wire contact, i.e., a socket that may have less than 100% efficiency. This issue is further discussed in the Pellow Report from Marmet Lock provided in Appendix B to this manual.

(a) After brooming (splaying of the wires as in Figure 5-5), immerse the broomed section of the wire rope into a solution of hot water (approximately (203 °F [95 °C]) and a zinc ammonium chloride galvanizing flux.

(b) Heat the molten zinc (Figure 5-9) to approximately 851-977 °F (455-525 °C). Not to exceed 1,000 °F (538 °C).

(c) Evenly heat the outside of the socket to 450 °F (232 °C).

(d) Add 1.2 cc of a tinning powder such as VersaTin Powder 20-70 into the socket basket. This powder will react with the hot, molten zinc to assist in removing impurities and air from the zinc as it is being poured into the socket basket.

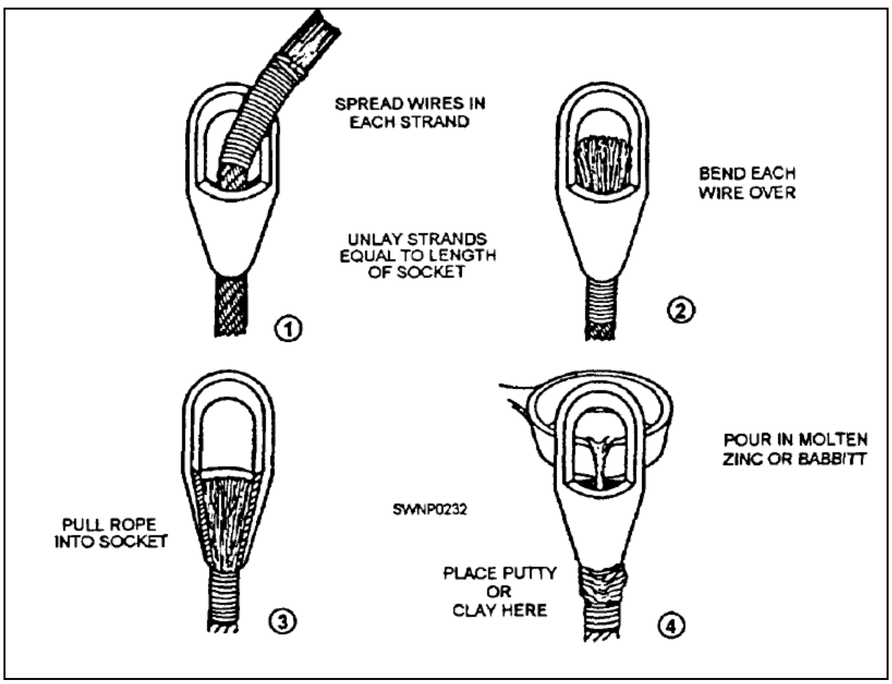

Figure 5-8. Spelter Socket Installation.

Figure 5-9. Zinc Melting Operation.

(3) Resin Speltering. Resin speltering offers several advantages over zinc speltering. One advantage is the process does not use molten metal, so no heating equipment is required. The process is therefore safer and requires less personal protective equipment (see Figure 5-9). Also, the process is not sensitive to socket preheating temperatures or the socketing medium temperature. For these reasons, resin speltering is more easily performed on site. Manufacturer’s instructions should be carefully followed. This is especially true when using epoxy in a saltwater environment with stainless steel wire rope. Crevice corrosion of stainless ropes has been found to accelerate when using epoxy speltered sockets in a saltwater environment. Crevice corrosion is the localized attack of a metal surface at or adjacent to adjoining surfaces. Stainless steel is susceptible to crevice corrosion in saltwater. Sockets are often supplied with circumferential groove(s) in their baskets as required by Fed Spec RR-S-550. Resin spelter manufacturer’s often recommend that these grooves be filled with putty or other method to ensure proper seating of the cone under load.

5-3. Materials/Coatings. If swaged or speltered sockets and their ropes are of dissimilar materials and are located under water or in wet environments, they will likely fail from galvanic corrosion. The designer/specifier must consider materials and coatings when selecting sockets for wire rope. It is important that the socket and spelter material are electro-chemically similar to the rope. That is, they all need to have approximately the same galvanic potential to minimize galvanic corrosion. A stainless steel rope attached to an epoxy-filled speltered socket of a compatible stainless steel would be ideal, as would a galvanized rope attached to a galvanized steel speltered socket. Coatings can be used to protect the more reactive element of the rope/socket combination, but are not recommended. Sockets can be coated with insulating materials, either on the inside for galvanic isolation from the rope or on the outside for protection from the environment. However, coatings are susceptible to problems from poor installation and damage from nicks, cuts, and wear. Additionally the designer and specification engineer should consider the materials for sheaves or gate areas in contact with the rope. A submerged carbon steel pulley in contact with a stainless steel rope will probably pit, and may cause significant abrasive wear to occur on the rope.

5-4. Drum and Miscellaneous Terminations.

a. Drum Anchorages. Drum anchorages for gate-operating devices can be bolt-on-clamps, wedge-type sockets, swaged sockets (Figure 5-10), or spelter sockets (Figure 5-11). They are often designed by the drum/equipment manufacturer. Alone, their efficiency may not be as high as required. To achieve 100% of the strength of the rope, the design should be developed using two, preferably three, dead wraps in combination with the anchorage termination efficiencies (Figure 5-10). This is true for grooved, plain, and multiple layered drums. See Chapter 4 for drum design considerations.

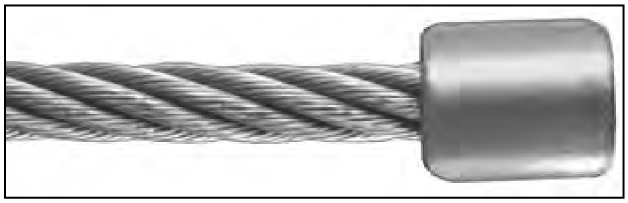

Figure 5-10. Typical Swaged Fitting Suitable for Drum End of Rope.

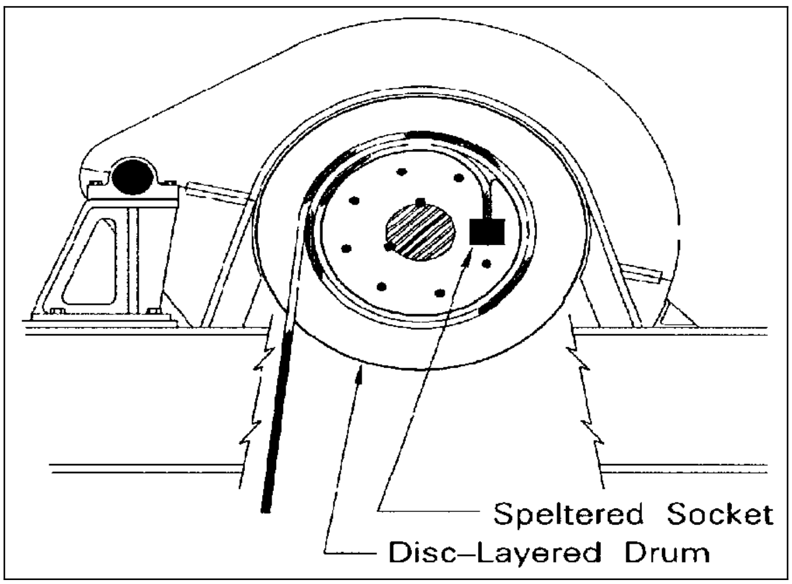

Figure 5-11. Typical Drum Anchorage Method.

b. Miscellaneous Terminations. There are a number of end terminations that are less efficient than swaged sockets, speltered sockets, and drum anchorages. They include clamps, clips, wedge sockets, etc. Figure 5-12 shows a clamped termination. Their use on gate-operating devices is not recommended because of their lower efficiencies, which generally range between 70 and 80% (Table 5-1 and Section 4-2, “Factors of Safety”). The orientation of the U-bolt clips shown in Figure 5-12 is correct, with the U-bolt over the dead end of the wire rope and the live end resting in the saddle. See the Wire Rope User’s Manual (WRTB 2005) for detailed instructions on the application of wire rope clips. Also, note that most of these type fittings should not be reused as a rope’s wires will swage into their metal mating surfaces. They only provide the proper grip during the first use.

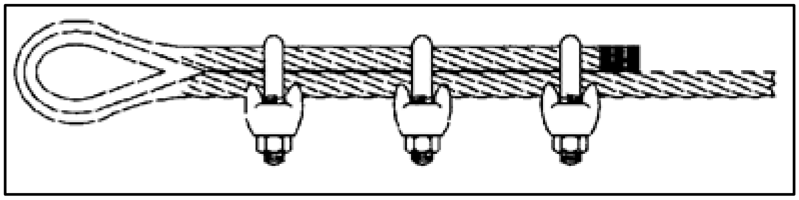

Figure 5-12. A Clamped Termination.

5-5. Seizing/Cutting/Splicing. Seizing, cutting, and splicing wire rope, except at the rope manufacturer's facilities is discouraged. This is especially true for splicing. However, there may be times when these procedures must be performed in the field.

a. Seizing. Proper seizing is required before cutting wire rope. The seizing must be placed on each side of the cut. Failure to adequately seize a rope will result in problems such as loosened strands, distorted and flattened ends, and eventual uneven load distribution. Seizing refers to a length of soft wire wrapped tightly and multiple times around the rope circumference adjacent to the cut. Seizing is designed to girdle the rope end and prevent unraveling, both during and after the act of cutting. Seizing prevents unraveling and misalignment of the individual wire rope strands or wires during or after the rope is cut. There are conventions for seizing placement, number of wraps, seizing wire size and type, but as with all wire rope operations, seizing quality depends on workmanship. Information on methods of seizing is given in the Wire Rope User's Manual (WRTB 2005).

b. Cutting. Cutting is reasonably simple if the proper tools are used. Several commercially available types of cutters and shears are specifically designed to cut wire rope. Although it is a common practice, wire rope should not be cut with a torch.

c. Splicing. Splicing is not a recommended practice for gate-operating devices. The efficiency of a spliced rope is likely to be very low. Information on splicing is given in the Wire Rope User's Manual (WRTB 2005).

5-6. Two-Piece Ropes. There are potential benefits for using two-piece ropes for some applications. For example, an existing carbon steel wire rope on a gate-lifting device may occasionally or usually be submerged at its gate end. The gate end will normally corrode severely, but the rest of the rope will not. The existing one-piece rope could be replaced with a two-piece rope. The longer upper section would be attached to the drum. It would always be above the water line, and would provide a long service life even if made of carbon steel. A shorter section would be used for the gate end. If the shorter section could be made of carbon steel, it would be replaced often, but at a much lower cost than replacing the previous one-piece rope. Another option would be to make the short piece of stainless steel. This would provide a longer service life at a lower overall cost than a one-piece stainless steel wire rope. It is recommended the connection between the two ropes be designed for replacement without having to re-socket the rope attached to the drum. It is also recommended the upper rope section be long enough so the connection does not contact the drum or sheaves when the gate is in the fully open position. The major disadvantage to the two-piece rope concept would be the cost for extra sockets and socketing.

CHAPTER 6

Specifying Wire Rope

6-1. General. This chapter presents information for ordering wire rope and information on requirements necessary to specify wire rope for Corps of Engineers civil works gate operating applications. It also presents information on availability and cost. Wire rope for civil works structures is specified using Unified Facilities Guide Specification (UFGS) 35 01 70.13, Wire Rope for Gate Operating Devices. The guide specification covers the requirements for supplying and installing new or replacement wire rope. Wire rope specified must comply with Federal Specification RR-W-410, Wire Rope and Strand. This Federal Specification is the benchmark standard for construction, material, workmanship, and testing and should be used and referenced for any wire rope procurement. ASTM A1023, Standard Specification for Stranded Carbon Steel Wire Ropes for General Purposes, is another common standard for wire rope that can be used for a number of applications.

6-2. Standard Nomenclature. Standard wire rope specification nomenclature gives the following rope requirements: length, direction and type of lay, diameter, finish, classification, material, preformed or non-preformed, and core type. For example, a rope manufacturer would consider the following description of a wire rope to be complete:

a. Metric or English units.

b. Steel or Stainless Steel Construction.

c. Diameter.

d. Construction (number of strands, wires e composition: Seale, Filler or other).

e. Core type (fiber or steel).

f. Lay (regular or Lang / right or left).

g. Preforming (preformed, non-preformed or semi preformed).

h. Lubrication (with or without lubrication).

i. Category of wire rope or resistance to traction of wires (PS, IPS, EIPS, EEIPS).

j. Minimum Breaking Force or Working Load.

k. Finishing (bright or galvanized).

l. Application.

m. Environment.

n. Length.

6-3. Additional Requirements. Additional requirements for wire rope that should be considered for inclusion in the specifications are:

a. Wire Strength and Ductility. Manufacturers occasionally blend stronger and weaker wires in one rope, which can have detrimental effects on its fatigue resistance (see Section 2-9 “Manufacturing”). Test procedures for strength and torsion ensure that fatigue resistance will not suffer because of this practice. Torsion test procedures are contained in ASTM A1007.

b. Rope tension test. New wire rope should meet the manufacturer’s published nominal strengths. It is standard practice to require a rope tension test, to failure, for verification that the expected performance level has been met. The procedure is as follows. The sample length is cut to not less than 0.91 m (3 ft) for rope diameters between 3.2 mm (⅛ in.) and 77 mm (3 in.). The test is only considered valid if failure occurs at least 51 mm (2 in.) from either the socket or holding mechanism. The relative speed between the testing machine heads (while tensioning) is not allowed to exceed 25 mm (1 in.) per minute.

c. Preforming. Preforming should be specified for any steel wire rope for any gate operating device. The standard test to verify performing is described in Federal Specification RR-W-410.

d. Stress relief. The standard wrapping test described in Federal Specification RR-W-410 verifies that stress relief has been accomplished. It applies to rope with either bare steel or galvanized steel wires. The procedure is as follows. Rope wires are wrapped in a helix about a mandrel for six complete turns, followed by unwrapping. No wires may break or fracture. The mandrel for bare and galvanized steel is no greater than two times the diameter of the wire.

e. Weld distribution. Welded (or brazed) wire joints should not be any closer than 45.7 cm (18 in.) in any strand.

f. Zinc coat test. Federal Specification RR-W-410 and ASTM A90 contain information for applying and testing the weight of the zinc coating.

g. Pre-stretching. As explained in Section 2-9, “Manufacturing,” this procedure is recommended for installations with multi-rope drums or any gate operating device. The standard procedure and a new dynamic procedure is discussed in that paragraph and in ASTM A1023. To account for twist introduced by pre-stretching, it is recommended to pre-stretch the wire rope before socketing. To assist with socket installation and rope installation, it is also required to draw a line on the wire rope under full load. See Paragraph (j) below and Chapter 5 of this manual for further information.

h. Lubrication. All wire rope should be lubricated and it is recommended wire rope be lubricated as shipped from the supplier. The designer should work with the supplier in determining the type of lubricant needed. The manufacturer will generally have equipment that can force the lubricant into the core area of a rope. The designer should reference EM 1110-2-1424 and also review Chapter 8 of this manual. EM 1110-2-1424 provides significant detail and guidance on wire rope lubrication.

i. Pitch length. A strand pitch of not less than 4½ times the nominal rope diameter is normally required for the ropes used in gate-operating devices.

j. Attaching and proof-loading terminations. As discussed in Section 5-2, “Sockets,” it is recommended that swaged and speltered sockets be attached at the rope manufacturer’s facilities and also be proof loaded before use. Proof loading is normally at 200% of the expected load (operating gate) or 40% of the nominal strength of the rope. It is practical to perform the proof testing as a part of a pre-stretching operation. As noted above, it is recommended that pre-stretching be done before socketing.

k. Core wires (IWRC). The number of wires in the core strand should be equal to or greater than the number of wires in the other strands. The wires should be of the same material as the wire in the other stands or of a material with a lower tensile strength.

l. Field acceptance. The designer and specification engineer should add several requirements as discussed in Section 7-1, “Field Acceptance,” to be certain that the rope purchased will be delivered and installed in good condition.

m. Shipping, Handling, and Storage. For requirements on shipping, handling, and storage refer to Section 7-2 and the Wire Rope User’s Manual (WRTB 2005). Wire ropes must be treated with a lot of attention during their storage and installation. In many cases, if any part of the surface of the wire rope is damaged, it may not be discovered until much later and that will affect its working life. Steel wire ropes should be stored in a clean, cool, dry place indoors. They must not be allowed to rest on the floor or ground and should be placed on pallets. Wire rope is typically shipped in cut lengths, either in coils or on reels. Great care should be taken when the rope is removed from the shipping package since it can be permanently damaged by improper unreeling or uncoiling.

6-4. Availability/Cost. The cost and availability of the options must be considered in the selection process. For example, sizes larger than 38 mm (1½ in.), some constructions, and most stainless steel rope are not readily available off the shelf. Extra delivery time will likely be required for any special order rope. Availability must be discussed with manufacturers early in the selection process. Also, quantities of 3,000 m (10,000 ft) and more are generally required for a standard production run. Runs for smaller quantities will have higher prices per unit length. There is a fixed amount of waste for any run due to normal production methods. Flat and other special shaped rope may not be available at any cost. Tables 6-1 through 6-3 present relative cost data for rope of various materials, types of construction, and sizes.

Table 6-1. Relative Cost Data (per Unit Length) for Wire Rope of Various Materials.

Wire Rope Material	Relative Cost
Iron or Extra Strength Traction Steel	0.4 to 0.5
Improved Plow Steel	0.96 to 0.98
Extra Improved Plow Steel	1.00
Galvanized Improved Plow Steel	1.25 to 1.35
Stainless Steel	2.5 to 3.1

Table 6-2. Relative Cost Data (per Unit Length) for Wire Rope of Various Constructions.

Rope Construction	Relative Cost
6 x 19 Class FC 6 x 19 FC 6 x 21 FC 6 x 25 FC 6 x 26 FC	0.93
6 x 19 Class IWRC 6 x 19 6 x 21 6 x 25 6 x 26	1.00
6 x 37 Class FC 6 x 31 FC 6 x 36 FC 6 x 41 FC 6 x 49 FC	1.08
6 x 37 Class IWRC 6 x 31 IWRC 6 x 36 IWRC 6 x 37 IWRC 6 x 41 IWRC	1.15
Flattened Strand FC or IWRC 6 x 25 Type B 6 x 30 Type G	1.65

Table 6-3. Relative Cost Data (per Unit Length) for Wire Rope of Various Sizes.

Nominal Rope Size (inches)	Nominal Rope Size (mm)	Relative Cost
½	13	0.38
⅝	16	0.47
¾	19	0.64
⅞	22	0.82
1	26	1.00
1⅛	29	1.20
1¼	32	1.43
1⅜	35	1.72
1½	38	2.06
1⅝	42	2.47
1¾	45	2.92

Table 6-3. Relative Cost Data (per Unit Length) for Wire Rope of Various Sizes (Continued).

Nominal Rope Size (inches)	Nominal Rope Size (mm)	Relative Cost
1⅞	48	3.33
2	51	3.78
2⅛	54	4.34
2¼	57	4.97
2⅜	60	5.43
2½	64	5.88

6-5. Buy American Act and Other Standards. The best wire rope has traditionally been (and still is) manufactured in the United States. It is highly recommended that wire rope for Corps gate-operating devices comply with the requirement to be manufactured in the United States, i.e., comply with the Buy American Act. The contract specifications for wire rope should conform to the Buy American Act requirements of Part 25 of the Federal Acquisition Regulations. Note that all domestically made rope is color coded within the strands with the specific manufacturer's colors for easy identification. The number of major U.S. wire rope manufacturers has decreased in recent years and a high percentage of the wire rope of foreign manufacture has given unsatisfactory service. Although some of the western European countries (France, Germany, United Kingdom, Netherlands for example) have manufacturers that produce high quality wire rope, buying foreign made wire rope from other countries can be problematic. Western European countries will generally use ISO (International Organization for Standardization) or DIN (Deutsches Institut für Normung) or British Standard Institution (BS) or European Standard (EN) standards for wire rope construction. These codes need to be followed if buying foreign wire rope. The following list is not complete and there are many other standards for wire rope. However, some other common standards include:

- American Petroleum Institute (API): API 9A, Specification for Wire Rope.
- BS ISO 4309, Cranes. Wire Ropes. Care and Maintenance, Inspection and Discard.
- BS EN 292, Safety of Machinery.
- DIN 3051-Sections 1–4, "Lifting Ropes"; "Steel Wires."
- DIN 15020 – Sections 1–2, "Hoists"; "Principles of Rope Reeving."
- DIN 15061 – Sections 1–2, "Cranes & Hoists"; "Grooves for Rope Sheaves & Drums."
- DIN 15100, "Serial Lifting Equipment"; "Nomenclature."
- EN 60204-32, "Safety of Machinery"; "Electrical Equipment of Machines"; "Requirements for Hoisting Machines."
- ISO 2408, "Steel Wire Rope for General Purposes."
- ISO 17893, "Steel Wire Ropes – Vocabulary, Designation and Classification."
- ISO 4345, "Steel Wire Ropes – Fibre Main Cores – Specification."

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CHAPTER 7

Field Acceptance and Installation and Tensioning

7-1. Field Acceptance.

a. Measurement of diameter. The diameter of a wire rope must be measured before installation to verify it is as specified and correct for its application, and also to verify it is within the industry and specified tolerance. The diameter should be measured across the wire rope in the longest direction. Another way of stating this is to simply draw a circle around the circumference that will enclose all the strands. The diameter of this circle is the diameter of the wire rope. The industry tolerances per the Wire Rope Technical Board (WRTB), for wire ropes over 8.0 mm ($^5/_{16}$ in.) are -0 and +5% of nominal diameter. Note that new ropes are usually larger than their published diameters, and as stated above, should never be smaller. Diameter shall be measured with the rope loaded between 10 and 20% of nominal strength. The Wire Rope User's Manual (WRTB 2005) indicates the proper method of measuring diameter. Also note that the diameter tolerance is indirectly specified through Federal Specification RR-W-410 by reference to ASTM A1023, which specifically states the diametrical tolerances for most, if not all, rope constructions.

b. Damage inspection. Upon receiving the wire rope, it is important to inspect for damaged packaging, dings, broken wires, and kinks (Figure 7-1). Field handling of the wire rope requires great care as rope damage can occur during this process. The inspection should be scheduled with the supplier present. A report of the results should be made upon completion of the inspection. Protruding wires are considered a defect and not more than one broken wire is acceptable in any 1,000-ft length of new rope per Paragraph 3.10 of Federal Specification RR-W-410E.

Figure 7-1. Wire Rope Kinks and Broken Wires.

7-2. Storage, Handling, and Unreeling.

a. Long-term storage. If wire rope must be stored for long periods, it should be in a well-ventilated, weatherproof building or storage shed. If stored on wooden spools in humid areas with low light and poor air circulation, damage from microbiologically influenced corrosion may occur. Wire rope should never be stored outdoors.

b. Handling/unreeling. Wire rope is wound on reels for shipping at the manufacturer's facility in the same direction as it bends during manufacturing. This bending direction is an inherent feature of the rope. It must be unreeled from its shipping reel and be installed onto its equipment, only bending in this same direction. Reverse bending may cause the rope to become twisted. It is best to keep wire rope under tension when handling to prevent it from becoming looped. Pulling on a loop may result in kinks, permanently damaging the rope. When installing new wire rope on a drum it is recommended to do so under tension, up to 2% of the breaking strength of the rope. The Wire Rope User's Manual (WRTB 2005) recommends a number of techniques for wire rope handling to avoid reverse bending and kinking.

7-3. Installation. The following paragraphs present guidance on wire rope installation. Requirements for installation should be presented in the specifications. It is also recommended that the specifications require both removal and installation plans as a submittal.

a. Drum attachment. Grooved, plain, and layered drums each require the adherence to certain rules when attaching/installing wire rope.

(1) Grooved drums. The rope must be wound under adequate and continuous tension, and must follow the groove, or it will be cut and crushed where it crosses. Two dead wraps are mandatory, and three are preferable.

(2) Plain drums. The rope must be wound under adequate and continuous tension. Each wrap must be guided as close to the preceding wrap as possible so there are no gaps between turns. Two dead wraps are mandatory, and three are preferable.

(3) Layered drums. The rope must be wound under adequate and continuous tension. Two dead wraps are mandatory, and three are preferable.

b. Dynamometer tests. A dynamometer test monitors wire rope tension during operation of its gate-operating device. The test link is normally mechanical. This test verifies that the rope is not subjected to a tension higher than intended. Appendix D includes information on dynamometer test links.

c. Break-in procedure. In addition to following the above procedures, it is best if wire rope is "broken in." Ideally, a light load and a slow speed would be used while the operating device is cycled through a few operations. However, in most gate-operating devices, both the load and speed are fixed and the wire rope is subjected to full load at break-in. The gate operating equipment should be cycled a few times while a number of personnel are stationed in positions to verify that the rope runs freely through all drums, sheaves, and guides.

7-4. Tensioning Multi-Line Wire Rope Hoists. It is important to achieve equal tension within a group of ropes in a gate-operating device that uses several ropes in parallel. The rope(s) having the higher tension will carry more load and are likely to wear and/or fatigue more rapidly than the others. When ropes are replaced, it is recommended that all ropes be replaced. Replacement of one or some of the ropes is not generally practical for two reasons. First, keeping the old and new ropes in equal tension would be difficult. The new ropes tend to stretch more quickly than the old ropes, causing the old ropes to carry a greater share of the total load. Frequent tensioning would be required to alleviate this problem. Second, when ropes are replaced piecemeal, installation costs would be greater over the life of the project. It is also difficult to equalize rope tension across large gates that are lifted from each side using different sets of ropes. Differences in rope loads from side to side can cause gate skew, overstress gate components, and reduce the life of the wire ropes and drive equipment. Refer to EM 1110-2-2610 (Chapters 2 and 9) and Chapter 4 of this manual (Section 4-12) for additional design of multiple wire rope connections including designs used within the Northwest Division and also for Tainter gates.

a. Rope tensioning discussion. In general, a reasonable specification is to have all wire ropes within a group to be within ±5% of the mean wire rope tension of the group. The total wire rope load on each side of a gate should be within a range less than or equal to 0.5% of the average of the two total wire rope loads. This criteria must be considered along with gate skew, however. Gate geometry and eccentricities in the center of gravity can cause wire rope loads to vary while keeping the gate level. Also under consideration is the force consistency between different gate lifts as they are a function of several things including the amount of space between the separator plates, the way that the wire ropes wrap around the hoists, and variations in sliding or rolling friction. If the wraps are not perfectly on top of each other, a small change in an individual wire rope length can occur from one wrap to the next due to slight changes in the radius on the drum. These are small variations, but can result in a greater than a 2% change in force for a specific wire rope between two gate lifts. Therefore, the results of these procedures are not always exactly repeatable.

b. Rope tensioning features. A number of fittings, features, and end connections can be used to facilitate tensioning groups of wire ropes on a single drum, or to equalize sides for skew control.

(1) U-Bolts. U-Bolts are typically used along with bridge sockets to connect the wire rope end to the structure. U-Bolts have threaded ends allowing fairly precise wire rope tension adjustments (Figures 7-2 and 7-3).

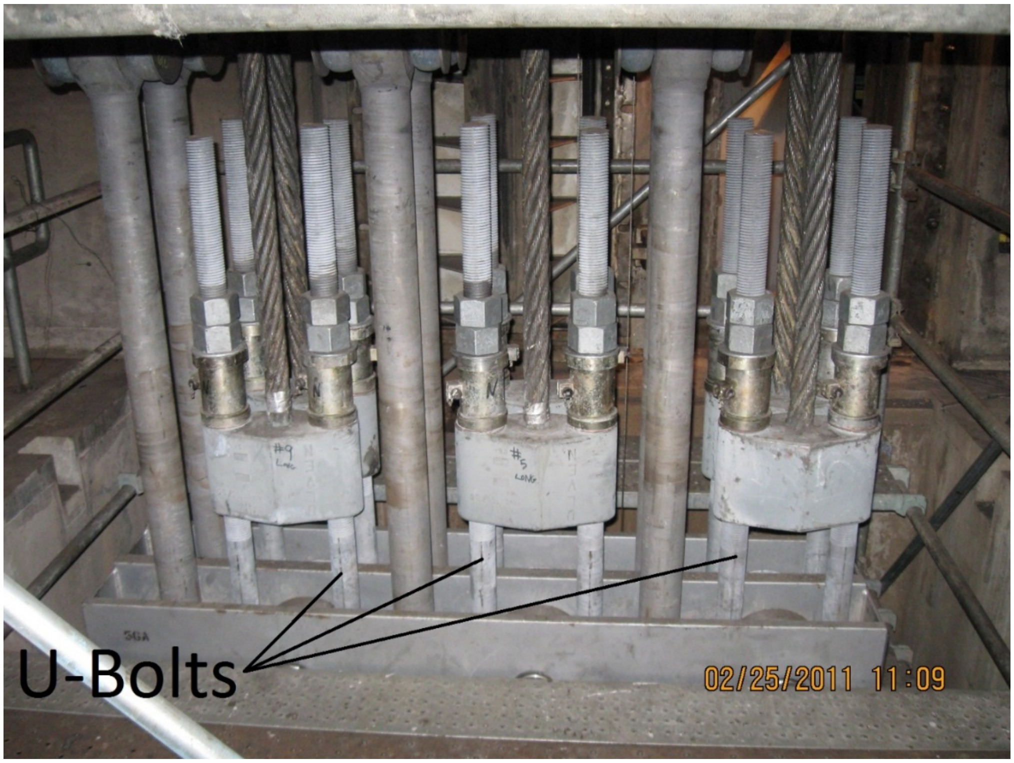

Figure 7-2. U-Bolts.

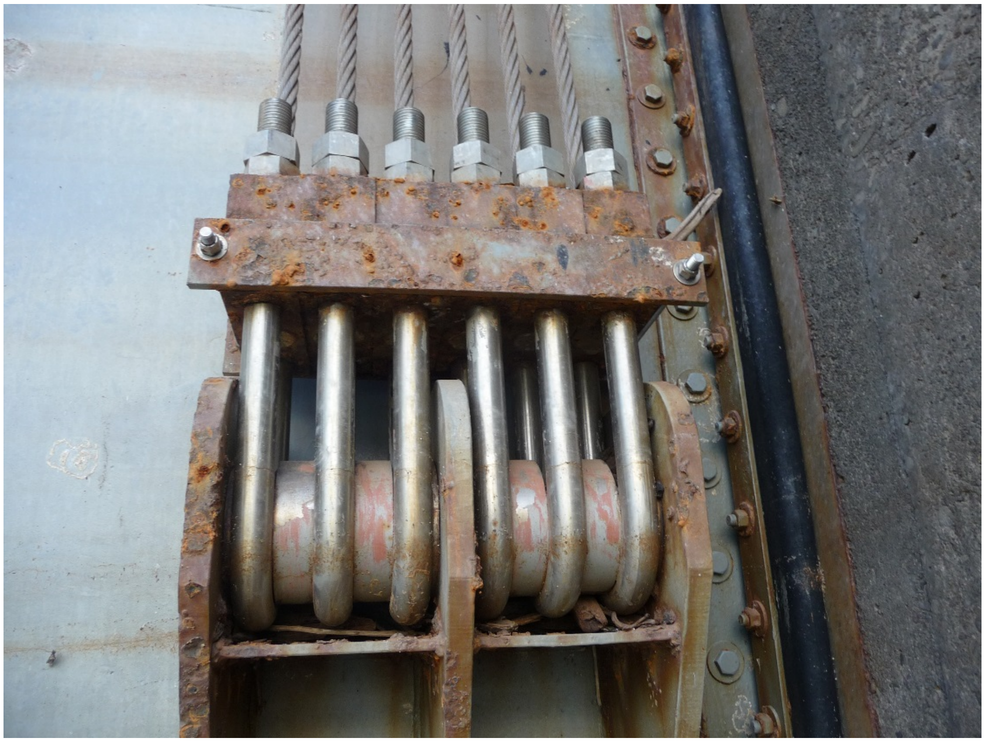

Figure 7-3. Tainter Gate Wire Rope U-Bolt Connection.

(2) Bridge Sockets. Bridge sockets are the devices that terminate the wire rope, providing for a variety of threaded devices that connect to the structure, and allowing for adjustments. Closed bridge sockets have U-Bolt connections (Figure 7-4) while open bridge sockets have threaded rods or double eye bolts (Figure 7-5).

Figure 7-4. Bridge Sockets.

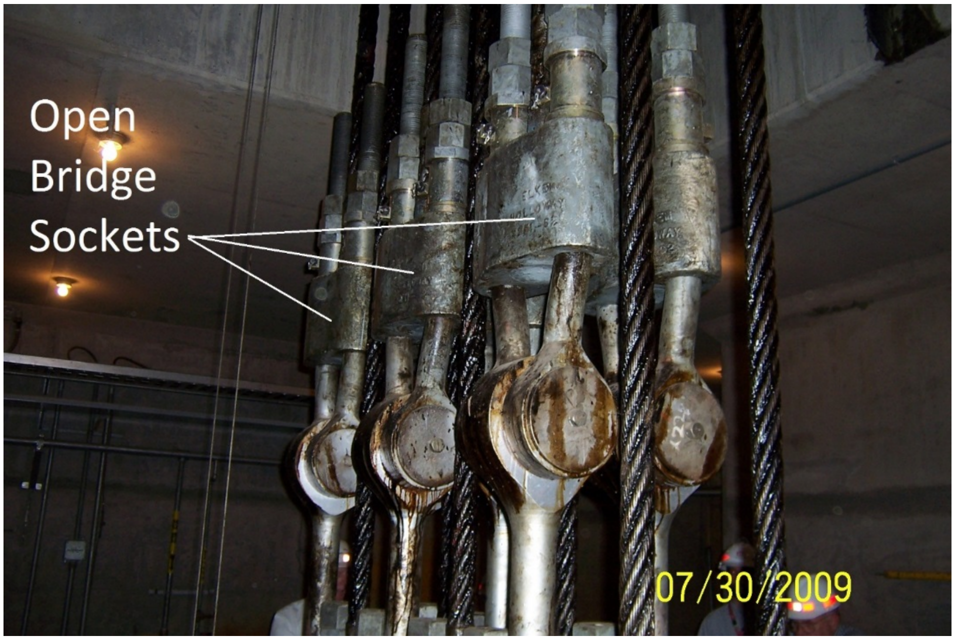

Figure 7-5. Open Bridge Sockets

(3) Connecting Rods. Connecting rods can be used in the scheme of connecting the wire rope termination to the structure. Connecting rods are useful when space limitations interfere with wire rope end connections. They can also have threaded ends that provide another method to tension the wire rope in the connection (Figure 7-6). Note that the rod ends in this figure are rotated 90 degrees relative to each other to maintain parallel bridges of both the open and closed bridge sockets used in the connection scheme.

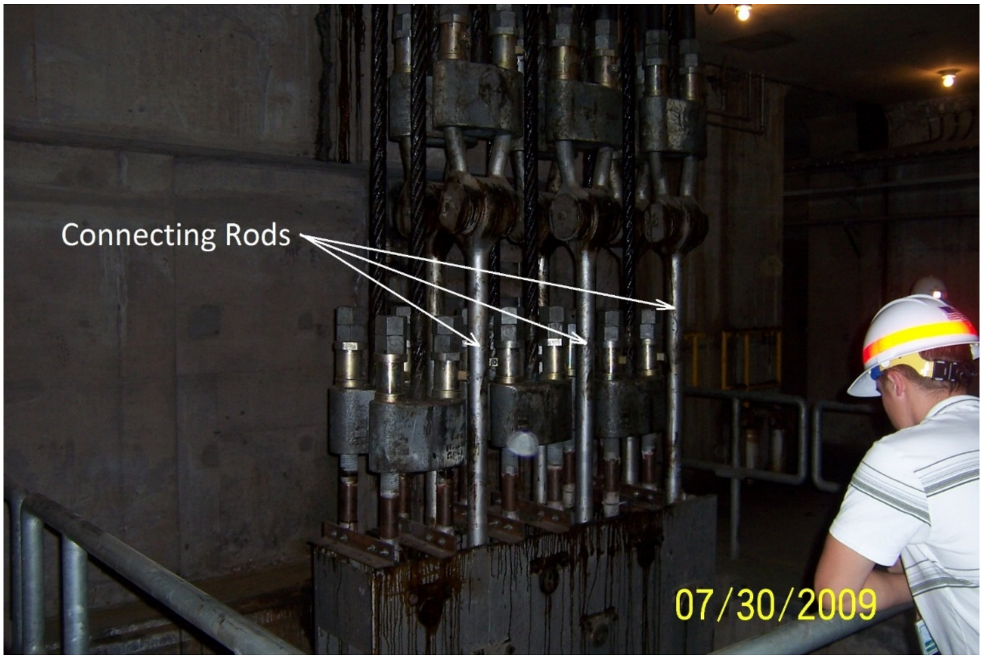

Figure 7-6. Connecting Rods.

(4) Turn Buckles. Turnbuckles are simple devices that can be used in a wire rope connection, and that allow for adjustment of rope tensions. They typically consist of two threaded connectors and a frame (Figure 7-7). The connectors are right and left hand threaded allowing tension adjustments by rotating the frame thus drawing the connectors closer together or further apart.

Figure 7-7. Turnbuckle.

(5) Equalizing Beams. Equalizing beams are used when two separate wire rope systems are used to hoist the same device (Figure 7-8). As wire ropes are wound on drums they may not wind synchronously even when the drums are tied together. As rope wraps on itself, it will likely not occur in exactly the same fashion between the two drums. An equalizing beam is used to take up small differences in changes in rope lengths between the two sides. The beam is pinned to the center of the structure being hoisted allowing it to rotate as required. This ultimately keeps the two ropes under similar tension as the structure is hoisted.

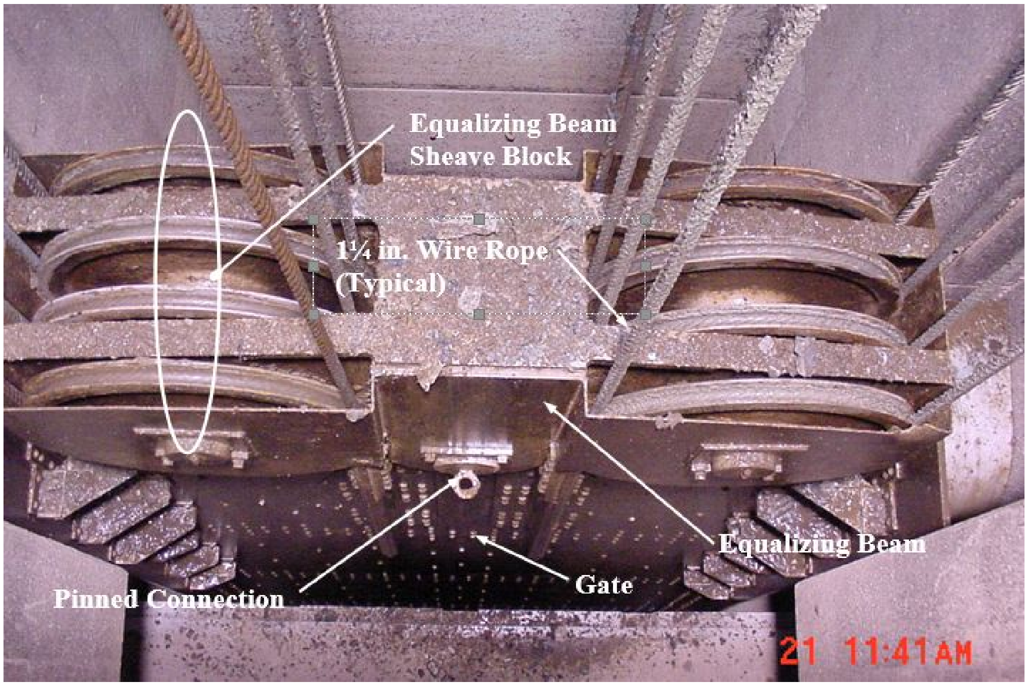

Figure 7-8. Equalizing Beam.

7-5. <u>Rope Tensioning Techniques and Analysis</u>. A number of various methods are used to measure and adjust tension in wire ropes to achieve desired results for rope tension within a group of ropes, or to balance systems that have two hoisting systems for one structure. Note that tensioning ropes in a group in an attempt to achieve equal tension within the group is an iterative process that can be quite time consuming. Each time a single rope tension is adjusted it changes tension in adjacent ropes. The equipment and expertise is somewhat specialized. Installation schedules and cost estimates must adequately address this task. The following paragraphs provide a discussion of different ways to analyze tension in wire ropes for gate drive systems.

a. Strain Gauges. Strain gauges can be used on the connecting hardware of wire ropes to measure tension and to do comparisons between ropes in a group. Figure 7-6 shows how strain gauges can be glued on to the connecting rods to measure strain directly, which is easily converted to tension if one knows the properties of the connecting rod. Of course, the gauges must be applied under a known tensile state, which can be problematic for systems already in service. Strain gauges can also be applied to rotating shafts in the drive train of a hoisting system that can be used to measure shaft torque and ultimately total hoisting forces on a system (Figure 7-9). Figure 7-10 shows the results of torque measuring on gate operating equipment where each side of the gate has a separate hoisting system.

Figure 7-9. Strain Gauge on Rotating Shaft.

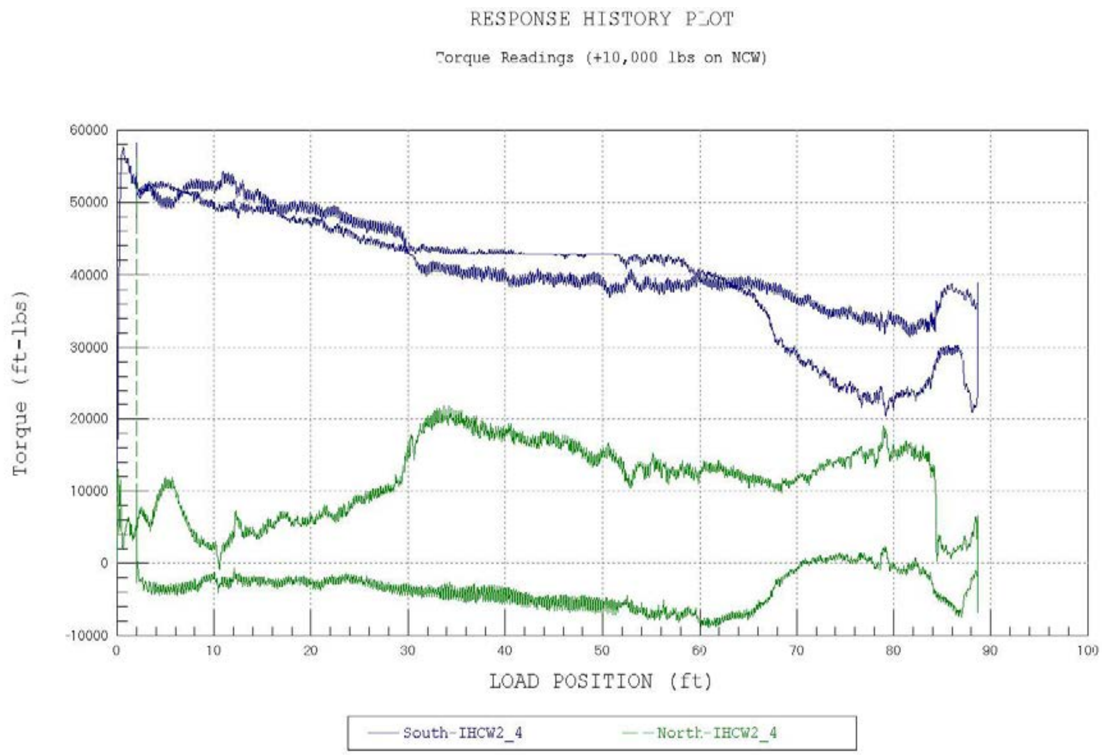

Figure 7-10. Strain Gauge Response on Hoist Shaft Torque.

b. Load Cells. Load cells can be placed in the system that allow direct measurement of wire rope tension (Figure 7-11). Figure 7-12 shows the typical load cell installation, which includes a 1-in. hardened steel washer between the load cell and the reaction nut. Concentric loading is further improved through the use of a two-part spherical washer on the bottom of the load cell. A ⅛-in. annealed copper washer installed below the spherical washer is advised to eliminate local stress concentrations caused by the uneven surface of the cast cable socket. Installing a load cell on each wire rope connection before applying the load is a fairly straightforward approach to reading rope tensions and making adjustments as required to bring the various ropes in a group to within specification for equal tension. Adjusting rope tension can be difficult in a highly loaded system, therefore a hydraulic wrench is often needed (Figure 7-13). Figure 7-14 shows the results from load cell measurements taken during gate movement to distribute loads across the wire rope group.

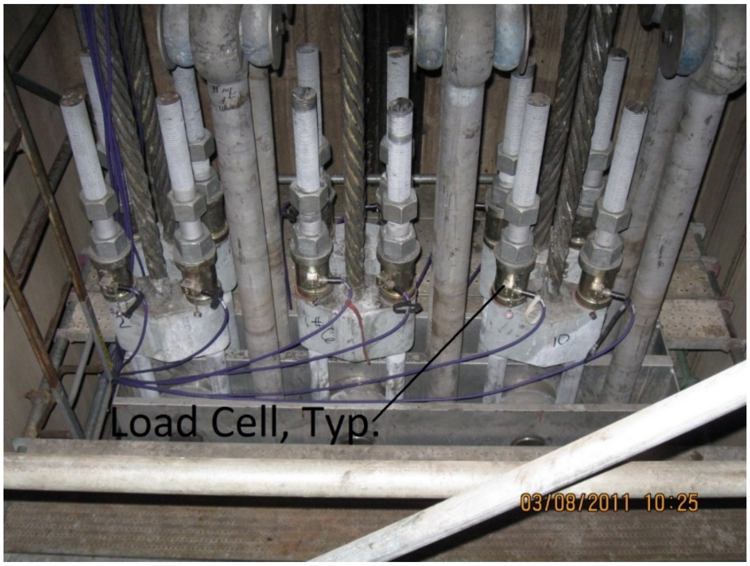

Figure 7-11. Load Cells on U-Bolts.

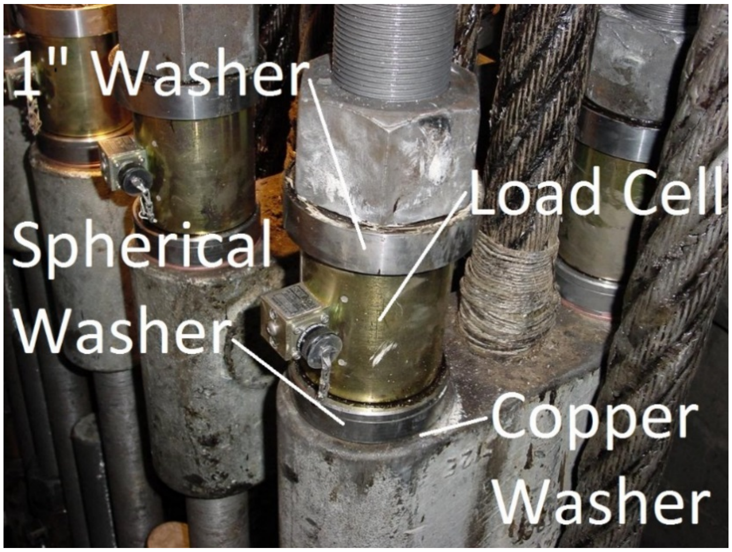

Figure 7-12. Load Cell Installation Details.

Figure 7-13. Hydraulic Wrench.

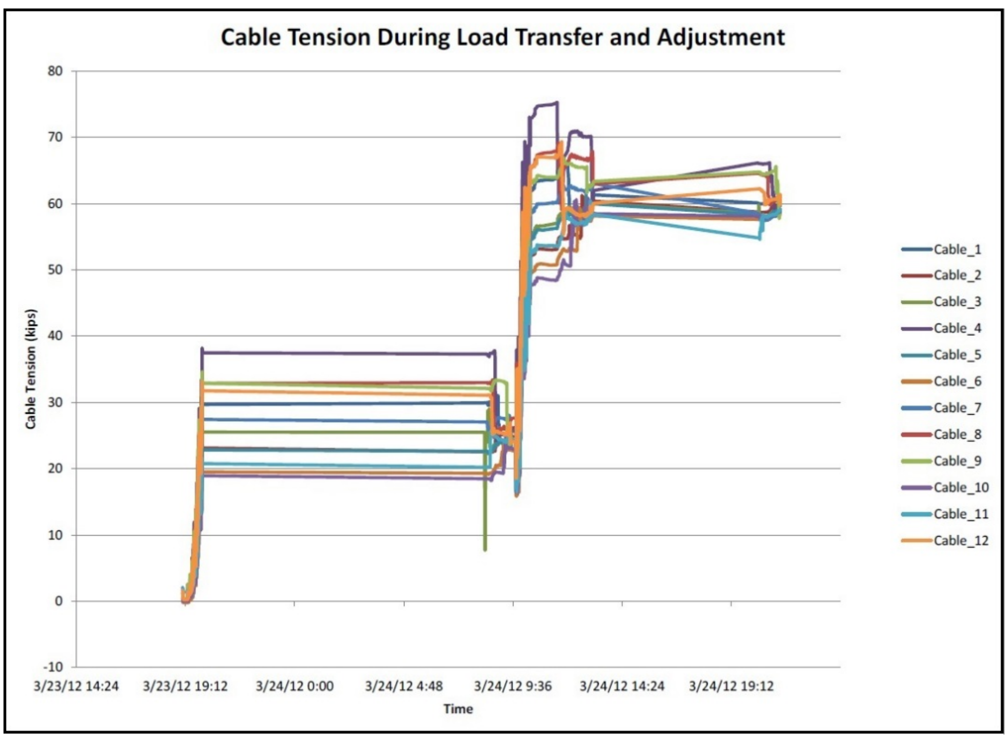

Figure 7-14. Load Cell Readings on a 12-Wire Rope Group.

c. Taut Cable Vibration Method (TCVM). TCVM is a method to compare tension in groups of wire ropes by collecting vibration measurements using accelerometers strapped to each wire rope in the group. The wire ropes are “activated” by striking them with a rubber mallet. Each accelerometer then sends data to a software package that typically displays results in the frequency domain. Actual tension values can be computed using the wire rope’s fundamental frequency and the physical properties of the rope, length, and weight per unit length. Wire ropes within a group can then be adjusted as required to achieve tensions required by the specifications. This method can be used for wire rope already loaded and in service with no need to insert an item into the wire rope connections, or to unload the ropes. This process is limited to ropes that can vibrate freely without obstruction and have relatively simple end-conditions however.

d. Wire Rope Deflection Meters. Wire rope deflection meters use the principle of deflecting the rope that is in tension since the amount of deflection for a given applied force varies with rope tension. The higher the tension in the rope being measured, the less it will deflect under a given load. The deflection meter provides relative values that can be used to compare rope tension within a group or to determine actual tension if properly calibrated for the rope being measured (Figure 7-15).

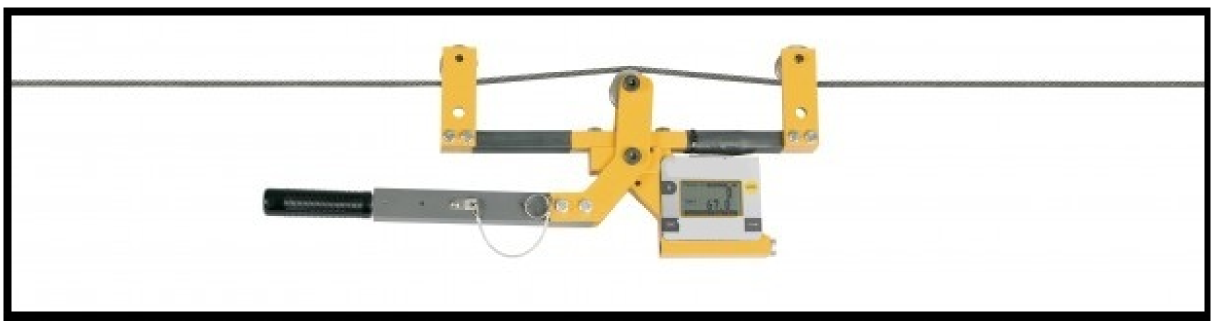

Figure 7-15. Wire Rope Deflection Meter

e. Tension Link Dynamometer. A tension link dynamometer is a calibrated load cell that is actually inserted into the rope system as a link. Using a tension link dynamometer is very similar to the use of a load cell except each tension link dynamometer is a “self-contained” calibrated unit. These are typically used in crane applications to provide feedback to the operator on the load being hoisted. Although they could be used in wire rope groups for tensioning purposes, it is likely more economical to use load cells or strain gages as real time monitoring of the load over time is not typically required in this application.

f. Turn of the Nut. Turn of the nut method can approximate actual rope tension and can be used to obtain equal tension between ropes in a group. If it is possible to start in some known state or wire rope tension then the amount you turn the various nuts on your adjustment connections will pull equal tension for equal turns. Tension can also be estimated by the torque value used to turn the nut in the connection by using a torque wrench. When equalizing tensions by this method, it is important to have similar hardware that is properly and evenly lubricated as the various friction values in different threaded connections can result in highly varied results.

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CHAPTER 8

Operation and Maintenance

8-1. Wire Rope Inspection.

a. Frequency of Inspection and Guidance Documents. The frequency of inspection required for wire rope at Corps facilities varies considerably, depending on usage, the environment the rope is subjected to, and the lubrication program. The inspection program should be formulated during development of a project's operations and maintenance (O&M) manuals. At some Corps facilities the gates are rarely operated making annual inspections adequate. At other facilities, gates are operated many times per day, and monthly inspections should be done. At a minimum, all wire ropes at all USACE civil works facilities shall be inspected at least once per year. This inspection requirement should primarily be a visual inspection of the outside of the wire rope that would cover condition of the outside wires such as wire breaks, corrosion, abrasive wear, etc. More detailed inspection criteria requirements that include inspecting the core of the wire rope are discussed below. More detailed inspections should generally be done when evidence exists of damage to the outside of the wire rope. Several guidance documents listed below can be used to not only define the frequency of inspection, but also provide guidance for O&M of wire rope. A yearly (at a minimum) visual inspection of wire rope at USACE facilities shall still be done regardless of the guidance document referenced (see Appendix E). The guidance documents below can provide criteria for more frequent inspections.

(1) The USACE Northwest Division (NWD) has published NWDR 1130-2-8 that defines inspection and operation requirements for NWD spillway gates. This is not applicable to all USACE gates, but may provide an example of common required criteria for operating and inspection of operating machinery including wire ropes. The NWD document criteria requires exercising at least one third of the spillway gates in an unloaded (dewatered) condition, throughout their full range of motion annually. If dewatering is not required, then all gates must be exercised yearly.

(2) The recent American Society of Engineers (ASCE) document, Water Control Gates, Guidelines for Inspection and Evaluation, also provides inspection criteria and O&M criteria for a number of gate types, operating machinery, and wire ropes. Table 5-1 in the ASCE document provides specific inspection guidelines for gates and operating equipment depending on the type of gate and the frequency of use. Chapter 7 provides requirements for visual inspection of gate operating equipment including wire rope.

(3) Engineering Regulation, ER 1110-2-8157, Responsibility for Hydraulic Steel Structures, can also be referred to for O&M guidelines and inspection guidelines. ER 1110-2-8157-6a defines a Hydraulic Steel Structure (HSS). It includes language that states: "Many components of the operating machinery are designed and function integrally with the structural components of the HSS. To the extent possible, the provisions of this regulation shall also apply to such components." For the purposes of this manual, wire rope and the corresponding mechanical operating systems shall be considered integral to the HSS components. ER 1110-2-8157 defines a 5-year frequency of inspections for HSS gates. This Engineering Regulation also defines the inspection methods for steel structures (Section 9c). Specific wire rope inspection methods to comply with the intent of ER 1110-2-8157 are discussed later in this chapter.

(4) Wire Rope User's Manual (WRTB 2005). This manual is an industry standard that covers all aspects of wire rope design, construction, operation, inspection, and maintenance. It includes discussion of wire rope components; identification and construction; handling and installation; operation, inspection and maintenance; and physical properties.

(5) Wire Rope Inspection Guidelines (WRTB 2005). This brochure includes guidelines for inspecting wire rope systems or installations. It is excerpted from the Wire Rope User's Manual (WRTB 2005). The publication provides a concise approach to assisting wire rope users' needs to comply with industry and governmental regulations that require inspections of individual ropes; fittings and attachments; and entire operating systems at regularly scheduled intervals. In addition to information and criteria, the brochure includes a blank wire rope inspection form.

(6) Occupational Health and Safety Administration Standard 1926.1413, Wire Rope Inspection for Cranes and Derricks. This standard is further discussed in Section 8-2 below. It provides specific inspection criteria for when wire rope should be taken out of service and provides specific inspection intervals for wire rope.

(7) The Wire Rope Examination and Inspection Manual (Casar Drahtseilwerk Saar GmbH, Aachen Germany). This manual covers a wide range of inspection criteria for wire rope. It provides guidance for how often to inspect wire rope, what to inspect for, and when wire rope should be discarded. It also discusses electro-magnetic testing of wire rope.

(8) Wire rope requirements for the mining industry can also be used. The Code of Federal Regulation, 30 CFR § 77.1434, provides important retirement criteria for wire rope used in the mining industry (regulated by the Mine safety and Health Administration [MSHA]); 30 CFR § 77.1437 provides important retirement criteria and for end attachment re-termination. Inspection of wire rope is more stringent due to life-safety concerns for hoisting mine personnel (30 CFR § 77.1433).

(9) The Roebling Wire Rope Handbook provides a means for determining and documenting wire rope breaks and provides guidelines for wire rope inspection.

8-2. Inspection Criteria. Regular inspection of wire rope can help determine when the rope must be replaced and potentially when it becomes a safety hazard. Regular inspection and a corresponding maintenance program can extend the service life of wire rope and can help detect unexpected damage or corrosion. Multiple inspection criteria can be used, including the guidance documents described above. These inspection criteria can be used to determine if replacement is warranted. For critical lifting applications including vertical lift gates, Tainter gates, Tainter valves, and bulkhead lifting or lowering systems, the Occupational Safety and Health Administration (OSHA) Standard 1926.1413, Cranes and Derricks in Construction, Wire Rope Inspection, should be used for USACE civil works facilities. This standard defines three distinct categories of wire rope deficiencies: Category I, Category II, and Category III. Appendix E provides a summary inspection sheet for this OSHA standard; refer to this for more clarification. Appendix E also provides a wire rope inspection form that is required for all wire rope inspections. Pictures of the various wire rope deficiencies are provided in Section 8-3. Refer to the Wire Rope User's Manual (WRTB 2005) and the Wire Rope Inspection Guidelines (WRTB 2005) for more details, descriptions, and photographs of wire rope deficiencies.

a. Category I Deficiencies.

(1) This category is defined as significant distortion of the wire rope structure such as kinking, crushing, unstranding, birdcaging, signs of core failure or steel core protrusion between the outer strands. Further definition of these terms and example photos is provided below in Section 8-3 and in the Wire Rope User's Manual. Category I deficiencies also include significant corrosion; pitting; electric arc damage (from a source other than power lines) or heat damage; improperly applied end connections; and significantly corroded, cracked, bent, or worn end connections (such as from severe service). Significant corrosion is difficult to quantify, but can be a more serious degradation than abrasion. Figure 8-1 shows an example of severe corrosion and pitting.

Figure 8-1. Severe Wire Rope Corrosion Including Pitting.

(2) Any pitting of the wire rope should put the wire rope in a Category I deficiency and be a reason for immediate removal from service. If a deficiency in Category I is identified, an immediate determination must be made by the inspector or competent person as to whether the deficiency constitutes a safety hazard. If the deficiency is determined to constitute a safety hazard, operations involving use of the wire rope in question must be prohibited until the wire rope is replaced. For localized deficiencies, this standard allows the wire rope to be "fixed" by severing the wire rope in two and shortening the length. This is generally not practical for USACE lifting applications, however, and is not recommended. If a wire rope is shortened under this scenario, it must be ensured that the drum will still have two wraps of wire when the load is at the lowest position.

b. Category II Deficiencies.

(1) Deficiencies include a diameter reduction of more than 5% from nominal diameter. This is further discussed in Section 8-3. Other deficiencies in this category include visible broken wires (Figure 8-2) as follows:

(a) In running wire ropes – six randomly distributed broken wires in one rope lay or three broken wires in one strand in one rope lay, where a rope lay is the length along the rope in which one strand makes a complete revolution around the rope.

(b) In rotation resistant ropes – two randomly distributed broken wires in six rope diameters or four randomly distributed broken wires in 30 rope diameters.

(c) In pendants or standing wire ropes – more than two broken wires in one rope lay located in rope beyond end connections and/or more than one broken wire in a rope lay located at an end connection.

Figure 8-2. Wire Rope – Broken Rope Wires.

(2) The Wire Rope User's Manual (WRTB 2005) and the Wire Rope Inspection Guidelines (WRTB 2005) define these wire rope deficiencies further. If a deficiency in Category II is identified, operations involving use of the wire rope in question must be prohibited until:

(a) The USACE site complies with the wire rope manufacturer's established criterion for removal from service, or follows a different criteria that the wire rope manufacturer has approved in writing for that specific wire rope to remain in service. This has to be fully documented. However, for USACE civil works sites, it is recommended that the wire rope be removed from service if it falls under a Category II deficiency.

(b) The wire rope is replaced.

(3) For localized deficiencies, the standard again allows severing the wire rope in two and using the undamaged portion. Joining lengths of wire rope by splicing is prohibited. If a rope is shortened under this paragraph, it must be ensured that the drum will still have two wraps of wire when the load is at the lowest position.

c. Category III Deficiencies. Category III deficiencies include a core protrusion or other distortion indicating core failure. Other deficiencies include a complete broken strand or prior electrical contact with a power line. If a deficiency in Category III is identified, operations involving use of the wire rope in question must be prohibited until the wire rope is replaced.

8-3. Wire Rope Inspection. This section discusses the common and critical inspection factors for wire rope. Ultrasonic testing (non-destructive testing) is also discussed at the end of the section. It is recommended that wire rope inspections also follow the Wire Rope Inspection Guidelines (WRTB 2005). This document provides further discussion on the topics below. Also, the CF&I Roebling Wire Rope Handbook is an informative but dated handbook with practical explanation and diagrams for rope defects and inspection. Flat wire rope should follow the same general inspection guidelines (as applicable).

a. Diameter reduction.

(1) The diameter of wire rope is reduced as it degrades from abrasion, corrosion, inner wire breakage, stretch, etc. The Wire Rope User's Manual (WRTB 2005) provides additional discussion on this topic. Also, the 30 CFR § 77.1432, Initial Measurement, provides additional consideration for establishing and monitoring rope stretch through diameter measurements and must be followed for USACE civil works structures. The following is taken from the 30 CFR document:

> After initial rope stretch but before visible wear occurs, the rope diameter of newly installed wire ropes shall be measured at least once in every third interval of active length and the measurements averaged to establish a baseline for subsequent measurements. A record of the measurements and the date shall be made by the person taking the measurements. This record shall be retained until the rope is retired from service.

(2) Diameter reduction is a critical deterioration factor and can be caused by:

- Excessive abrasion of the outside wires.
- Loss of core diameter/support.
- Internal or external corrosion damage.
- Inner wire failure.
- A lengthening of rope lay.

(3) It is important to check and record a new rope's actual diameter when under normal load conditions. During the life of the rope the inspector should periodically measure the actual diameter of the rope at the same location under equivalent loading conditions. This procedure, if followed, carefully reveals a common rope characteristic. Generally, after an initial reduction, the overall diameter will stabilize and slowly decrease in diameter during the course of the rope's life. This condition is normal. However, if diameter reduction is isolated to one area or happens quickly, the inspector must immediately determine (and correct, if necessary) the cause of the diameter loss, and schedule the rope for replacement. A one-time comparison between a rope's measured diameter and its nominal diameter is not a true indicator of its condition. Measured diameters must be recorded and kept for historical reference. This procedure will typically show a rapid initial reduction in the rope's diameter followed by a slower more linear reduction. A sudden diameter decrease marks core deterioration and indicates a need for replacement. A Category II deficiency is a diameter reduction of more than 5% from nominal diameter

(4) The generally accepted method of measuring rope diameter for compliance is to use a caliper with jaws broad enough to cover not less than two adjacent strands. The measurements must be taken on a straight portion of rope at two points at least 1 meter (3 ft) apart. At each point, two diameters at right angles should be measured. The average of the four measurements is the actual diameter.

b. Stretch. Before wire rope is installed on a gate, a method should be devised to periodically measure rope stretch. For example, on a Tainter gate application, the rope length can be checked at a specific point in the gate travel while under load. Mark these points on the wire rope for future inspections. Rope stretch typically occurs in three distinct stages. The first stage is constructional stretch. It is rapid and of a short duration and can be reduced by pre-stretching. Constructional stretch is influenced by the type of core, the rope construction, and the wire rope material. In the second stage, a small amount of stretch takes place over an extended time and is referred to as elastic stretch. This results from normal wear, fatigue, etc. Most wire rope manufacturers can provide calculations for determining the elastic stretch of wire rope. This should be done during the design phase and should be included in the project O&M manual. The Wire Rope User's Manual (WRTB 2005) also provides tables for determining elastic stretch. The third stage is marked by an accelerating rate of stretch. This signals rapid degradation of the rope from prolonged wear, fatigue, etc. Replacement is required when the rope enters this stage.

c. Abrasion. Rope abrasion (Figure 8-3) occurs when the wire rope passes over drums and sheaves. Abrasion damage can also occur when the rope contacts an abrasive medium. In short, "abrasion" refers to a condition in which the outer surface of the wire rope is worn away. It is vital that all components be in proper working order and of the appropriate diameter for the rope. A badly corrugated or worn sheave or drum will seriously damage a new rope, resulting in premature rope replacement. The wire rope should be replaced if the outer wire wear exceeds one-third of the original wire diameter. Since wear occurs mostly on the outer wires' outer surfaces, measuring or determining the exact amount of wear is difficult. Abrasion causes a flat wire surface by wearing away the circular crown of the wire due to the wire rope's sliding contact with another object.

Figure 8-3. Lock 7 Tainter Valve - Wire Rope Showing Abrasion and Bird Caging.

d. Crushing. Crushing or flattening of the strands can be caused by a number of different factors. These problems usually occur on multilayer spooling conditions, but can occur by simply using the wrong wire rope construction. Most premature crushing and/or flattening conditions occur because of improper installation of the wire rope. In many cases, failure to obtain a very tight first layer (the foundation) will cause loose or gap conditions in the wire rope, which will cause rapid deterioration. Failure to properly break-in the new rope, or worse, to have no break-in procedure at all, will cause similar poor spooling conditions. Therefore, it is imperative that the inspector know how to inspect the wire rope and how that rope was installed. Crushing occurs at the same location in the length of the rope as scrubbing, but occurs on the top and bottom of the rope. Because the rope goes from having two lines of contact when resting in the valley to a single point of contact during the cross over, the contact pressure is twice as high. This commonly leads to crushing of the rope at the cross-over point. This will distort the roundness of the rope structure and damage individual wires. In addition to the damage, this inhibits the free movement of the wires and strand thus affecting fatigue life. The more layers of wire rope on a drum, the more likely that crushing will occur. In some severe operating conditions, crushing can occur where the rope rests in a valley.

e. Broken wires.

(1) The number of broken wires (Figure 8-4) on the outside of a wire rope provides an index of its general condition. Wire rope on gate-operating devices must be replaced per OSHA 1926.1413 if the number of broken wires per lay length reaches the values noted above (Category II deficiencies). If more than one wire fails adjacent to a termination, the rope must be replaced immediately. It is common for a single wire to break shortly after installation, which may not be a concern. However, if more wires break, the situation should be investigated. Once breaks begin to appear, many more will generally occur within a relatively short time. Attempts to get the last measure of service from a rope can create a dangerous situation (e.g., Figure 8-5).

Figure 8-4. Dillon Dam - Plastic Coated Wire Rope Showing Broken Wires.

Figure 8-5. Mel Price Vertical Lift Gate Wire Rope Cable Breakage – Note Corrosion.

(2) Broken wires in the valleys of rope (between the strands) indicate a very serious condition. The Wire Rope Users Manual (WRTB 2005) and the Wire Rope Inspection Guidelines (WRTB 2005) both provide specific guidance on this type of breakage. When two or more such fractures are found, the rope must be replaced immediately. A determination of the cause of wire breaks should be made before replacing the rope. Valley breaks are difficult to see. However, if one valley break is seen, there are more hidden in the same area. Crown breaks are signs of normal deterioration, but valley breaks indicate an abnormal condition such as fatigue or breakage of other wires such as those in the core. Once crown and valley breaks appear, their number will steadily and quickly increase as time goes on. The broken wires should be removed as soon as possible by bending the broken ends back and forth with a pair of pliers. In this way the wire is more likely to break inside the rope where the ends will be tucked away. If the broken wires are not removed, they may cause further damage.

f. Corrosion. Corrosion may be the most common and serious form of rope degradation on gate-lifting devices. There is no known method of calculating the strength of a corroded rope. It will often occur internally before any evidence appears on the external surface. Many of the USACE Civil Works wire rope failures have been the result of corrosion. A slight discoloration from rust is usually just an indication that lubrication is overdue. However, severe rusting leads to fatigue failure, especially in areas that normally would not fail such as near terminations, where bending is not required. Pitting is the worst form of corrosion (Figure 8-6). It is essentially removes wire rope material and reduces the strength of the wire rope. If pitting is observed, the rope must be immediately taken out of service and replaced. Not only do the pits damage the wires on which they occur, they also prevent the rope's component parts from moving freely when moving over sheaves and drums, thereby contributing to abrasion and fatigue.

Figure 8-6. Pitting Corrosion (and Broken Wires) Lock 24 Culvert Valve

g. Peening. Wire rope peening is a permanent distortion resulting from cold plastic metal deformation of the outer wires. Continuous pounding against a sheave is one cause of peening. Again, the Wire Rope Users Manual (WRTB 2005) and the Wire Rope Inspection Guidelines (WRTB 2005) both provide specific guidance. It can occur when a rope vibrates against another component, or if the rope is continuously worked against a drum or sheave at high pressure. Heavy peening can result in wires cracking and breaking and may eventually require rope replacement.

h. Scrubbing. Scrubbing occurs when a rope rubs against itself or another object. Its effects are normally evident on only one side of a rope. If corrective measures are not taken in time, rope replacement may be required. Scrubbing occurs when rope on a layer (other than the bottom layer) comes to the point where there is a previous wrap already in that valley between the two ropes on the layer below. The rope coming onto the drum contacts the rope already on the drum and slides or “scrubs” against it. This contact forces the rope coming onto the drum to cross over to the next valley on the drum. This scrubbing contact occurs on the side of the rope and can cause damaged, displaced, and/or broken wires, but does not significantly affect the roundness of the wire rope.

i. Localized Conditions. It is typical for gate operating devices at USACE installations to position the wire rope at only one or two locations for majority of the service life. This concentrates wear or damage at these locations. Also, special attention should be given to rope in the areas of equalizing sheaves. Only slight movement occurs over them, usually a rocking motion. This causes a concentration of bending and abrasion where the rope meets the sheave groove. Look for worn and broken wires. Note that this is an area where deterioration may not be readily detected. Careful checking and operating of the gate may be required to make rope damage more visible. End fittings are especially susceptible to damage if they are submerged.

j. Other forms. There are several other forms of rope damage, all of which call for immediate rope replacement. They include kinks, bird caging, protruding cores, and heat damage. Shockloading (birdcaging) of the rope is another reason for replacement of the rope. Shockloading is caused by the sudden release of tension on the wire rope and its resultant rebound from being overloaded. The damage that occurs can never be corrected and the rope must be replaced. Any time a rope’s core is visible, the rope must be replaced. Heat damage is usually evident as a discoloration of the rope wires, and also calls for rope replacement.

k. Over-stressing. There have been occasions when a gate jams, or one or more ropes on a multi-rope gate breaks. On these occasions, the wire rope (or wire ropes) may be overstressed compared to the design load. Determining if the rope was damaged may be impossible in many cases. In some instances, damage may be indicated by a change in lay length. If so, the area of change may be small, so finding this evidence may be difficult. If a wire rope is damaged due to overstressing, it must be replaced. Overstressing may be even more of a concern at the end of the wire rope service life or if the wire rope was damaged before overstressing.

l. Inspection reports. In addition to planning and carrying out an inspection program, it is necessary to store and analyze the data. Appendix E includes a sample inspection report form. Inspection reports must be signed and dated. They should be kept for the life of the rope and after its replacement. The report data should be compared with previous reports to identify trends. Include a recommendation to include inspection criteria for wire rope in the project O&M manual. Retain inspection records and old version(s) of inspection reports.

m. Non-Destructive Testing (NDT) of Wire Rope. NDT can be used to determine the internal condition of wire rope. However, there are conditions that cannot or may not be detected, such as breaks in small wires, closely-spaced broken wires, broken wire versus pit corrosion, and possibly other defects. The percentage of outer wires compared to the total cross sectional area of wire rope is usually between 36% and 44%. Thus, NDT can provide valuable information on the condition of over 50% of the wire rope area. The end user should recognize that NDT is a valuable tool that nevertheless does have some limitations. It also does not require opening up the rope and damaging it in the process. The loss of metallic cross-sectional area and local faults, such as broken individual wires and strands can usually, but not always be detected. The equipment (Figure 8-7) generally employs the Magnetic Flux Leakage principle. The magnetic head is installed on a rope and travels along the rope during the test. The magnet’s field saturates the rope section in the longitudinal direction. Irregularities in the rope such as loss of area and local faults cause redistribution of the magnetic flux surrounding the rope. These are then detected by sensors. It is recommended that all USACE civil works sites incorporate NDT testing of wire rope in their inspection procedures.

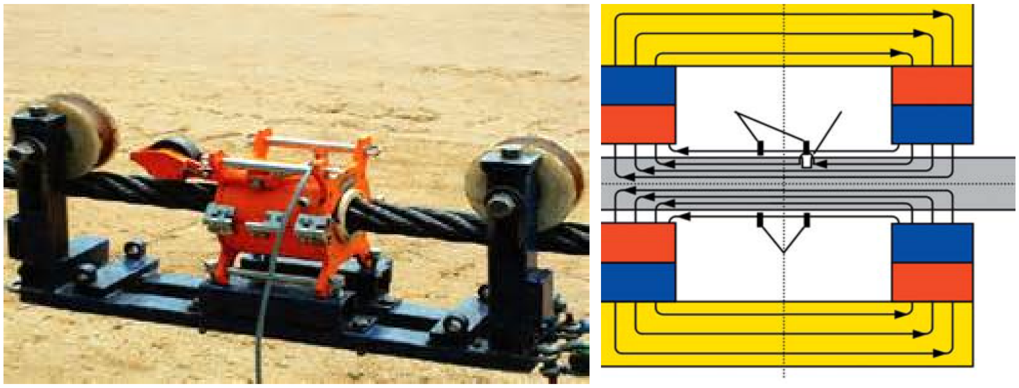


Figure 8-7. NDT Wire Rope Testing Equipment.

8-4. Inspection of Sheaves and Drums. Inspection of sheaves, pulleys, drums, fittings, and any other machine parts or components coming into contact with the wire rope is also required. The inspection of these components must be performed at the same time as the wire rope inspection and the results should likewise be documented. The Wire Rope User's Manual (WRTB 2005) provides some guidelines for inspections of sheaves and drums and should be referenced.

a. Sheaves, pulleys, and drums. A properly machined sheave or drum groove allows a wire rope to pass over or through unhindered by friction or obstructions. Sheaves and drums should be checked periodically for wear in the grooves, which may cause abrasion, pinching, and bird-caging of the rope. If the groove shows signs of rope imprints, the sheave must be replaced or re-machined and re-hardened. The correct size sheave is required to minimize wear and tear on the rope or wire. When grooves become overly worn or are too large, they may allow excessive movement, which stresses the rope and reduces its longevity. A tight groove in a sheave or drum will subject the rope to enormous radial pressure. Likewise, too small of a groove compresses the rope and reduces its useful life because the rope will roll into the sheave groove introducing torque and twist, which may cause high stranding and bird-cages.

b. The first item to be checked when inspecting sheaves (Figure 8-8), pulleys, roller guides, and (grooved) drums (Figure 8-9) is groove size. Wire rope will wear the bottom of the groove to a radius smaller than the radius of the sheave. To determine the amount of wear, place the proper size gauge in the sheave and shine a light behind the gauge. Light should not be detected between the gauge and the root of the groove. If wear is evident, the sheave should be re-machined or replaced. To check the size, contour and amount of wear, a groove gage is used. The recommended size for a sheave gauge is the nominal rope diameter + 6% to +10%. As Figure 8-10 shows, the gage should contact the groove for about 150º of the groove arc. Two types of groove gages are in general use and it is important to note which of these is being used. The two differ by their respective percentage over nominal rope diameter. For new or re-machined grooves, the groove gage is nominal plus the full oversize percentage. The gage carried by most wire rope representatives today is used for worn grooves and is made nominal plus a standard tolerance. This latter gage is intended to act as a sort of "no-go" gage. Any sheave with a groove smaller than this must be re-grooved or, in all likelihood, the existing rope will be damaged. When the sheave is re-grooved, it should be machined to the dimensions for "recommended minimum new groove." A sheave gauge is an extremely useful tool for use sheave maintenance by:

(1) Measuring sheave contour wear at the root.

(2) Measuring the amount of wear at the groove wall.

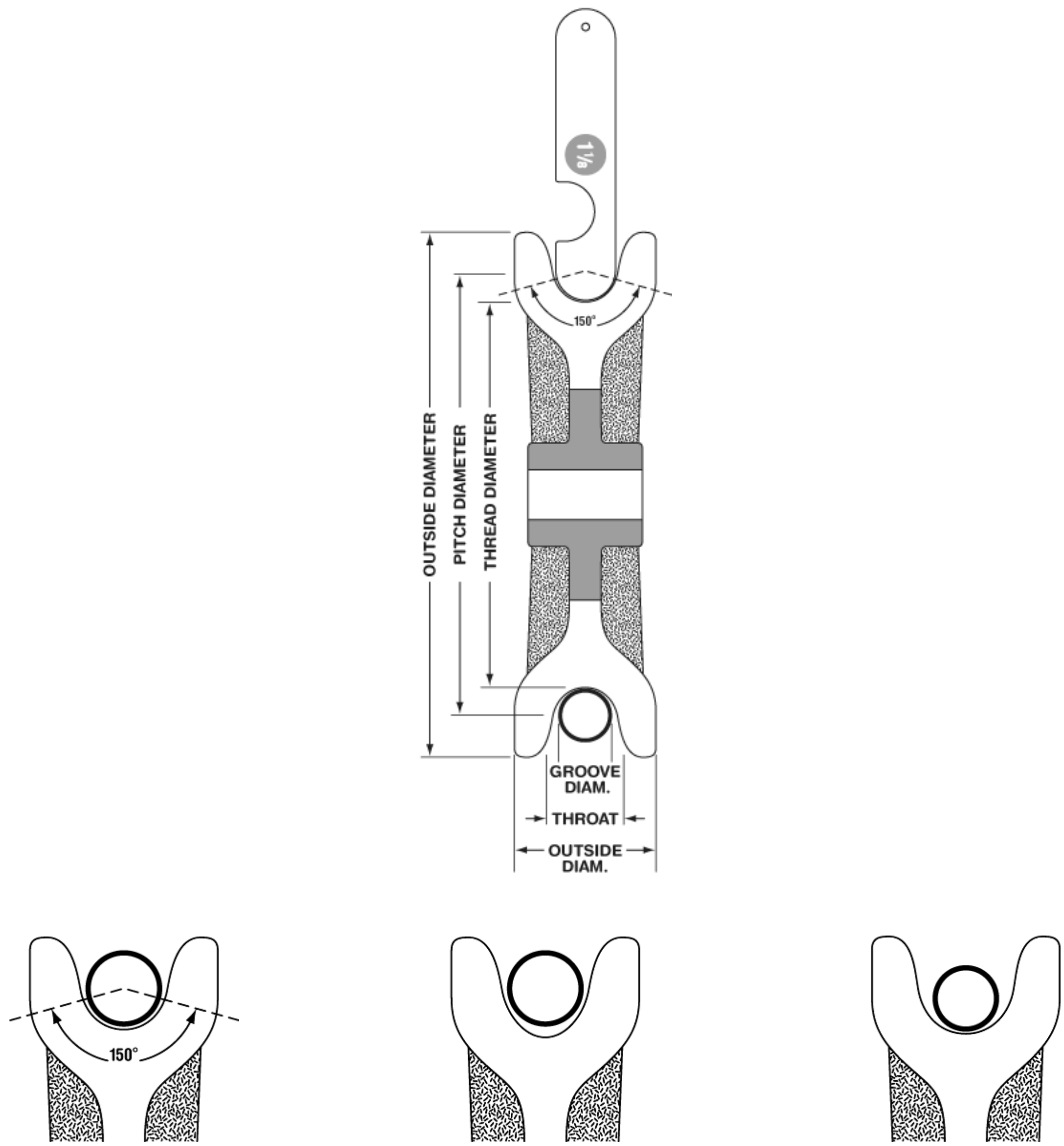
(3) Measuring the diameter of the wire rope.

Figure 8-8. Wire Rope Cable Sheaves – Lockport.

Figure 8-9. Grooved Drum for Rolling Gate.

c. Fittings. Cracked, bent, worn, or broken fittings must be replaced. Look for broken wires and loose or damaged strands adjacent to fittings. If more than one wire has failed adjacent to a termination, the rope must be replaced immediately.

d. Corrosion and Flanges. Excessive corrosion and pitting of the sheaves and drums will also damage the wire rope. If drums or sheaves are pitted, they should be re-machined or replaced. The flanges of sheaves should also be inspected. Sheaves with broken flanges will allow the wire rope to jump from the sheave (see Figure 8-11).



A new wire rope in a new sheave groove. The optimal arc of contact between the rope and the sheave groove is generally about 120 to 150 degrees.

A new rope in a worn sheave. Wire rope would get pinched and could develop damages like "Bird Cages" or "High Stranding"

A worn rope in a worn sheave. The rope should be replaced and the sheave re-machined.

Figure 8-10. Sheaves Cross Sections Demonstrating Three Wire Rope Seating Conditions.

Figure 8-11. Sheave with Broken Flanges.

8-5. Replacement of Wire Rope and Retirement. When to replace and retire wire rope has been a controversial topic within USACE. The inspection criteria provided in Section 8-2 and the referenced OSHA standard provides criteria for when wire rope must be replaced and retired, especially for wire rope that has been damaged. It is also difficult to quantify whether wire rope should be replaced based on reduced FOS. This requires physically testing the wire rope to failure. A better means would be to periodically conduct NDT testing on the wire rope as discussed above. A more controversial question is whether wire rope should be replaced based on age. There are applications within USACE where wire rope has been in service for 75 years or more. However, there are applications where wire rope has failed in less than 10 years. This manual provides no specific recommendation for replacement. The replacement criteria will depend on application, service environment, and loading conditions. It is imperative and mandated that all wire rope at USACE civil works structures be inspected on a consistent basis. Inspection data shall be the basis for any wire rope retirement. All inspection reports shall be properly documented in an electronic maintenance data base.

a. Failure analysis. A failure analysis should be performed on any failed rope to determine its prime failure mode(s). This will allow corrective measures to be taken for the new wire rope. As part of this process, a strength test should be done for the retired wire rope to determine its reduced strength and FOS. Test wire rope per ASTM A931.

b. Disposal of wire rope. The disposal of failed or retired wire rope may pose a problem. Wire rope is not easily processed by the shredders used to prepare scrap metal for re-melting. Lubricated wire rope cannot be buried in landfills in some states. Wire rope sizes 13 mm (½ in.) through 22 mm (⅞ in.) may be suitable for drag line use. However, most wire rope used for USACE gates are larger in size and will generally not be in demand for other uses such as drag lines. If replacement wire rope will be installed by contract, having the contractor “remove and dispose of properly” may be the best option.

8-6. Lubrication.

a. Refer to EM 1110-2-2610 and EM 1110-2-1424 for additional discussion on this topic. Consistent with these manuals, all wire rope must be lubricated including stainless steel rope. Stainless steel wire rope should be lubricated to help prevent abrasion as the rope goes over sheaves and drums. The principal functions of wire rope lubricants are:

(1) To reduce friction as the individual wires move over each other.

(2) Reduce abrasion as wire rope goes over sheaves or drums.

(3) To provide corrosion protection and lubrication in the core and inside wires and on the exterior surfaces.

b. Ropes should be lubricated by the manufacturer during fabrication to provide internal lubrication to the wire rope core. The manufacturer will generally have shop equipment that can force lubricant into the core area of the rope. The outside of the wire rope can be lightly lubricated during shipment. This initial treatment is generally adequate for transport and storage, and it will usually protect the rope for a short time after initial use. Once in service, the outside of the wire rope should then be fully lubricated. Periodic cleaning and lubrication are then necessary.

c. Determine the type of wire rope lubricant. There are two types of wire rope lubricants, penetrating and coating. Penetrating lubricants contain a petroleum solvent that carries the lubricant into the core of the wire rope then evaporates, leaving behind a heavy lubricating film to protect and lubricate each strand. Coating lubricants penetrate slightly, sealing the outside of the cable from moisture and reducing wear and fretting corrosion from contact with external contamination and moisture. However, because most wire ropes fail from the inside, it is important to make sure that the center core receives sufficient lubricant. A combined approach is recommended in which a penetrating lubricant is used to saturate the core, followed with a coating to seal and protect the outer surface. It is also recommended to use pressurized lubricators (Figure 8-12) when possible. EM 1110-2-1424 and EM 1110-2-2610 discuss this further. Wire rope lubricants can be petrolatum, asphaltic, grease, petroleum oils, or vegetable oil-based. EM 1110-2-1424 provides discussion on Environmentally Acceptable Lubricants that can be used.

(1) Mineral based lubricants, with the proper additives, provide excellent corrosion and water resistance and are recommended for most applications.

(2) Asphaltic compounds generally dry to a very dark hardened surface, which makes inspection difficult. They adhere well for extended long-term storage, but will crack and become brittle in cold climates. Asphaltics are the coating type of lubricant.

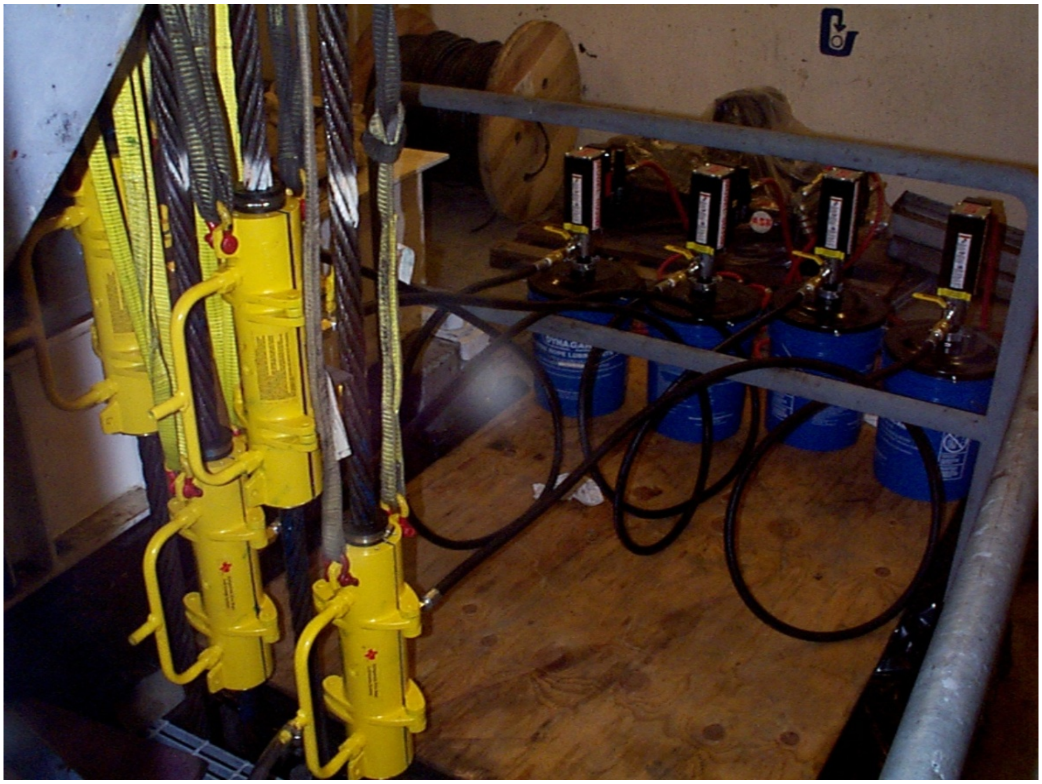


Figure 8-12. Pressurized Wire Rope Lubricator.

d. Various types of greases are used for wire rope lubrication. These are the coating types that penetrate partially, but usually do not saturate the rope core. Common grease thickeners include sodium, lithium, lithium complex, and aluminum complex soaps. Greases used for this application generally have a soft semifluid consistency. They coat and achieve partial penetration if applied with pressure lubricators. Petroleum and vegetable oils penetrate best and are the easiest to apply because proper additive design of these penetrating types gives them excellent wear and corrosion resistance. The fluid property of oil type lubricants helps to wash the rope to remove abrasive external contaminants.

e. Wire ropes should be lubricated during the manufacturing process. If the rope has a fiber core center, the fiber should be lubricated with a mineral oil lubricant. The core will absorb the lubricant and function as a reservoir for prolonged lubrication while in service. If the rope has a steel core, the lubricant (both oil and grease type) is pumped in a stream just ahead of the die that twists the wires into a strand. This allows complete coverage of all wires.

f. Once in service, wire ropes should be cleaned before applying new lubricant. If a cable is dirty or has accumulated layers of hardened lubricant or other contaminants, it must be cleaned with a wire brush and petroleum solvent, compressed air, or a steam cleaner before re-lubrication. The wire rope must then be dried and lubricated immediately to prevent rusting. Field lubricants can be applied by spray, brush, dip, drip, or pressure boot. Lubricants are best applied at a drum or sheave where the rope strands have a tendency to separate slightly due to bending to facilitate maximum penetration to the core. If a pressure boot application is used, the lubricant is applied to the rope under slight tension in a straight condition. Excessive lubricant application should be avoided to prevent safety hazards. A wire rope can be cleaned with a stiff wire brush dipped in solvent, with compressed air, or with superheated steam. The object of cleaning is to remove any foreign material and old lubricant from the valleys between the strands and from the spaces between the outer wires. New lubricant is applied by continuous bath, dripping, pouring, swabbing, painting, or by spray nozzle.

g. Determine Lubricant Performance Measures. Some key performance attributes to look for in a wire rope lubricant are wear resistance and corrosion prevention. Some useful performance benchmarks include high four-ball extreme pressure (EP) test values, such as a weld point (ASTM D2783) of above 350 kg and a load wear index of above 50. For corrosion protection, look for wire rope lubricants with salt spray (ASTM B117) resistance values above 60 hours and humidity cabinet (ASTM D1748) values of more than 60 days.

h. Sheave lubrication. Sheave bearings should be lubricated periodically. Increased friction at wire rope sheaves can significantly affect the tension required to lift a given load. Lubrication points for sheaves should be in accessible locations. If this is not true for existing equipment, modifications should be considered.

8-7. Ice and Debris Removal. The presence of ice or debris in or on gates or gate equipment produces conditions of excessive stress, which in turn may cause failure of wire ropes or gate equipment. Ice may make gates impossible to move. Debris trapped in multi-line hoists can cause unequal tension in the wire ropes. Safety devices that limit rope tension can reduce the probability of such failures.

8-8. Painting. When painting is performed around wire ropes, special care should be taken to make sure that they are protected from overspray. Sandblasting of the gates, which is also typically done, can also damage wire rope. Some paint contains chlorides (and other chemicals), which may contribute to corrosion of the wire rope. It is important to cover and protect wire rope during any painting project.

8-9. Cathodic Protection. Cathodic protection is often used for gates, but is less often used for wire rope. Cathodic protection of submerged wire rope is possible while protection of wire rope in damp environments is not. The sacrificial anode method, using magnesium anodes, is recommended over the impressed current method. The anodes must be grounded to the rope socket and located close to the rope sockets.

APPENDIX A

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APPENDIX B

Engineering Case Studies

B-1. General. This appendix describes several wire rope failures at USACE civil works structures. Several recent failures have prompted the update of this engineering manual including a wire rope failure of the vertical lift gate at Mel Price lock. Wire rope failures can have a significant impact on navigation traffic or can impact the ability to open or close dam gates. Wire rope failures on a flood control dam can increase the risk of flood damage during a flood event. These case studies demonstrate the need to inspect wire rope on a regular basis as described and required in Chapter 8. As discussed in Chapter 8, a failure analysis should always be done for any wire rope that fails in service.

B-2. Case History of Failures. The following paragraphs will provide a summary of the USACE wire rope failures. The majority of these failures include an engineering report or a summary report of the failure. Table B-1, located at the end of this appendix, lists these reports and provides links to their original content.

B-3. Mel Price.

a. The upstream side of the Mel Price lock uses a multiple leaf vertical lift gate, which is lifted with wire rope (Figure B-1). This includes an upstream leaf, middle leaf, and a downstream leaf. The downstream leaf is designed with a nappe section for submergence under flowing water. Each lift gate leaf is approximately 118 ft wide by 13 ft – 6 in. high by 10 ft deep. Each leaf is designed to overlap by approximately 9 in. The approximate weight of the upstream leaf is 274,000 lbs. The approximate weight of the middle leaf is 280,000 lbs. Each gate leaf is lifted with a wire rope drum on each side with 12 parts of wire rope cable.

b. The Mel Price vertical gate and wire rope cable were originally installed in the mid- to late-1980s. On 28 December, 2013, a hoisting cable failed on the 1200-ft Main Lock of the Mel Price Lock and Dam. This was the third cable in the system that failed thereby increasing the risk above a tolerable level resulting in the closure of the main lock. All of the hoisting cables, including the counterweight cables, were originally designed as 1½ in.-diameter, Type 302 stainless steel, 6x30, Style G, flattened strand wire rope with an Independent Wire Rope Core (IWRC). Maintenance records indicate that these were replaced with galvanized wire rope in 2007. New wire rope installed after the failure in 2014 is now Type 304 stainless steel. Each wire rope was originally rated for a breaking strength of approximately 204,000 lbs. The new Type 304 stainless steel wire rope is also rated for 204,000 lbs breaking strength. Two of the 12 hoisting cables were originally designed to sustain the maximum hoist operating load, without consideration of the load reduction due to counterweighting.

c. Twelve round wire ropes, zinc cast into removable sockets at each end, connect the hoist drum to the cable connection bracket assembly mounted on the end of the gate within the monolith recess. A pair of 12-groove hoist sheaves, designed to re-direct the wire rope 180 degrees, are mounted atop the lock wall above each hoist. The wire ropes go upward from the hoist inside the lock wall, traversing a horizontal distance to the gate leaf recess, then downward to the gate.

Figure B-1. Vertical Gate Leafs with Hoist Drums in Background.

d. The failure summary, engineering report, and additional photographs are included in Documents No. 1-3 in Table B-1. A timeline of the wire rope failure (and Figures B-2 and B-3) is noted below. There are two engineering test reports also provided in this Appendix. A summary from the engineering report concluded that:

> This analysis indicates that the fractured cable section, which had undergone severe corrosive attack (Figure B-4), had ultimately (catastrophically) failed as a result of ductile overload fracture. This would indicate that the fracture had occurred due to a one-time load that exceeded the strength of the cable when the remaining (non-corroded) effective cross-sectional area could no longer support the applied loads. No evidence of fatigue fracture, which results from cyclic loading conditions, was observed. Additionally, no evidence of localized mechanical damage (due to wear or impact with foreign objects) was observed in the vicinity of the failure.
>
> The majority (approximately 80%) of the outer 6 x 36 strands/wires had undergone severe localized thinning due to corrosive attack with no evidence of mechanical fracture. It was noted that the corrosive attack had primarily occurred due to general corrosion with some possible erosion-corrosion. Additionally, it appears that the

majority of the zinc (galvanized) coating was missing due to the severe corrosive attack. The presence of primarily red rust (iron-based corrosion products) and the absence of significant white rust (zinc-based corrosion products) support this conclusion.

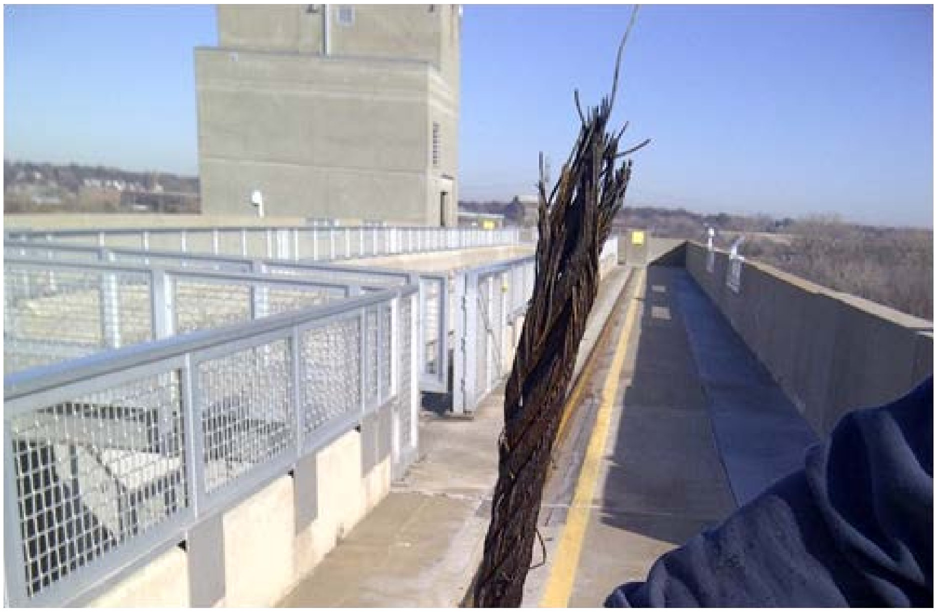

Figure B-2. Failed Cable – Failure Point Is Just above the Sockets. Must Dewater to Access.

Figure B-3. View of Cable/Socket Connection to Gate Leaf from Top of the Leaf Looking into the Slot.

Figure B-4. Close up of Corroded Wire Rope.

- June 2007. During a 45-day closure of the lock, all hoisting cables on all leafs were replaced.
- 15 Sep 2013. Hoisting cable on Missouri side of middle leaf fails. Cable is cut out and removed. Engineering Division determined there was sufficient factor of safety (5) to continue operating with just 11 cables on that side.
- 20 Dec 2013. A second hoisting cable in the same area fails. The cable is removed. Though the factor of safety is still sufficient with just 10 of 12 cables, there is concern about why two have failed. Decision is made to hire a wire rope expert to determine what is causing the failures. Section of failed cables are sent to expert for examination. Lock is put back in service.
- 28 Dec 2013. A third cable fails in the same area. Cable is removed and lock is closed indefinitely. Planning commences for emergency dewatering and inspection of all cables.

e. During the Mel Price lock initial start-up, an incident occurred in which the normal operating leaves became stuck within their slots, while almost 10 ft of hoist cable unspooled from the drum. There were no “slack cable” limit switches or hoist motor current sensors to indicate any problem, and the cables were unspooling within the machinery rooms located inside the lock walls out of operator view. When operations personnel felt the vibration in the structure from the free-fall of the gate, they stopped the hoist and investigated. On one side of the gate they found one of the hoist cables wrapped around the outside of a drum divider flange. That one cable, which for a time was supporting one half, or more, of the total gate leaf load, was permanently damaged. Before any of the potential solutions to the gate “sticking” problem could be implemented, it happened again. This time the gate stayed “stuck.” This incident drove home the severity of the safety problem that needed an immediate solution even if the occurrences were infrequent or unrelated to chamber overfill. The maintenance personnel reasoned that by carefully raising the hoist, while guiding the cables back into their drum slots, that they could "free" the gate leaf and prevent cable damage. Three independent systems were developed, which provide three levels of safety protection, to stop the hoist motors when the hoisting cables begin to "slack." The middle and last levels of protection are associated with the hoist cable system. The last level of protection is the installation of lever-type limit switches with a thin actuator rod beneath the horizontal run of the hoist cables between the hoist sheaves atop the lock wall. If the cables become slack, they sag downward to trip the limit switch.

B-4. John Day Navigation Lock.

a. Two recent failures have occurred at the John Day lock concerning the wire rope on the upstream vertical lift gate. Both engineering reports on these failures are included in Table B-1 as Documents No. 4 and 5. One failure occurred in 2002 and one failure occurred in 2008. The John Day upstream navigation lock gate is a lattice type vertical lift gate approximately 90 ft wide x 27 ft high x 12 ft deep with an upstream skin plate. The gate weighs approximately 208,000 lbs (it is somewhat buoyant in water, which reduces the load) and is operated by two hoists, one on each side of the gate. Each hoist includes a 10-foot diameter upper friction drum with four wire rope grooves and is driven by a hydraulic motor through a speed reducer gear box. The gate is suspended from four wire ropes on one side of the drum and a counterweight weighing approximately 90,000 lbs is suspended by the ropes on the other side of the drum. The wire ropes are 1½-in.-diameter, galvanized, 6 x 26 Improved Plow Steel (IPS), IWRC, regular lay ropes manufactured by Broderick and Bascom Company.

b. On 17 November 2002, the upstream gate experienced catastrophic failure of all eight wire ropes while the gate was being lowered.

(1) The wire ropes had been in service for 11 years before their failure. An independently conducted investigation concluded that undetected excessive wear and abrasion were the primary cause of the rope failure. The gate dropped 27 ft to the bottom of the gate slot and both counterweights fell to the bottom of their respective shafts. Damage to the gate included end plate and truss damage and the counterweights were deemed unrepairable. The lock gate machinery did not experience any significant damage during this incident. As a result, portions of the trusses and end plates on the gate were replaced as well as both counterweights. The gate was also stripped and painted during the repair contract as well as having all the guide wheels replaced

(2) It was noted that all eight wire ropes had failed at a distance of approximately 8 ft from the point of their attachment to the gate. This would place the points of failures on the friction drums, on the side of the gate (as opposed to the counterweight side), between the 10 and 12 o'clock position. All eight broken wire ropes exhibited similar features including:

- Severe abrasion of crown and some inner wires.
- Corrosion and lack of lubricant in failed area (approximately 8 ft).
- Evidence of wire-to-wire contact damage.
- Evidence of possible fatigue.

(3) Both friction drums were examined and found to be in similar condition. Grooves were found to contain significant amounts of corrosion products, which appeared to have come from the

wire ropes. No evidence of any significant corrosion or pitting was found on the drum itself. Also, no evidence was found of any significant wire rope impressions or corrugated groove or wear pattern on the drums. The friction drums were within the acceptable tolerances for the wire rope used.

(4) Laboratory examination of the failed wire ropes indicated that each of the six strands contained very severe wear (abrasion) at lay length intervals where the rope made constant contact with the drum when the lift gate was raised and left in raised or up position. At the abraded areas, all of the outer crown wires were severed. Many of the inner wires were reduced in section by wear and some had broken. The inner wire fractures exhibited characteristics typical of a mixed mode failure, including:

- Abrasion (wear), loss of section.
- Fatigue, square end breaks.
- Overload and cup-cone break, which were limited to the remaining intact wires, and which failed due to tension overload.

(5) The investigation concluded that wear and abrasion were the main causes of the rope failure. The wear that caused the failure was not the common wear and abrasion normally associated with the relative movements of wires and strands in the rope when loaded and moving over the drums. They were rather due mostly to small lateral movements of the ropes in the drum grooves (mainly in the upstream and downstream direction) as a result of wind and wave actions on the gate, as well as the lock vibrations when the lock filling and emptying valves are operated.

c. The John Day upstream gate and related machinery were damaged during the upstream lockage of a tug and four barges on 28 February 2008 (see Figures B-5 to B-7).

(1) While the lock was being filled, the forward barges drifted under the upstream gate. The towing knees of the barges, which are vertical posts on the end of the barges, came up inside the bottom bowstring gate truss and lifted the gate. The uplift of the barges separated the gate from its sealing surface and raised the gate above the lock sill. As the gate rose, it impacted the friction drums and components in both machinery rooms. After water levels stabilized in the lock chamber, the gate rested precariously in the guides and on the parapet wall. The gate's wire rope connection points failed during the event, which allowed both counterweights to fall to the bottom of their shafts.

(2) The wire rope lifting plates on both sides of the gate were replaced as they both were torn off the gate allowing the counterweights to fall to the bottom of their respective shafts. The north 10-foot diameter friction drum was broken off its pedestal and was perched on the pinion gear. The south friction drum was close to its original position, but the drum anchorage and pedestals were both severely damaged.

(3) Contracts were done to repair and replace damaged hoisting equipment machinery. All wire rope was replaced including the counterweight connections. Hoisting equipment machinery repairs included the north and south friction drums, ring gears, and pillow block bearings.

Figure B-5. John Day Lock Upstream Gate Sheave before 2008 Accident.

Figure B-6. John Day Lock Upstream Gate Sheave after 2008 Accident.

Figure B-7. John Day Lock Upstream Gate after 2008 Accident.

B-5. Bluestone Dam.

a. Bluestone Dam in Hinton, WV is a concrete gravity structure with a gated spillway consisting of 21 spillway crest gates. These gates are 31 ft wide and 31.5 ft high and are raised and lowered by a wire rope hoist mounted over the gate and reeved in eight parts per side as shown In Figure B-8. The machinery, gates, and wire rope were installed in 1952, making the wire rope 62 years old at the time of its eventual replacement in 2014. Over their life, the ropes had seen varying levels of lubrication, and in recent years lubrication had been minimal due to accessibility concerns. The wire rope was 1 in.-diameter, 6 x 25 filler wire, right regular lay, poly core, plow steel. The gates are only operated for exercise and only once, as a test, have been operated with water against them.

b. The ropes exhibited areas of surface corrosion and some pitting as a result of the lack of lubrication. This combined with the age of ropes raised concerns during the Potential Failure Mode Analysis/Issue Evaluation Study (PFMA/IES) and identified the ropes as one of the risk drivers for the hoist machinery. Operational Condition Assessments (OCAs) during the same period rated the ropes no lower than a “C–.” This rating is not normally low enough to elevate an item up in budget priority to facilitate funding. See the Memorandum for Record, “White Paper – Crest Gate Machinery Wire Rope Analysis” (included as Document No. 6 in Table B-1) for a more detailed sequence of events, results of testing, and conclusions (included in this appendix).

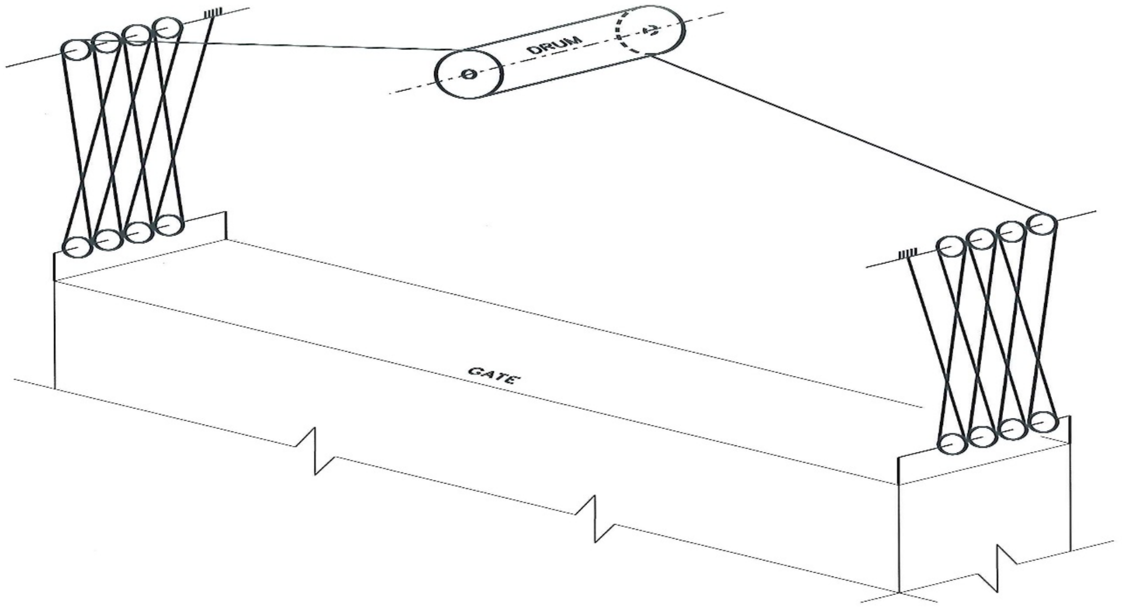

Figure B-8. Bluestone Wire Rope Reeving Diagram.

c. In an effort to resolve the conflict in the Periodic Inspection findings, which in turn provides the basis for the PFMA/IES and the OCA, it was decided to remove and replace the ropes on one gate. Samples from the removed rope were cut and sent to an independent consult for internal analysis, and other samples were cut and sent for break testing. See the Wire Rope Evaluation reports by Pellow Engineering Services, Inc. (included as Document No. 7 Table B-1) for a detailed report of the internal inspection of the rope samples. Samples from sections of the rope with both little corrosion and the most corrosion were sent for analysis. The conclusion was that the surface corrosion and pitting did not extend into the interior of the ropes and that even the rope in the worst condition had some remaining life if they could be re-lubricated. Break tests for four samples of rope all resulted in the ropes breaking at or near the minimum breaking strength for the rope of 71,000 lbs, with the lowest being 70,930 lbs. The results illustrated the difficulty in applying age based replacement criteria to components that are not operated or loaded nearly as often as might be common at other industrial facilities.

d. The results from the internal analysis and the break tests were not justification for lowering the OCA rating. However, the District as part of an ongoing effort to rehabilitate the crest gate hoist machinery to ensure future reliability, decided to procure new wire rope and install it on all 20 of the remaining gates.

B-6. Greenup.

a. The full accident report on Greenup is included as Document No. 9 in Table B-1). The wire rope was severely damaged as a result of this accident. It was determined during the investigation report that the wire rope and sheave assembly initiated the failure. On the morning of 9 August 2006, an Equipment Mechanic at Greenup Locks and Dam, on the Ohio River, was operating the 390-ton capacity bulkhead crane to raise the maintenance/emergency bulkheads. The bulkheads were fully submerged and resting on the dam sill, upstream of Dam Gate No. 3. During this bulkhead hoisting operation, a catastrophic failure occurred in the hoisting machinery. At the time of failure the crane was lifting at maximum capacity, consisting of four dam bulkheads and the lifting beam with a total load 390-tons. The failure resulted in the free fall of the bulkhead assembly, the destruction of the hoist drive machinery, and was accompanied by a fire on the hoist machinery platform. The bulkhead assembly fell approximately 13 ft. into the water and came to rest on the gate sill. A 1-in. diameter wire rope leads into a 12-part reeve hoist on the lifting beam. As a result of the accident, the hoisting cable unspooled from the four hoist drums. The wire rope cables were damaged along with their sheave blocks. See Figures B-9 and B-10.

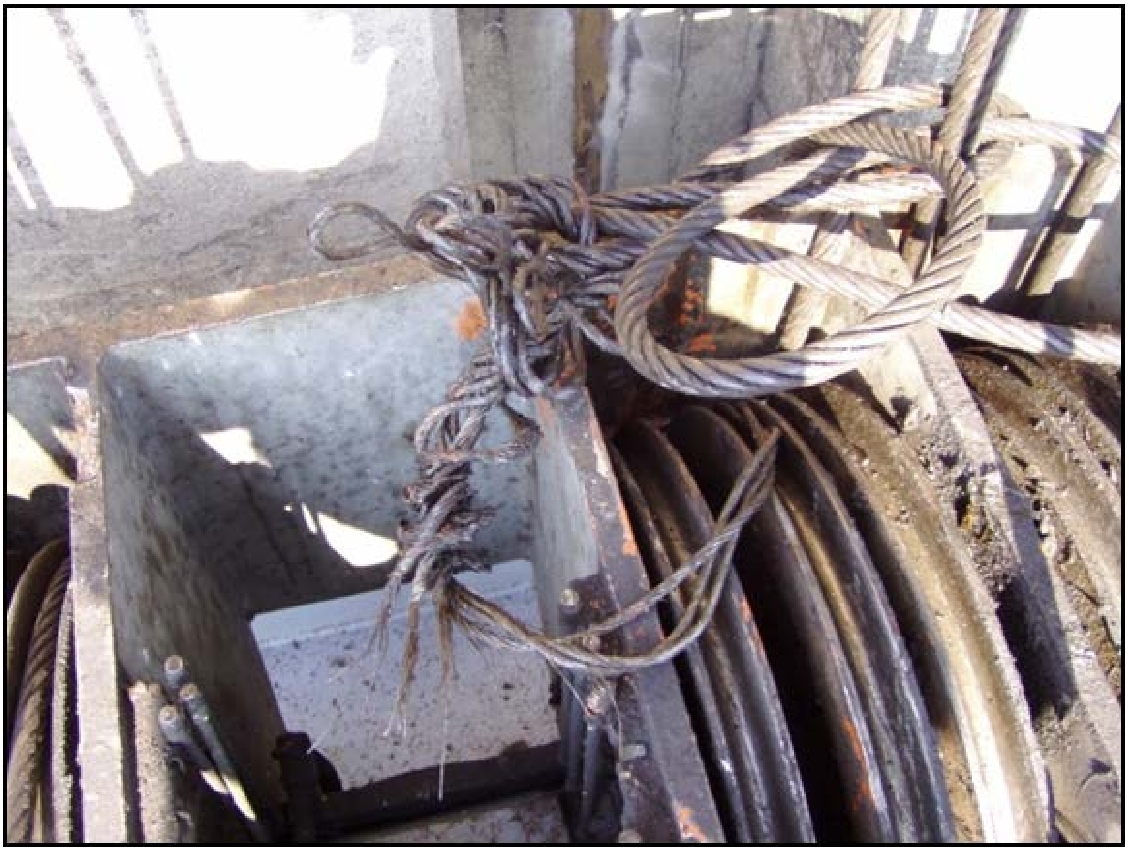

Figure B-9. Greenup Wire Rope Failure – Sheave Block.

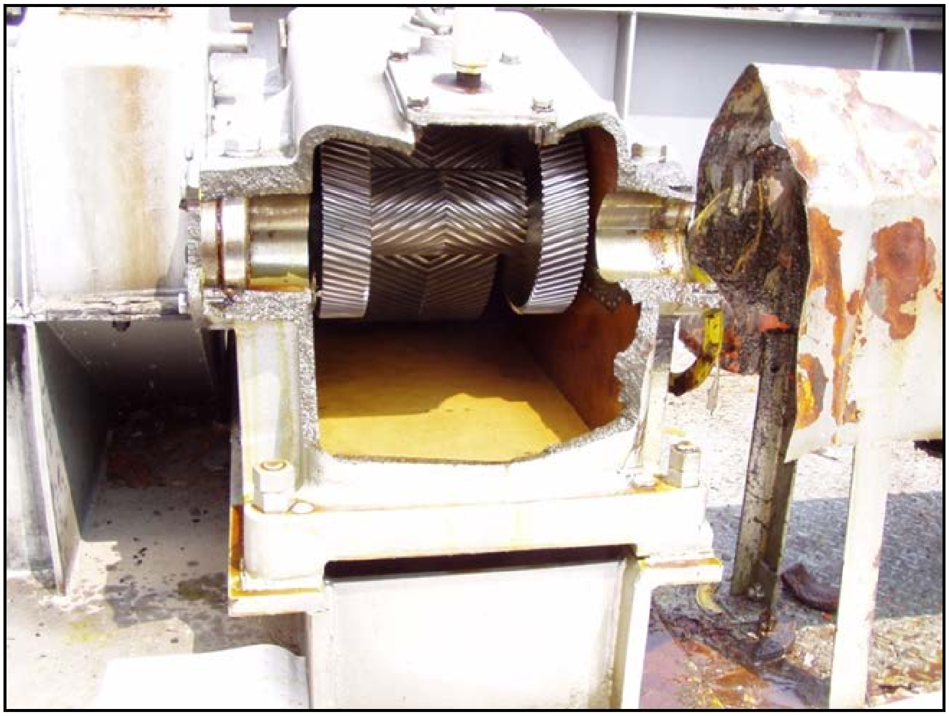

Figure B-10. Greenup Wire Rope Failure – Damaged Gear Box.

b. As the bulkhead assembly was raised and had reached a height of approximately 13 ft above the sill, one of the four hoisting wire ropes jammed in a sheave assembly on the downstream Kentucky side (another way to describe this is that binding occurred between the wire rope and sheave). At this point, there was a critical load transfer and impact load to the Kentucky side of the hoisting system. This impact load was transferred through the Kentucky side machinery components and caused the following:

- Shearing of a key in the flexible coupling connecting the Kentucky side machinery to the Cone Drive Worm Gear Reducer.
- Failure of gears within the Cone Drive Worm Gear Reducer, (single tooth on the worm, all of the teeth on the bronze worm gear). This resulted in a fire in the gear box.
- Tripping of the overload relay in the control circuit for the hoist motor causing the motor to stop and the brake to set.
- Free fall of the bulkheads.

c. This bulkhead crane and all of its components, including the wire ropes and the lifting beam, were original equipment and were 45 years old at the time of the accident. The crane was designed in 1960 according to the design standards of the time. The hoisting machinery was specifically designed to lift the total weight of all four of the dam bulkheads as well as the lifting beam (total load 390-tons). The load of the bulkheads and lifting beam is equally shared by four 12-part sheave blocks. The wire rope used on the crane is a 1-in.-diameter, 6x37, IPS with an independent wire rope center and has a breaking strength of 49.1 tons and provides a safety factor 5.4 based on the rated load.

d. Kentucky Side Downstream Sheave and Wire Rope. The full investigation report concluded that:

> The damage and multiple modes of failure of the wire rope connected to the Kentucky Side Downstream Sheave assembly makes it nearly impossible to determine the exact cause and location of binding of the wire rope in the sheave nest. The wire rope was well lubricated and showed no sign of internal deterioration, reduced diameter or stretch in the lengths of the rope that were loaded and that had traveled through the sheave nests. It is suspected that wire came out of the lower sheave nest and may have been passing in between the first and second sheave traveling on the spacer. Even with the physical evidence on these sheaves and spacer, there is no way of determining when the wire rope left the sheave. The overall consensus of the Board, however, is that there is enough evidence to conclude that the failure began with the binding of this wire rope and sheave assembly.

B-7. Lockport.

a. A failure of the wire ropes on the vertical lift gate occurred in 2012. Figure B-11 shows the Lockport wire ropes and sheave in the vertical lift gate. Documents No. 10 to 14 included in Table B-1 show the wire rope failure (including multiple photos). An engineering report on the failed wire rope is included in this appendix also. Documents showing the testing of the new wire rope and socket assembly are also provided. One issue with this site and all the lock sites on the Illinois Waterway is the high pollution and waste and sewage from the City of Chicago that is in the water, which contributes to the corrosion of the wire rope. The original wire ropes were 1½ in., 6X36, stainless steel and installed in 1985. There are seven ropes per side of the service and emergency vertical lift gates. The original ropes experienced severe wire breakages and were replaced with in-kind stainless steel in 1994. The second set of wire ropes also experienced severe wire breakages. The lock and Operations staff in Rock Island were dissatisfied with the life of the stainless steel so they replaced the stainless with galvanized Extra Improved Plow Steel (EIPS) in 1998 to see how it would perform. The EIPS steel only lasted a few years due to severe corrosion and was replaced with Stainless Steel around 2001. The wire ropes were replaced again in 2010 and galvanized wire rope EIPS was again used.

b. The wire ropes were not lubricated (the stainless wire rope) in the early years or properly tensioned, which probably contributed to the less than expected life. The lock site has since started lubricating the ropes and installed load pins to more easily monitor the tension between the ropes. Since this change, the ropes have had a longer life. A lessons learned for other sites is to conduct water quality samples to gauge the amount of corrosion potential of the water and the amount of pollution in the water.

Figure B-11. Lockport Wire Ropes and Sheave – Vertical Lift Gate.

c. In August 2012, the service gate right side (facing downstream) wire rope failed causing the right side of the gate to drop and lodge in the gate slot (see Figure B-12). The engineering report noted that:

> The wire failures at the rope failure area were further examined. The failure area was cleaned in a solvent tank to remove any excess lubrication that was present and apparent in Picture 7. This lubrication appeared to be transferred onto the rope from another source. The wires in the failed strands and the failed wires exhibited a significant amount of pitting corrosion and crevice corrosion in the strand to strand and strand to core contact, Figure 15. These areas showed significant loss in cross sectional area. Some wires had the entire cross section corroded through. The lack of internal lubrication was present in this area of the rope. A loss of ductility was present in the wires that had been subject to severe corrosion, Figure 16.

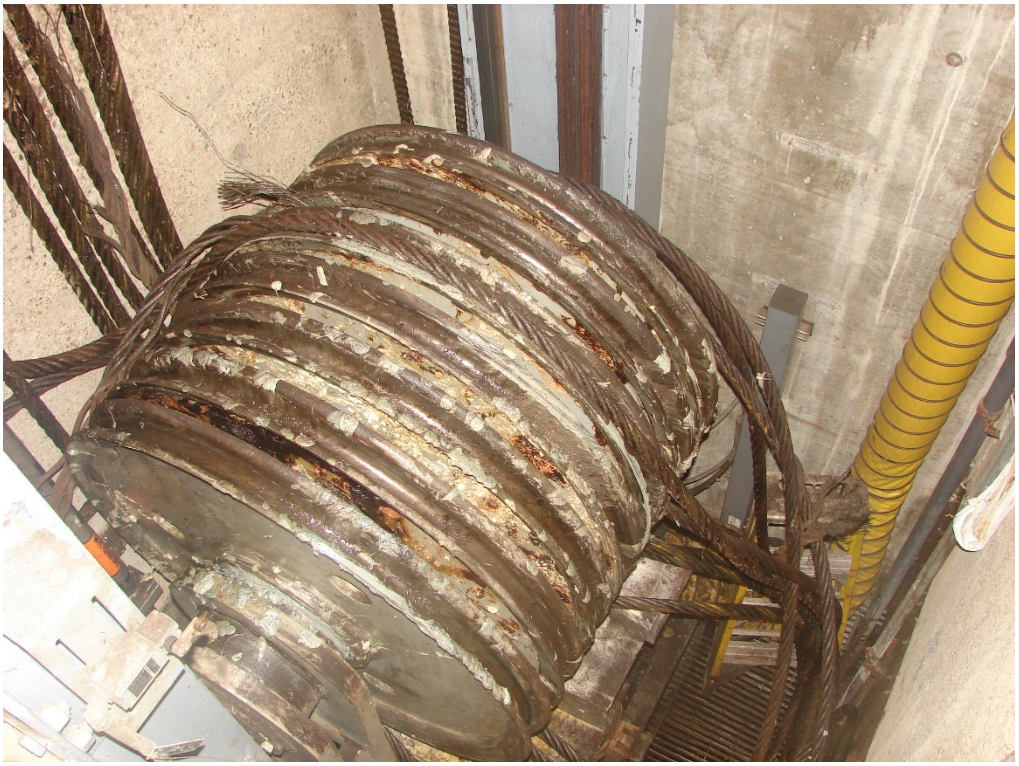

Figure B-12. Lockport Wire Rope Failure 2012.

d. The engineering report concluded that:

> Corrosion was present for approximately 12 ft of the assembly and was isolated to one end. The corrosion in this 12 ft varied with areas of slight to some corrosion to areas of severe corrosion. The areas exhibiting the most severe corrosion could be associated with the splash zone or oxygenate portion of the water when submerged. This portion of the water environment has been shown to be a more active corrosive environment. The line of wear and abrasion present on the assembly would indicate the rope coming into contact with an object in the rope system. This could also be attributed to sheave alignment or a worn sheave. Periodic inspection of the entire rope during service could have resulted in early detection of excessive wear, broken wires and corrosion before the failure. The condition of the rope indicates the numerous broken wires, and high amounts of corrosion were present before the failure. The failure occurred at 10 ft from the socket. Recoil from the failure was present at 6 ft, 8 in. from the socket to the failure and was only present on onside of the failure. This could an indication that one side of the failure was restricted or support. This could be an indication the failure occurred at the tangent point on a sheave. The wire failures were the result of a combination of corrosion, wear, and the effects of corrosion on the wire performance. The pitting, reduced cross sectional area, and corrosive action on the wire would have affected the ductility of the wires and decreased the strength. No broken wires were present in the assembly away from the corroded length.

e. After the 2012 failure, the service gate wire ropes were replaced with stainless steel. The emergency gate wire ropes were replaced with stainless steel in 2015. A couple of other items were noted regarding the Lockport wire rope failures. The site has had issues with foreign wire rope suppliers. Several times, suppliers had bought the wire overseas and then assembled the wire rope in the United States.

B-8. Benbrook Dam.

a. This site is a flood control dam in Texas and the wire rope failure occurred during a flood event. On Wednesday, 10 June 2015, the Lake Manager began opening the Benbrook Dam service gates. While operating Service Gate 1, he heard a loud pop and water/oil started to spew from the cable hoist system. He then shut down the cable hoist system and noticed one of the wire ropes had loosened and began unspooling from the sheave block. Fixing the gate was critical due to the flooding situations in the Trinity Region. The service and emergency gates at Benbrook Dam are cable-hoisted tractor type roller gates. The cable system consists of an electric motor, a cable drum and two sheave blocks, one permanently attached to the gate and the other attached to the cable-hoist platform. The wire rope referenced in the Operations and Maintenance manual is a 6x19 IWRC, regular right lay, IPS. The cables were previously replaced in 1997 so they had been in service 18 years. The Dam Safety Incident Response Situation Report is included as Document No. 15 in Table B-1.

b. The drum/sheave arrangement gives the cable a 10:1 lifting ratio advantage. The upper sheave block has four sheaves and the lower has five sheaves. The diameter of wire rope specified in the O&M manual is 1 in. and the sheave pitch diameter is 27 in. The maximum required lifting force is 210,000 lbs (210 kips), which includes the approximate weight of the gate; 22,000 lbs.

c. Immediately after the failure and on first observation of the cable hoist system, water and lubricant were observed on the cable hoist platform and service deck floor. Two sheaves on the sheave block were missing wire rope. Personnel on site suspected that the wire rope had snapped and Service Gate 1 fell into the closed position. To test this theory, Service Gate 2 was lowered to the closed position to detect changes in flow rates. No flow was observed exiting the conduit into the stilling basin after gate closure, which proved that Service Gate 1 closed. The water and lubricant observed on the deck were from the cable snapping and unspooling from the sheaves at a fast rate.

d. After a contract was awarded for wire rope replacement; the Contractor recovered the snapped portion of the rope and it was found that it failed due to corrosion. The wire rope selected for immediate replacement was AISI 304 stainless steel, nominal 1-in. diameter; with a nominal tensile capacity of 85,400 lbs. The wire ropes were replaced on Service Gate 1 and 2, and the emergency gate overhead crane. The wire ropes used were fabricated in South Korea, which caused concern regarding the quality control used in fabrication. Wire ropes were tensile tested in accordance with ASTM A931 to verify their strength. The Contractor who replaced the wire ropes saved test portions from each spool.

B-9. Red Rock Dam.

a. This is a dam in Rock Island District. The wire ropes failed during the 1993 flood event. The full engineering report is included as Document No. 16 in Table B-1. Wire rope cables are 6x30 flattened strand, IWRC. Minimum breaking strength noted as 49.6 tons.

b. The failure analysis of the wire rope indicated that:

> The inside cable at the south end of the cable fractured near the gate connection. The cables were observed to be subject to vibration during high water, and at least 6 ft of the cable was under water due to the increase in pool depth. The fracture was observed to have occurred close to the connections to the gate. The results of the visual examination of the cable and the end socket indicate that the cable was severely rusted and abraded. Photographs taken at the four foot interval above the socket shows extensive corrosive damage on all four cables. The wires on the exterior layer are broken and rusted through and in many areas all four cables exhibited the same damage. Severe cable damage was noted on two cables, at 10 to 12 in. above the socket.

c. A conclusion of the engineering report is summarized as:

> The wires on the cables shown in Figures 1 through 4 display what visually appears to be only slight corrosive damage. However, on closer examination of the cables the individual strands were severely corroded and they exhibited severe metal loss and breakage. The most severe abrasive losses and fractured wires are approximately 10 to 12 in. above the socket. This coincides with the steel guide welded to the gate. It is concluded that the main cause of failure is due to the corrosion and erosion phenomena. This process consists of the formation of a corrosion residue on the surface (rust that is subsequently removed by abrasion against the metal guide and adjacent wires). This exposes the surface, which then starts to corrode and to build up more residue, which is also subsequently removed. The cycle continues until the wire fractures from the high bending stresses or tensile stresses due to the severe loss of metal. The paint on the cables is most likely a vinyl chloride based paint that will leach out some chlorides. These chlorides will attack the unprotected surfaces of the cable (See Figure 3). The crevice between the strands is an ideal spot for corrosion to occur. The presence of chlorine and calcium carbonate in the water results in a more rapid corrosion of the wires.

B-10. R.C. Byrd Failure. R.C.

a. R.C. Byrd has two parallel locks, a main lock 110 x 1200 ft, and an auxiliary lock 110 x 600 ft, both with miter gates. An emergency gate (Figure B-13) is included upstream of the upper miter gates in both locks. The emergency gate consists of a two-leaf vertical lift gate that is normally stored on the lock floor behind a concrete sill. Essentially, there is an upstream leaf and a downstream leaf. The downstream leaf uses a 16-part wire rope sheave system (see Figure B-14). The primary purpose of these vertical lift gates is to provide emergency closure, but they are also used to pass ice or flush silt from the chamber. The locks were activated on 30 January 1993. In January 1994, the wire rope on the auxiliary lock (downstream leaf) emergency gate failed. This put the lock out of commission. It also resulted in an open river condition with 3 ft of water going over the gate. The river was at a high water condition and the lock was also passing ice. The build-up of ice on the wire ropes caused the wire rope to jam in the gate sheave. This overloaded the wire rope and caused the wire rope to break.

b. On 22 January 1994, at approximately 11:40 p.m., the wire rope on the land wall side of the auxiliary lock emergency gate (downstream leaf) broke. At the time of the rope failure, the gate was being used to pass ice. The gate was being lowered back down to the ice passing position after having been raised to minimize approach conditions affecting tow entry into the main lock. After the rope failed, the gate dropped down on the land wall side about 1.83 ft and wedged in the recess. In the wedged position, the gate crest was about 5.5 ft under water and it was estimated that about 13,000 cu ft/second was being passed over the gate. This prevented the closure of the miter gates, however, there was no real concern for loss of pool.

Figure B-13. R.C. Byrd Vertical Lift (Emergency) Gate.

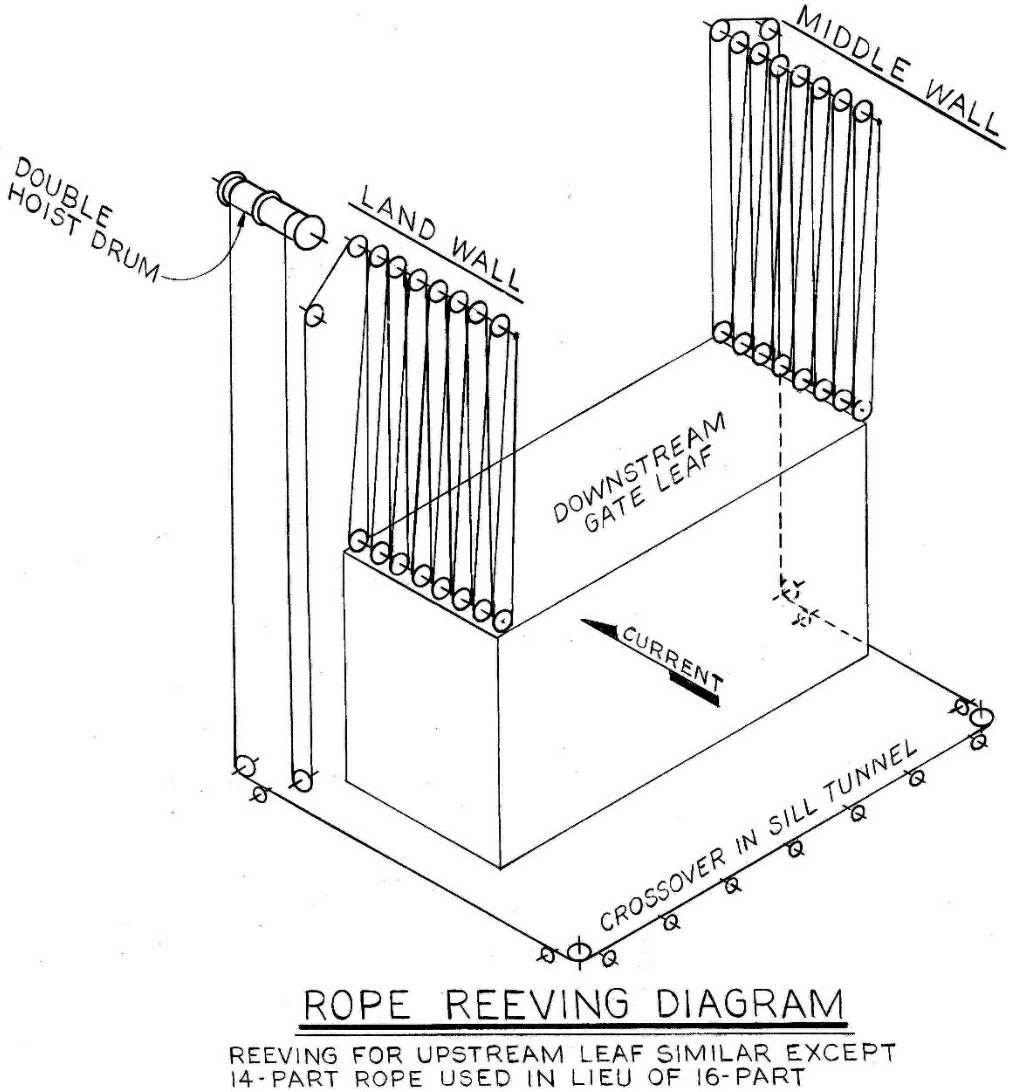

Figure B-14. R.C. Byrd Reeving Diagram for Emergency Vertical Lift Gate.

c. Some field notes for this failure at R.C. Byrd were obtained. The lock operator indicated that he had been operating the gate and that, to improve approach conditions to the lock, they would raise the gate above the ice passing elevation to allow easier tow entry and then return the gate to the lower ice passing elevation. In doing this, he was operating the gate down 1 ft at a time, stopping and checking the cables for tension and then going down another foot. After he stopped the gate after lowering for a third time increment, he heard a noise and saw that the rope had broken and the gate had dropped down on one side.

d. The following is excerpted from field notes:

> It was observed that five pairs of ropes were still hanging across the upper sheaves. They appeared to be tangled in the recess where they were on the gate sheaves. The gate sheaves were not visible. There was a large amount of ice in the recess. Sections of the rope had large pieces of ice attached. These pieces of ice appeared to be

approximately 4 to 5 in. in diameter at the top and decreased in diameter down the rope in a somewhat conical shape. There was a considerable amount of water entering the recess from holes in the trash screen, which made observation difficult. We then climbed up into the hoist house on the landwall side and inspected the machinery. Everything looked pretty much normal except there was no rope on the two upstream sheaves. There were scratches in the frost on the sheave, which indicated the broken rope had passed through the sheave. The condition of the upper sheave nest appeared normal except for the lack of the two ropes. Everything appeared normal with the hoist machinery. There were ice shavings on the floor in the pier house on the lockward side of the sheave beam. The quantity did not appear sufficient to indicate that anything other than light coating had occurred. (Temperature in the pier house was below freezing).

We then went to look at the main lock emergency gate rope recess. This hoist had not been operated during the recent ice conditions and to pass ice. The recess was a solid sheet of ice. We shook the ropes but could not move them enough to break the ice around them. We then went to look at the middle wall pier and machinery for the auxiliary lock gate. Everything appeared normal with the same type and amount of ice shavings on the pier house floor and sheave support beam as observed on the other side.

e. During the analysis of the failure, the lock staff indicated the auxiliary lock emergency gate was operated from the middle wall. The operator indicated he had raised the gate and after pushing stop. The gate stopped, but he noticed that there appeared to be some small amount of slack in the two upstream hoist ropes. Then there was a loud noise and jerk in the ropes. It would appear that this side of the hoist had also jammed at some point within the sheave nest, just prior to the sheaves nearest the anchor.

f. The investigation focused on the fact that, when the gate is lowered, if something should cause a rope to bind at a sheave or some other obstruction, then the only ropes carrying the load will be those from the point of binding to the anchor. If the binding occurs near the anchor, only a few ropes may be left to carry the load. In this case, the higher value force control switch should act to stop the hoist by virtue of the fact that it is in the main contactor circuit. This same problem can also occur on raising, but in this case, the ropes from the point of binding to the anchor would not carry the load and consequently both force control switches would be ineffective for operation in the direction in which they were intended to provide protection. In this case, a low tension force control switch would have been useful in sensing this condition. Modern load cells can be programmed to sense multiple set points including high and low tension.

B-11. Other Failures.

a. Whittier Narrows (LA District) dropped a counter-balanced Tainter gate due to a wire rope that failed at a swaged block connection. The wire rope was severely corroded.

b. Walla Walla District experienced a wire rope failure at Little Goose Lock and Dam (Figure B-15). The failure involved a 1-in. diameter plastic (Tuff-Kote) coated wire rope for the upstream navigation lock Tainter gate. The wire rope failed at the gate connection that cycles between submerged and dry conditions. The failure occurred at the rope and socket interface. The lesson learned from this failure is that special care needs to be taken during the potting process to protect any exposed wires.

Figure B-15. Little Goose Lock and Dam Wire Rope Failure.

c. At Dworshak Dam in Idaho, a wire rope failure occurred on a flood control rolling gate, i.e., a regulating outlet gate penstock gate (vertical gate). This caused the wire rope to completely unspool.

d. In the Portland District in 2009, a wire rope failure occurred at two of three gates at Big Cliff, which led to an emergency wire rope replacement.

e. Document No. 17 included in Table B-1 contains the full text of a relevant related article title, "Extended Field Testing of Stainless Wire" (Paret 1960).

Table B-1. Reports on Wire Rope Failures at USACE Locks and Dams.

No.	Location	Report
1	Mel Price Lock and Dam - Alton IL	Wire Rope Failure Storyboard (30 Jan 2014)
2	Mel Price Lock and Dam - Alton IL	Failure Analysis (Wire Rope Failure Final Report from Testing Lab, 14M0018-1)
3	Mel Price Lock and Dam - Alton IL	Wire Rope Failure Photos with Final Testing Report (14M0018-2)
4	John Day Navigation Lock	John Day Navigation Lock Upstream Lift Gate Wire Rope Failure Investigation Report (2003)
5	John Day Navigation Lock	John Day Navigation Lock Upstream Lift Gate Repairs 2008 Letter Report
6	Bluestone Dam, Hinton, WV	White Paper – Crest Gate Machinery Wire Rope Analysis (23 April 2014)
7	Bluestone Dam, Hinton, WV	Wire Rope Evaluation for US Army Corps of Engineers Huntington District (April 2014)
8	Marmet Lock and Dam, Marmet, WV	Pellow Report Wire Rope Socket Installation
9	Greenup Lock and Dam	Bulkhead Crane Accident Final Report
10	Lockport Lockport Lock and Dam, Grafton, IL	Wire Rope Failure – Lockport Lock – Upper Vertical Lift Gate – Date of Failure 23 June 2012 – Draft Raymond W Martin (Revised 12 July 2012)
11	Lockport Lockport Lock and Dam, Grafton, IL	Wire Rope Failure – Lockport Lock – Upper Vertical Lift Gate – Date of Failure 23 June 2012 – Draft Raymond W Martin (Revised 17 July 2012)
12	Lockport Lockport Lock and Dam, Grafton	MacWhyte Wire Rope Engineering Report: IL Upper Vertical Lift Gate Failure, Failure Analysis (426-199935-1)
13	Lockport Lockport Lock and Dam, Grafton, IL	Wire Rope Prestressing and Installing Sockets (07 November 2012) Worldwide Wire Co., St Joseph MO, Raymond W. Martin

Table B 1. Reports on Wire Rope Failures at USACE Locks and Dams (Continued).

No.	Location	Report
14	Lockport Lockport Lock and Dam, Grafton, IL	Wire Rope Testing Results – Destructive Testing (19 October 2012) Worldwide Wire Co., Sedalia MO, Raymond W. Martin
15	Benbrook Dam	Dam Safety Incident Response Situation Report (Benbrook Dam)
16	Red Rock Dam	Failure Analysis of the Red Rock Tainter Gate Cables (1993)
17	General Information	Extended Field Testing of Stainless Wire

APPENDIX C

Calculations

C-1. Derivation of Sheave Friction Tension.

a. Discussion.

(1) This appendix will show the derivation of Equation 4-3 in Chapter 4, which is for dynamic rope tension caused by sheave friction. This derivation will assume the rope is engaged on the sheave (see Figure C-1) for 180 degrees. This is a conservative approach as it will provide for the largest reaction force on the sheave bearing. The free body diagram (Figure C-2) can be revised to account for a different angle if desired.

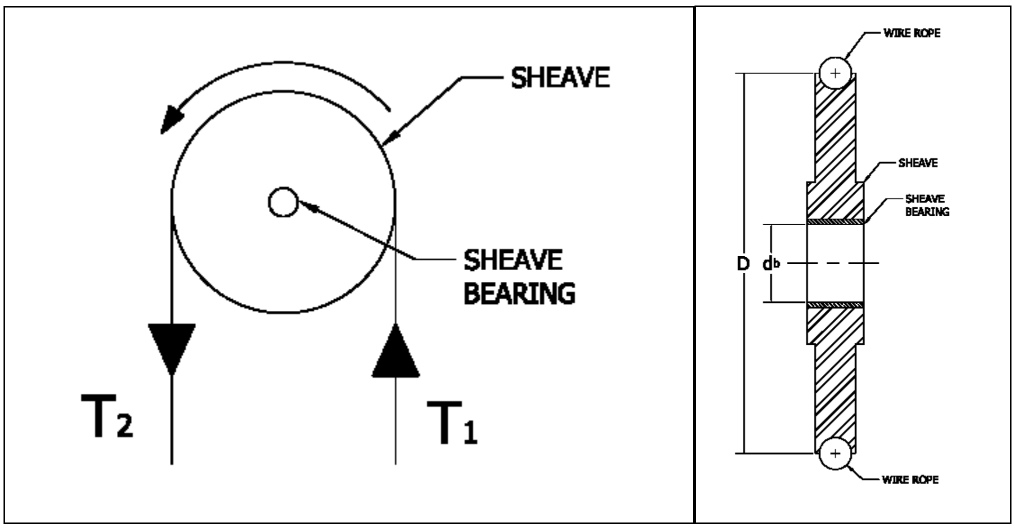

Figure C-1. Sheave Diagram.

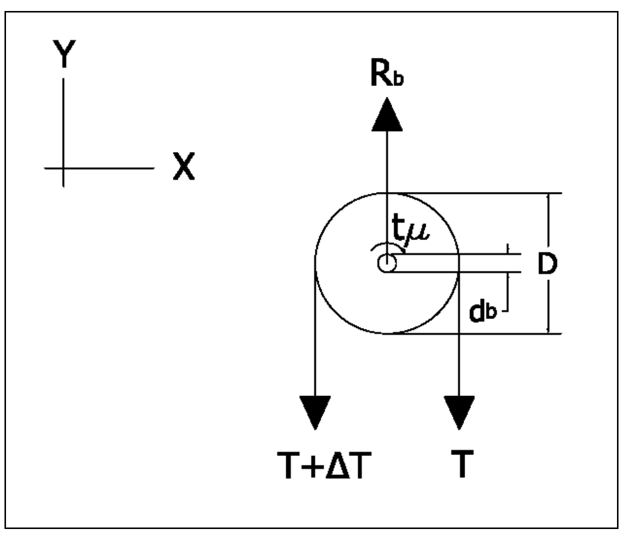

Figure C-2. Sheave Free Body Diagram.

(2) The terms in Figure C-2 are defined as follows:

R_b = sheave bearing reaction force.
T = static rope tension.
ΔT = tension increase due to sheave bearing friction.
μ = sheave bearing friction.
t_μ = torque to overcome sheave friction.
D = sheave pitch diameter (centerline diameter of rope running over sheave).
d_b = sheave bearing diameter.

b. Derivation.

(1) Summing forces along the Y-axis obtains:

$$R_b = T + (T + \Delta T) = 2T + \Delta T \qquad \text{Eq C-1}$$

(2) Summing moments around the center of the sheave obtains:

$$(T + \Delta T)\frac{D}{2} = t_\mu + (T)\frac{D}{2} \qquad \text{Eq C-2}$$

(3) It is now possible to write an expression for the torque needed to overcome sheave friction. This is equal to the force of friction multiplied by the bearing radius:

$$t_\mu = R_b(\mu)\frac{d_b}{2} = (2T + \Delta T)\mu\frac{d_b}{2} \qquad \text{Eq C-3}$$

(4) Substituting Equation C-3 into Equation C-2 and solving for DT, the tension increase to overcome the sheave friction is found to be:

$$(T + \Delta T)\frac{D}{2} = (2T + \Delta T)\mu\frac{d_b}{2} + (T)\frac{D}{2} \qquad \text{Eq C-4}$$

$$T\frac{D}{2} + \Delta T\frac{D}{2} = 2T\frac{\mu(d_b)}{2} + \Delta T\frac{\mu(d_b)}{2} + T\frac{D}{2} \qquad \text{Eq C-5}$$

$$\Delta T\left(\frac{D}{2} - \frac{\mu(d_b)}{2}\right) = T\mu(d_b) \qquad \text{Eq C-6}$$

$$\Delta T = T\left(\frac{2\mu(d_b)}{D-\mu(d_b)}\right) \qquad \text{Eq C-7}$$

(5) It is now possible to write the expression for the dynamic rope tension:

$$T + \Delta T = T + T\left(\frac{2\mu(d_b)}{D-\mu(d_b)}\right) = T\left(1 + \frac{2\mu(d_b)}{D-\mu(d_b)}\right) \qquad \text{Eq C-8}$$

(6) Simplifying Equation C-8 yields:

$$T + \Delta T = T\left(\frac{D-\mu(d_b)}{D-\mu(d_b)} + \frac{2\mu(d_b)}{D-\mu(d_b)}\right) \qquad \text{Eq C-9}$$

$$T + \Delta T = T \left(\frac{D+\mu(d_b)}{D-\mu(d_b)}\right) \qquad \text{Eq C-10}$$

C-2. Sample Problem 1: Spillway Tainter Gate.

a. Problem Description.

(1) Discussion. When designing a wire rope hoist system for a set of new spillway Tainter gates, the hoist system will use a disk layered drum similar to that shown and discussed in Chapter 4. The overall hoist system is shown in Figure C-3. The wire ropes will run along the upstream skin plate and connect via speltered bridge sockets near the bottom of the gate. This sheet will cover the considerations for selection of the wire rope for this system.

(2) Frequency of Operation. The gates are expected to operate approximately once every 10 years to pass flood events. The gates are also cycled (fully raised and lowered) annually for periodic maintenance.

(3) Service Life. Based on an evaluation of Engineering Regulation 1110-2-8159, the design service life of the mechanical hoist system has been determined to be 50 years.

(4) Operating Environment: The ropes are exposed to the forebay reservoir. The reservoir is fresh water. The forebay pool is high enough to submerge the gates/ropes during the summer months when the pool is raised for irrigation. The pool is lowered in the winter months to accommodate flood and rain events. The ropes are submerged by the forebay approximately 6 months of the year.

b. Failure Mode Evaluation. To select an appropriate wire rope, it is important to understand the most likely failure mode(s). As discussed in Chapter 4, it is typically best to select a rope type based on resisting the predominant failure mode. The potential failure modes are evaluated below based on the known problem information.

(1) Abrasive Wear. The rope runs along the skin plate is spooled onto the drum. The rope does not run through sheave or block assemblies. In addition, the ropes experience relatively few operational cycles. Therefore, the potential for abrasive wear is very low.

(2) Fatigue. The gates are expected to operate approximately once per year. This results in a very small amount of operational cycles over the lifecycle of the hoist system. Therefore, there is little to no potential for a fatigue failure.

(3) Excessive Stress. Excessive stress can be caused by loads delivered by the hoist system, operating loads, or environmental loads. The wire ropes will be sized for the maximum load the hoist can deliver. There is no down pull or unknown operating loads that will contribute to rope tension. The determination of required hoisting loads accounts for environmental factors (wind, wave loads, ice, etc.). Therefore, the determination of design loads adequately accounts for excessive stress.

(4) Corrosion. The ropes will be submerged or exposed to a fresh water marine environment for their full life. Therefore, there is a large potential for corrosion. Corrosion will be the predominant failure mode for the wire ropes.

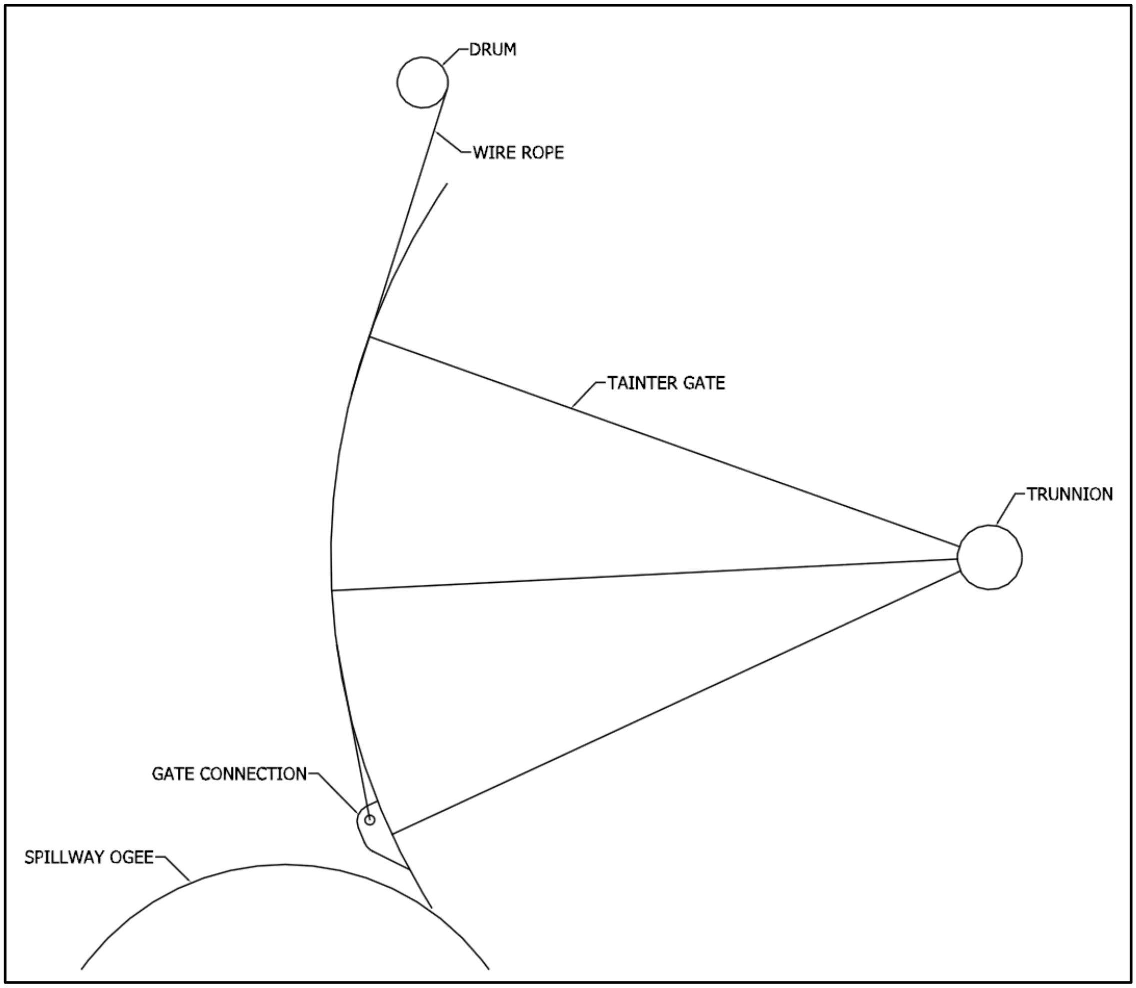

Figure C-3. Sample Problem – Tainter Gate.

c. Initial Selection Considerations. Wire ropes for gate operating devices have specific selection considerations. These are discussed in Chapter 4.

(1) Core Type. Due to improved crushing resistance, higher strength, and higher durability independent wire rope core (IWRC) ropes must be used on gate operating devices. Solid core ropes are also acceptable on small ropes. Therefore, select ropes with an IWRC.

(2) Material. Corrosion has been identified as the predominant failure mode. Bright finished ropes should not be used. Therefore, limit rope materials to either galvanized or stainless steel ropes.

(3) Wire Size. There is a low potential for fatigue and abrasive wear. There is a high potential for corrosion. Therefore, if non-stainless steel ropes are selected, the wire size should be large enough to prevent corroding through a small wire size.

(4) Rope Diameter. Availability benefits can be realized if a standard rope diameter is selected. Therefore, start by assuming a 1-in. diameter rope. This size selection will be checked later to confirm it is a reasonable choice.

d. Known Loads.

(1) Normal Operating Rope Tension. This is the tension all the wire ropes on the gate need to deliver to operate the gate under the worst case normal operation. Per EM 1110-2-2610, the normal operating rope tension is found by creating a free body diagram of the gate and applying operating loads including gate weight, ice and mud loading, hydro forces, seal friction, trunnion friction, wire rope tension, etc., then summing moments and forces to solve for the rope tension. The normal operating rope tension will be referred to as Load Case A (LCA).

$$T_{LCA} := 165 \text{ kip}$$

(2) Maximum overload tension. The maximum overload tension is found by assuming the gate is jammed and the maximum motor torque is applied to the hoist system. (Note that this value is a function of the motor and any torque limiting devices in the system.) This overload condition will be referred to as Load Case B (LCB) and for this example is as follows:

$$T_{LCB} := 270 \text{ kip}$$

(3) Maximum LCB overload tension per side of the gate. Per the requirements of EM 1110-2-2610, Section 9-2m(5)(c), designers should design spillway Tainter gate systems that have one motor driving separate drums with an assumed 70/30 load split between the drums. The following tensions are the design overload rope tensions for the 70% and 30% load sides respectively:

$$T_{LCB.70} := 0.70 \cdot \left(T_{LCB}\right) = 189 \cdot kip$$

$$T_{LCB.30} := 0.30 \cdot \left(T_{LCB}\right) = 81.0 \cdot kip$$

e. Total Required Strength.

(1) Normal Loading (LCA) Criteria. Per Chapter 4, the normal operating tension factor of safety must be at least 5.0 based on the rope minimum breaking strength.

(2) Overload Criteria (LCB). Per Chapter 4, the maximum tension factor of safety must not exceed 70% of the rope nominal breaking strength (factor of safety of 1.43). In addition, per EM 1110-2-2610 Section 9-2m(5)(c), it is assumed the maximum overload condition has a load distribution of 70/30 between sides of the gate.

(3) Total breaking strength (sum for all ropes) required under LCA.

$$S_{B.LCA} := 5 \cdot \left(T_{LCA}\right) = 825 \cdot kip$$

(4) Total breaking strength (sum for all ropes) required under LCB. The 70/30 load sharing could occur on either side of the gate. Each sides will be sized to handle a 70% loading condition. Therefore, the 70% load value for one side is multiplied by two to find the total rope strength required.

$$S_{B.LCB} := 2\left(\frac{T_{LCB.70}}{0.70}\right) = 540\ kip$$

f. Option 1 – 6X19 Class, 6X26 WS, IWRC, EIPS, Galvanized. Based on the considerations above a 6x19 class rope will be the best of the commonly available ropes. The wire size for a 6x19 class (relative a 6x36 class) is larger which is ideal for corrosion. The disadvantage of larger wire sizes is reduced fatigue performance. Fatigue has not been identified as a concern so the larger wire size should not impact performance.

(1) Minimum breaking strength of 6x19 class, IWRC, EIPS, bright finished rope (ASTM A1023, Table 10).

$$\mathrm{BS}_{6x19} := 103.4\ kip$$

(2) Breaking strength with galvanizing reduction. Per the note at the bottom of ASTM A1023, Table 10, the breaking strength of galvanized rope is 10% lower than bright rope. This strength reduction is typical for most galvanized ropes.

$$BS_{6x19.gv} := 0.90\cdot\left(BS_{6x19}\right) = 93.06\cdot kip$$

(3) Breaking strength with curved surface reduction. The ropes are wrapped onto the wire rope drum that is the smallest diameter the ropes are wrapped over. As discussed in Chapter 4, wrapping a rope over a curved surface causes an uneven load distribution across the rope and a corresponding strength reduction. The drum will be designed in accordance with the Wire Rope User Manual D/d ratio recommendation. The D/d ratio for 6x26 WS construction rope is 30/1. Per Wire Rope Users Manual, this D/d ratio results in a reduction to approximately 94% of the straight line strength.

$$\mathrm{BS}_{6x19.gv.c} := 0.94\left(\mathrm{BS}_{6x19.gv}\right) = 87.48\cdot \mathrm{kip}$$

(4) Total ropes required to meet LCA and LCB:

$$\frac{S_{B.LCA}}{BS_{6X19.gv.c}} = 9.413 \quad \frac{S_{B.LCB}}{BS_{6X19.gv.c}} = 6.173$$

(5) Summary. Load Case A governs. Ten 1-in. diameter, 6x19 class, 6x25 FW, EIPS, IWRC, galvanized wire ropes (five per side) would be required to meet the design criteria for LCA and LCB. The galvanized wire ropes would resist corrosion, but may need to be replaced at less than the 50-year design life if corrosion becomes significant. The wire ropes must be inspected on a regular basis.

g. Option 2 – 6X19 Class, 6X25 FW, IWRC, Stainless Steel. Stainless steel rope will have a better corrosion resistance over a galvanized rope; 6x19 class ropes are typically readily available in stainless steel.

(1) Minimum breaking strength of 6x19 class, IWRC, stainless steel rope (FS RR-W-410, Table 4-4. Note, ASTM A1023 does not cover stainless steel wire rope).

$$BS_{6x19.ss} := 83.3kip$$

(2) Breaking strength with curved surface reduction. As discussed above, a strength reduction is experienced from wrapping the rope over the drum. Per the Wire Rope Users Manual, the D/d ratio for 6x25 FW construction rope is 26/1. This D/d ratio results in a reduction to approximately 93% of the straight line strength.

$$BS_{6x19.ss.c} := 93\%\left(BS_{6x19.ss}\right) = 77.47 \cdot kip$$

(3) Total ropes required to meet LCA and LCB:

$$\frac{S_{B.LCA}}{BS_{6X19.ss.c}} = 10.649 \quad \frac{S_{B.LCB}}{BS_{6X19.ss.c}} = 6.971$$

(4) Summary. Again, Load Case A will govern. Eleven ropes are required. However, the same number of ropes must be used on each side. Therefore, select 12, 1-in. diameter, 6x19 class, 6x25 FW, IWRC, stainless steel ropes (six per side) to meet the design criteria for LCA and LCB. The stainless steel will have the best corrosion resistance. Since fatigue is not a concern, they should not require replacement for the 50-year desired lifespan.

h. Rope Selection. Select the 1-in. diameter, 6x19 class, 6x25 FW, IWRC, stainless steel ropes. This rope is typically commonly available and best resists corrosion, which is identified as the predominant failure mode.

i. Factor of Safety.

(1) LCA factor of Safety. The rope strength is multiplied by the number of ropes (12). The factor of safety is required to be a minimum of 5.

$$FS_{LCA} = \frac{12(BS_{6x19.ss.c})}{T_{LCA}} = 5.63$$

(2) LCB factor of safety. This will be evaluated for one side with an assumed 70% load distribution. The rope strength is multiplied by the number of ropes on one side (6). The factor of safety is required to be a minimum of 1.43.

$$FS_{LCB} = \frac{6(BS_{6x19.ss.c})}{T_{LCB.70}} = 2.46$$

j. Conclusion. Twelve 1-in. diameter, 6x19 class, 6x25 FW, IWRC, stainless steel ropes will have a LCA factor of safety of 5.63 and will not exceed the 70% of breaking strength under LCB. The stainless ropes will provide the best corrosion resistance and are not expected to require replacement for the 50-year design life. This is estimated to be the lowest life cycle cost option. The 1-in. diameter rope is a reasonable size as it is a common size and does not require an excessive number of ropes, nor does it provide an excessive factor of safety.

C-3. Sample Problem 2 - Vertical Lift Gate.

a. Problem Description.

(1) Discussion. As a part of a hoist system rehabilitation assume that there is a need to select replacement ropes for a multi-part wire rope hoist system for a vertical lift gate (shown in Figure C-4). The hoist system uses a grooved drums similar to what is shown in Chapter 4. The gate has a single motor that drives two rope drums. There are a total of two ropes, one for each drum, that connect to each side of the gate lifting beam (Side X & Side Y). Each wire rope is reeved through a system of sheaves shown below. This sheet will cover the considerations for selection of the wire rope for this system.

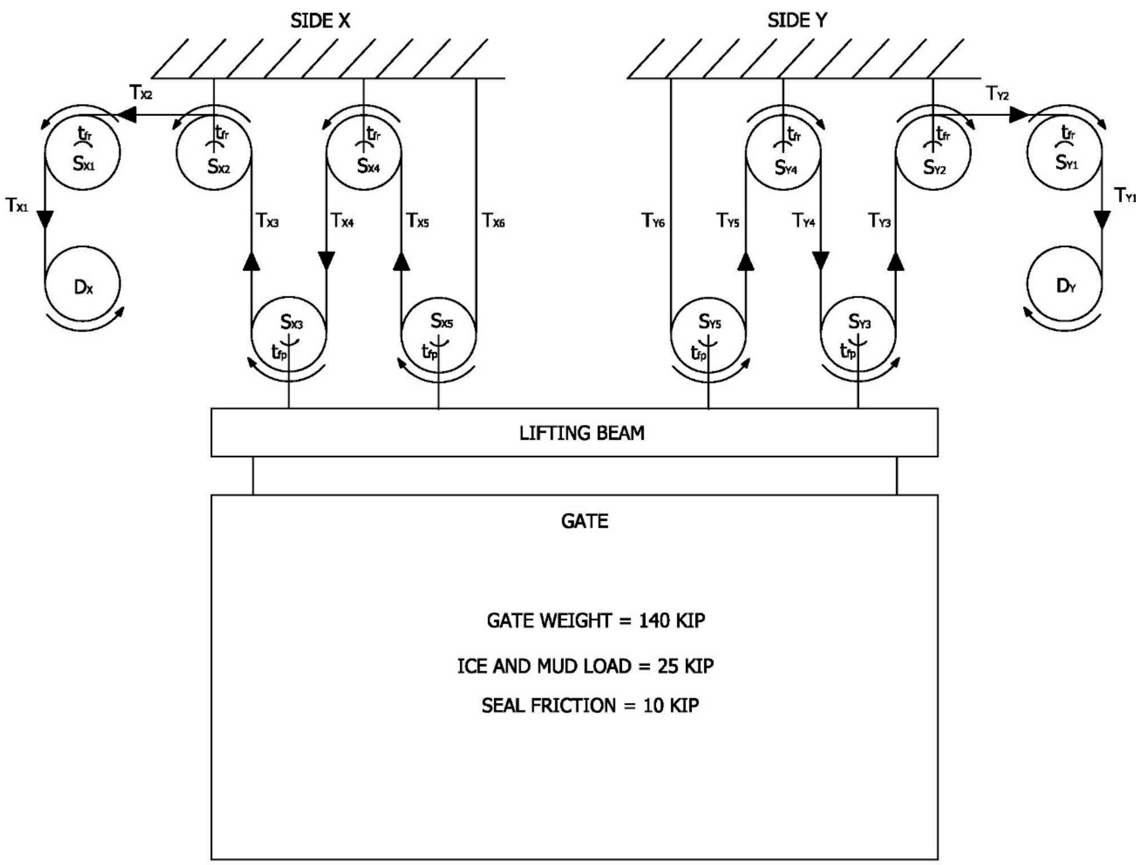

Figure C-4. Sample Problem 2 – Vertical Lift Gate.

(2) Existing Rope. The existing rope is 1¼-in. diameter, XIPS, galvanized 6x19 class, 6x26 Warrington Seale. The rope has been in service for 45 years. To be in compliance with the requirements of ER 1110-2-8157, the operations staff performed a detailed condition assessment during the last maintenance outage. The inspection findings included minor corrosion of the ropes, abrasive wear of the outer wires in some lengths of the ropes, and a number of square end wire

breaks along the crown wires of the rope. The diameter was measured to be 97% of the nominal diameter. No valley wire breaks or other rope damage was found.

(3) Existing Sheave Blocks. The sheaves and block assemblies were inspected during the last maintenance outage. The sheave grooves have experience some wear and are approaching the maximum groove dimensions recommended. No other sheave damage or unusual wear was noted. As a part of the rehabilitation, the sheave bearings will be replaced and the sheave grooves machined to the recommended new groove dimensions.

(4) Frequency of Operation. The gates are operated through a full raise and lower cycle approximately twice per day.

(5) Service Life. Based on an evaluation of Engineering Regulation 1110-2-8159, the desired service life of the mechanical hoist system has been determined to be a minimum of 50 years.

(6) Operating Environment. The ropes are not submerged during operation, but are exposed to the weather and the high moisture environment around the gate.

b. Failure Mode Evaluation. To select an appropriate wire rope, it is important to understand the most likely failure mode(s). As discussed in Chapter 4, it is typically best to select a rope type based on resisting the predominant failure mode. The potential failure modes are evaluated below based on the sample problem background information. Findings from existing system inspections or condition assessments are often the best source of information to determine potential failure modes.

(1) Abrasive Wear. Areas of abrasive wear were noted during the last inspection of the existing ropes. The diameter was measured to be 97% of the rope nominal diameter. The recommended diameter loss retirement criteria is when 95% of the nominal diameter is reached. Based on the findings from the inspection, the rope will experience abrasive wear. However, after 45 years of operation, the abrasive wear is at an acceptable level. Therefore, there is a moderate potential for an abrasive wear failure mode of the new ropes over the next 50-year service life.

(2) Fatigue. A number of crown wire breaks were noted during the last inspection of the existing ropes. This is indicator of rope fatigue. These signs of fatigue are not surprising given that the ropes pass through a system of sheaves and experience a relatively large number of operating cycles. The primary reason for retiring the existing rope is the fatigue breaks that were discovered. Therefore, there is a high potential for the new rope to experience a fatigue failure mode. Fatigue is identified as the predominant failure mode.

(3) Excessive Stress. Excessive stress can be caused by loads delivered by the hoist system, operating loads, or environmental loads. The wire ropes will be sized for the maximum load the hoist can deliver. No down pull or unknown operating loads are present on this gate. The environmental factors (wind, wave loads, ice, etc.) are being accounted for in the determination of required hoisting loads. Therefore, excessive stress is being adequately accounted for in the determination of design loads.

(4) Corrosion. During the last inspection of the existing ropes, areas of surface corrosion were noted. The ropes are not submerged, but are exposed to the elements and to high moisture conditions

for their full life. Based on that fact, the existing rope only have areas of surface corrosion. After a 45-year service life, there is a low potential for corrosion failure mode.

c. Initial Selection Considerations. Wire ropes for gate operating devices have specific selection considerations. These are discussed in Chapter 4.

(1) Core Type. Due to improved crushing resistance, higher strength, and higher durability independent wire rope core (IWRC) ropes should be used on gate operating devices. Therefore, select ropes with an IWRC.

(2) Material. Fatigue has been identified as the predominant failure mode. Corrosion has been identified as a low concern. Stainless steel ropes have a low fatigue life and therefore will not be the best material choice. Bright finished ropes are also not recommended due to the high moisture environment. Therefore, limit rope material to galvanized steel ropes.

(3) Wire Size. There is a high potential for fatigue failure modes, a moderate potential for abrasive wear, and a low potential for corrosion. Therefore, select a rope with a wire size that accommodates fatigue and check the wire size based on the expected rate of abrasive wear to make sure the rope will not experience an abrasive wear failure over the design life.

(4) Rope Diameter. It is desired to keep the existing wire rope size. Therefore, evaluate 1¼-in. diameter ropes for replacement.

d. Known Loads.

(1) Normal Operating Rope Tension. This is the force the hoist system needs to deliver to operate the gate under the worst case normal operation. Per EM 1110-2-2610, the normal operating loads are found by creating a free body diagram of the gate and by applying operating loads including gate weight, ice and mud loading, hydro forces, seal friction, trunnion friction, wire rope tension, etc., then summing moments and forces to solve for the rope tension. The normal operating rope tension will be referred to as Load Case A (LCA). For this application the gate loads contributing to the rope tension include a gate weight of 140 kips, an ice and mud load of 25 kips, and a side seal friction of 10 kips.

$$T_{LCA} := 140kip + 25kip + 10kip = 175 \cdot kip$$

(2) Maximum overload tension. The maximum overload tension is found by assuming that the gate is jammed and the maximum motor torque is applied to the hoist system. (Note that the maximum motor torque is a function of the motor and any load limiting devices in the system.) This overload condition will be referred to as Load Case B (LCB). For this example Load Case B is as follows:

$$T_{LCB} := 400\ kip$$

(3) Maximum LCB overload tension per side of the gate. Per the requirements of EM 1110-2-2610, Section 7-4, the design criteria for vertical lift gates should match that of Tainter gates per Section 9-2m(5)(c). Therefore, it is assumed the maximum overload condition has a load

distribution of 70/30 between sides of the gate. The following tensions are the design overload rope tensions for the 70% and 30% load sides, respectively:

$$T_{LCB.70} := 0.70 \cdot (T_{LCB}) = 280 \cdot kip$$

$$T_{LCB.30} := 0.30 \cdot (T_{LCB}) = 120.0 \cdot kip$$

e. LCA Frictionless Rope Tension.

(1) LCA frictionless tension for rope sections sharing the load. LCA values will be designated with an "A". Frictionless values will be designated with an "f."

$$T_{X3.A.f} := \frac{T_{LCA}}{8} = 21875\,lbf \quad T_{Y3.A.f} := T_{X3.A.f} = 21875\,lbf$$

$$T_{X4.A.f} := T_{X3.A.f} = 21875\,lbf \quad T_{Y4.A.f} := T_{X3.A.f} = 21875\,lbf$$

$$T_{X5.A.f} := T_{X3.A.f} = 21875\,lbf \quad T_{Y5.A.f} := T_{X3.A.f} = 21875\,lbf$$

$$T_{X6.A.f} := T_{X3.A.f} = 21875\,lbf \quad T_{Y6.A.f} := T_{X3.A.f} = 21875\,lbf$$

(2) LCA frictionless tension for the other sections of rope.

$$T_{X2.A.f} := T_{X3.A.f} = 21875\,lbf \quad T_{Y2.A.f} := T_{Y3.A.f} = 21875\,lbf$$

$$T_{X1.A.f} := T_{X2.A.f} = 21875\,lbf \quad T_{Y1.A.f} := T_{Y2.A.f} = 21875\,lbf$$

f. Sheave Known Values:

(1) Sheave friction coefficients for roller (r) and plain (p) bearings. The roller bearing friction coefficient is designated with an "r" and the plain bearing with a "p." These are based on the recommended values from Chapter 4. The coefficients of friction are as follows:

$$\mu_r := 0.06 \quad \mu_p := 0.3$$

(2) Sheave pitch diameter.

$$D := 30in$$

(3) Sheave axle diameter:

$$\mathrm{d_b} := 4\mathrm{in}$$

(4) Total tension friction multiplier. This is from Chapter 4, Section 4-4.

$$\phi_r := \frac{D + \mu_r \bullet (d_b)}{D - \mu_r \bullet (d_b)} = 1.016 \quad \phi_p := \frac{D + \mu_p \bullet (d_b)}{D - \mu_p \bullet (d_b)} = 1.083$$

g. LCA Total Tensions.

(1) Tensions with increases for friction losses.

$$T_{X6.A} := T_{X6.A.f} = 21875\,lbf \quad T_{Y6.A} := T_{Y6.A.f} = 21875\,lbf$$

$$T_{X5.A} := \phi_p \cdot (T_{X6.A}) = 23698\,lbf \quad T_{Y5.A} := \phi_p \cdot (T_{Y6.A}) = 23698\,lbf$$

$$T_{X4.A} := \phi_r \cdot (T_{X5.A}) = 24080\,lbf \quad T_{Y4.A} := \phi_r \cdot (T_{Y5.A}) = 24080\,lbf$$

$$T_{X3.A} := \phi_p \cdot (T_{X4.A}) = 26087\,lbf \quad T_{Y3.A} := \phi_p \cdot (T_{Y4.A}) = 26087\,lbf$$

$$T_{X2.A} := \phi_r \cdot (T_{X3.A}) = 26508\,lbf \quad T_{Y2.A} := \phi_r \cdot (T_{Y3.A}) = 26508\,lbf$$

$$T_{X1.A} := \phi_r \cdot (T_{X2.A}) = 26935\,lbf \quad T_{Y1.A} := \phi_r \cdot (T_{Y2.A}) = 26935\,lbf$$

h. LCB Static Tension.

(1) LCB frictionless tension for rope sections sharing the load. This analysis will look at the 70% load side to determine the maximum tension under LCB. The 70% load could occur on either side. LCB values are designated with a “B.” Therefore, the X and Y side designator will be dropped. Frictionless tension will be designated with an “f.”

$$T_{3.B.f} := \frac{T_{LCB.70}}{4} = 70000\,lbf$$

$$T_{4.B.f} := T_{3.B.f} = 70000\,lbf$$

$$T_{5.B.f} := T_{3.B.f} = 70000\,lbf$$

$$T_{6.B.f} := T_{3.B.f} = 70000\,lbf$$

(2) LCB frictionless tension for the other sections of rope:

$$T_{2.B.f} := T_{3.B.f} = 70000\,lbf$$

$$T_{1.B.f} := T_{2.B.f} = 70000\,lbf$$

(3) LCB tensions with increases for friction losses:

$$T_{6.B} := T_{6.B.f} = 70000\,lbf$$

$$T_{5.B} := \phi_p \cdot (T_{6.B}) = 75833\,lbf$$

$$T_{4.B} := \phi_r \cdot (T_{5.B}) = 77056\,lbf$$

$$T_{3.B} := \phi_p \cdot (T_{4.B}) = 83478\,lbf$$

$$T_{2.B} := \phi_r \cdot (T_{3.B}) = 84824\,lbf$$

$$T_{1.B} := \phi_r \cdot (T_{2.B}) = 86192\,lbf$$

i. Total Required Strength.

(1) Normal Loading (LCA) Criteria: Per Chapter 4, the rope normal operating tension factor of safety must be at least 5.0 based on the rope minimum breaking strength.

(2) Overload Criteria (LCB): Per Chapter 4, the maximum tension must not exceed 70% of the rope nominal breaking strength (factor of safety of 1.43). In addition, per EM 1110-2-2610, Section 7-4, the design criteria for vertical lift gates should match that of Tainter gates per Section 9-2m(5)(c). Therefore, it is assumed the maximum overload condition has a load distribution of 70/30 between sides of the gate.

(3) Individual rope breaking strength required under LCA. The largest LCA dynamic tension is used to evaluate the LCA criteria.

$$S_{B.LCA} := 5 \cdot (T_{X1.A}) = 135 \cdot kip$$

where:

$$T_{X1.A} := \phi_r \cdot (T_{X2.A}) = 26935\,lbf$$

(4) Individual rope breaking strength required under LCB. The 70/30 load sharing could occur on either side of the gate.

$$S_{B.LCB} := \frac{T_{1.B}}{0.70} = 123 \cdot kip$$

(5) Summary. The required rope strength is governed by the LCA criteria. This load case requires a minimum rope breaking strength of 135 kips.

j. Option 1 – 6X36 Class, 6X36 WS, IWRC, EIPS, Galvanized, Regular Lay. Fatigue has been identified as the predominant failure mode for the application. To determine the best replacement rope type, rope constructions with the best bending properties will be investigated. From the Wire Rope User's Manual, the bending life of various constructions can be compared. A 6X36 WS construction has a smaller wire size relative to its nominal diameter compared to other common gate operating ropes. The smaller diameter wire gives it better bending fatigue resistance, but also lower abrasion and corrosion resistance.

(1) Minimum breaking strength of 6x36 class, IWRC, EIPS, bright finished rope (ASTM A1023, Table 12).

$$BS_{6x36} := 79.9 tonf = 159.8 \cdot kip$$

(2) Breaking strength with galvanizing reduction. Per the note at the bottom of ASTM A1023, Table 12, the breaking strength of galvanized rope is 10% lower than that of bright rope. This strength reduction is typical for most galvanized ropes.

$$BS_{6x36.gv} := 0.90 \cdot \left(BS_{6x36}\right) = 143.82 \cdot kip$$

(3) Breaking strength with curved surface reduction. The ropes are reeved over sheaves and onto the wire rope drum. As discussed in Chapter 4, wrapping a rope over a curved surface causes an uneven load distribution across the rope and a corresponding strength reduction. The smallest curved surface the ropes run over are the sheaves that have a nominal diameter of 30 in. The 1¼-in. rope size gives a D/d ratio of: 30 in./1¼ in. = 24. From the Wire Rope Users Manual, this D/d ratio results in a reduction to approximately 94% of the straight line strength.

$$BS_{6x36.gv.c} := 0.94\left(BS_{6x36.gv}\right) = 135.19 \cdot kip$$

(4) Summary: The 6x36 class, 6x36 WS, IWRC, EIPS, galvanized rope meets the strength requirements for the application. The improved bending resistance of this rope over the 6x26 WS construction will result in approximately 27% longer bending life. The existing rope should be retired after a 45-year service life based on square end (bending fatigue) breaks. The increased bending fatigue life of 6x36 WS is expected to increase the service life to the target of 50 years. A similar amount of abrasion resistance should be expected with the 6x36 WS rope. The existing rope is 97% of its original diameter after 45 years of service. The new 6x36 WS rope should be retired when abrasive wear reaches 95% of its original diameter. Based on this rate of abrasive wear, it is estimated that the rope will reach the target 50-year service life before abrasive wear retirement criteria is met. A detailed inspection of the rope should be performed on regular intervals in accordance with ER 1110-2-8157. The O&M manual should indicate that the rope inspectors should specifically monitor fatigue, abrasive wear, and corrosion.

k. Option 2 – IWRC, EIPS, Galvanized, Lang Lay. Lang lay rope exhibits better bending and fatigue properties than do regular lay ropes. The increased length of outer wires gives lang lay a 15–20% greater bending fatigue resistance. This greater outer wire length also increases the bearing and wear area to improve abrasion resistance. The disadvantages of lang lay include severe rotation if not adequately supported, lower crushing resistance, incompatibility with swage sockets, and lower availability. This application will be well supported against rotation; the sheave sizes and loads are in compliance with recommended guidelines; and spelter sockets can be used at end terminations. The availability of lang lay rope may be an issue, but can be evaluated with market research. The strength of lang lay matches that of regular lay. If available in lang lay, the 6x26 WS or 6x36 WS constructions would meet the strength requirement.

l. Rope Selection. Select 1¼ in. diameter, 6x36 class, 6x36 WS, IWRC, EIPS, lang lay, galvanized rope. This rope will provide the best balance between bending and abrasion resistance.

m. Factor of Safety.

(1) LCA factor of safety. The factor of safety is required to be a minimum of 5.

$$FS_{LCA} := \frac{BS_{6X36.gv.c}}{T_{X1.A}} = 5.02$$

(2) LCB Factor of Safety. This will be evaluated for one side with an assumed 70% load distribution. The factor of safety is required to be a minimum of 1.43.

$$FS_{LCB} = \frac{BS_{6x36.gv.c}}{T_{1.B}} = 1.57$$

n. Conclusions.

(1) The new 1¼-in. diameter, 6x36 class, 6x36 WS, IWRC, EIPS, lang lay, galvanized rope will have a LCA factor of safety of 5.02 and will not exceed the 70% of breaking strength under LCB. This rope selection will provide significantly better bending fatigue and abrasion resistance. This new rope is expected to meet the target service life of 50 years. If market research finds that lang lay is not available, the regular lay will also meet the target service life, but will have a reduced bending fatigue and abrasion resistance.

(2) The condition of the replacement rope should be inspected on a regular basis per the requirements of ER 1110-2-8157. The O&M manual should indicate that fatigue and abrasion are expected to be the most likely failure modes.

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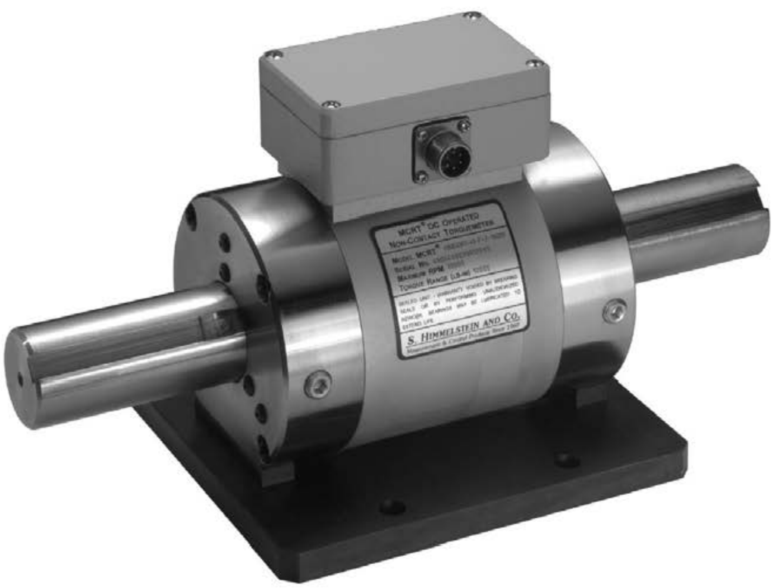
APPENDIX D

Load Limiting Devices White Paper

US Army
Corps of Engineers



Load Limiting Device White Paper

PREPARED BY
US ARMY CORPS OF ENGINEERS
PORTLAND DISTRICT
JANUARY 2016

Contents

D-1. Executive Summary.

This White Paper was conceived due to the need to limit excessive machinery hoist loads to Tainter gates. Army Corps engineering manuals such as EM 1110-2-2610, Mechanical and Electrical Design for Lock and Dam Operating Equipment and ETL 1110-2-584, Design of Hydraulic Steel Structures discuss hoist loads and make general mention to various load limiting devices (LLDs). These hoist loads can typically be two to five times the required lifting load, a condition which can lead to failure and/or uneconomical designs. It was felt that more specific information was needed on LLDs so that they could be effectively incorporated into design. Therefore, a team of cross-disciplinary design engineers was formed to research and evaluate various LLDs. The team brainstormed available devices by reaching out to: other USACE Districts; industry vendors that deal with electrical and mechanical components; and past Portland District projects.

The team researched the LLDs and developed evaluation criteria that was felt to be important relative to electrical, mechanical, structural, operational, and maintenance concerns. This evaluation criteria was ultimately used to grade and rank the LLDs relative to a new or retrofit installation. The evaluation process included significant discussion among the team members, which served to examine the pros and cons of the LLDs in detail.

The top three LLDs recommend by the team are: (1) custom-wound motor, (2) C-faced torque transducer, and (3) torque switch. Ultimate selection of the proper LLD is left to the design engineer and the specific situation that is being addressed. The evaluation matrix that is presented in this paper can facilitate in selecting the LLD that makes the most sense for the specific situation at hand.

At the time of this writing, custom wound motors have been installed at the Fall Creek spillway gates and tested under normal operating conditions.

D-2. LLD Committee Purpose.

The purpose of this committee is to research load limiting devices that may be applicable for use with radial spillway gates in the Portland District with the intent to provide standardized components for future PDTs.

D-3. Background.

Since spillway Tainter gates were first installed there have been many lessons learned about how they function. In particular there have been failures, accidents, and misoperation that have brought to light new information on the overload conditions they can experience. As a result, required design assumptions for overload conditions have become more conservative. This has led to a need to use LLDs to keep design of spillway gate system reasonable and cost effective.

Overload cases per USACE design criteria have been calculated for various NWP spillway Tainter gates. The max overload condition is determined by finding the motor torque that results in the gate jamming. This is used to set the load limit on the system as any more load applied to the gate after jamming occurs does not add value. This overload limit is most often determined to be approximately 140% of the motor FLT. The 140% of FLT limit is a fraction of the overload torque most motors are capable of producing. This helps limit the load the system needs to be designed to withstand.

D-4. LLD Functionality Requirements and Operating Environment.

a. General. To provide more context to the reader, this section briefly discusses the functionality requirements and operating environment in which this evaluation is based on. A different operating environment may emphasize different evaluation factors thus resulting in the selection of different LLDs for the reader.

b. Functionality Requirements. Functionality requirements that can serve as a basis are.

- Overload protection is provided for 100% of the time that the motor is running.
- Minimum lag time before the LLD is actuated.
- Reliable operation based on the operating environment.
- All LLDs need to be load holding (dropping a suspended load is unacceptable).

c. Startup Considerations.

When a motor is first energized, under typical across the line start conditions, the motor torque is often slightly larger than the normal running torque. This is a result of inertial effects of the system the motor is moving. Inertial torque increases at a startup need to be accounted for in the design of the LLD. Inertial torque at start up may be large enough to cause nuisance trips of the LLD in some cases. Torque at start up to overcome system inertia is often assumed to be 115% of the full load motor torque. However, designers should quantify the startup torque to understand how it may impact the LLD.

The inertial effects at startup have been investigated for many NWP spillway Tainter gates. The hoists of almost all NWP spillway Tainter gates are designed to operate the gate at a wire rope speed of 1 ft/min or less. This is a common gate speed, but is a very slow speed compared to many motor hoist or operating system applications. The inertia of a system is a function of the system mass, change in speed, and the time over which the speed change occurs. For the case of most NWP spillway Tainter gates, the mass of the gate is large. At start up, the gate starts at zero speed and is accelerated to a very slow speed (~1ft/min). This speed change happens over a moderate amount of time (~¼ to ½ sec). Overall, despite the large system mass the very small amount of acceleration results in negligibly small inertial effects at start up. Again, the system start up effect should be investigated to determine impacts to the design of a LLD.

Note, inertial torque at start up should not be confused with in-rush current. In-rush current at start up can be many times the running current and does not translate to an increase in torque at the motor shaft.

d. Operating Environment. The following is a list of operating environment conditions that serves as a basis:

- Remote operation of spillway gates is limited.

- Spillway gate movements range from once a year for annual maintenance to daily for minimum flow requirements.
- Outdoor environment.

D-5. LLD Committee Members.

- Bill Fortuny, EC-DE.
- Dave Hamernik, EC-DS.
- Matt Hess, EC-DM.
- Anil Naidu, OD-V.
- Steve Tanner, OD-V.

D-6. Acronyms. Table D-1 lists acronyms and abbreviations used in this appendix.

Table D-1. Acronyms and Abbreviations.

Acronym	Meaning
AC	alternating current
DC	direct current
ECB	engineering circular bulletin
EM	engineering manual
ETL	engineering technical letter
hp	horse power
LLD	load limiting device
MFR	manufacturer
ms	milliseconds
NEMA	National Electrical Manufacturer's Association
PC	personal computer
PLC	programmable logic controller
Vac	alternating current volts
Vdc	direct current volts
VFD	variable frequency drive

D-7. Load Limiting Device Types Evaluated.

a. General. This committee evaluated the following devices that are presented in detail in the following pages. While PLCs have not been evaluated as a standalone load limiting device, it is acknowledged that PLCs can be used in conjunction with most of the devices evaluated as part of the "load limiting device protection system".

- C-Faced Torque Transducer.
- In-Line Torque Transducer.

- Variable Frequency Drive.
- Running Line Tensionometer.
- Custom Wound Motor.
- Torque Switch.
- Overload Device.

b. Torque Transducers. There are two types of torque transducers: C-faced and in-line. Both of these devices measure torque and then transmit the information to components in the motor control system. They are a reactionary device meaning that there is a delay from when an overload torque is detected until it is relayed to have the motor turned off.

c. C-Faced Torque Transducer.

C-Faced torque transducers are mounted between the motor and the primary reducer (Figures D-1, D-2, and D-3). The torque applied by the motor creates a reaction force at the motor mounts. C-faced torque transducers serve as the motor mounts and measure the equal and opposite torque required to hold the motor in place as it delivers torque to drive the system. C-faced torque transducers have a rigid metal frame that is used to mount the motor to the primary reducer. Strain gauges are placed on the rigid metal frame to measure the torsional strain developed to hold the motor in place. These devices are available with various output signal options i.e., ±10VDC, which can be used to drive a control relay to drop out the motor control circuit on an overtorque condition. The additional equipment needed to be added to the electrical control system are an external power supply (10VDC), and a control relay, both of which are very reliable for a high number of operations.

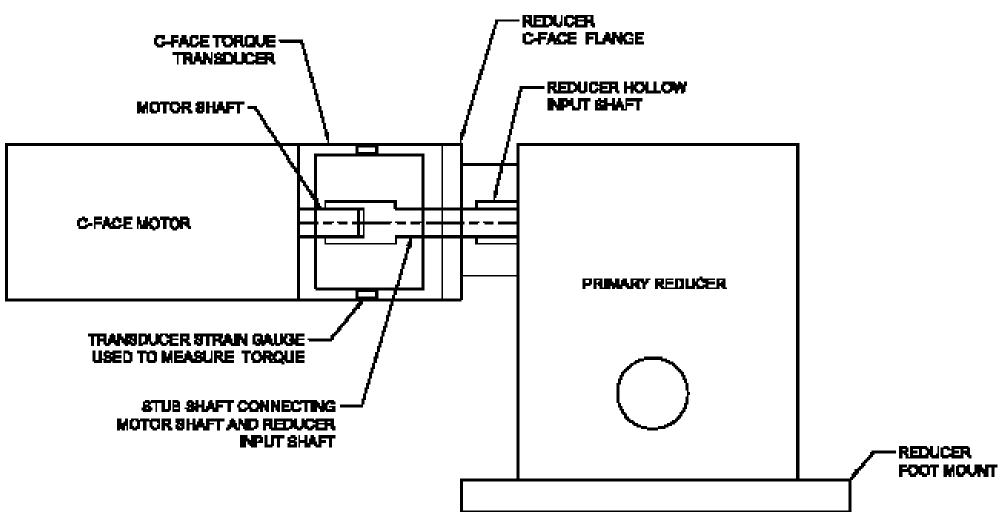


Figure D-1. C-Faced Torque Transducer Typical Installation.

Figure D-2. C-Faced Torque Transducer (Motor and Gearbox Not Shown).

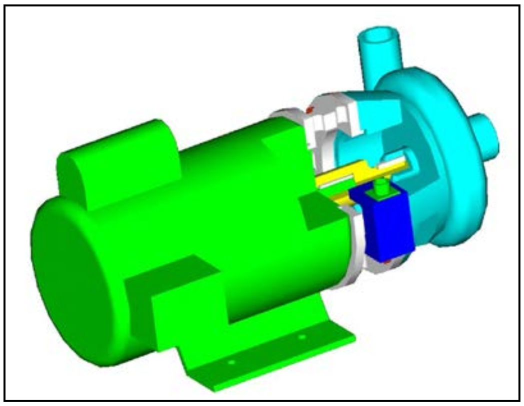


Figure D-3. C-Faced Torque Transducer Shown between and Motor (Green) and Pump (Light Blue).

(1) Lag Time. Torque transducers are reactionary devices. This means that an undesirable torque needs to be applied to the system before the device can measure the undesirable torque and shut the system down. The total lag time of C-faced torque transducers is a function of the response time of the electronic equipment plus the lag time of the relay(s) used in the control circuit. The estimated worst case lag time from when the overtorque occurs to when the motor circuit is opened is 41 ms (lag time is calculated based on refresh rate of device and pick-up/dropout time of control circuit relay). See attached sample of how to quantify the force increase experienced at the gate structure due to device lag time.

(2) Accuracy. Manufacturers quote C-Faced torque transducers to be +/-0.07% accurate for the enhanced version and +/-0.1% accurate for the standard version based on torque measured vs.. actual applied torque.

(3) Calibration. C-faced torque transducer MFR is recommended for recalibrating the devices on a regular basis. Calibration of a torque transducer is performed by applying a known torque to the device and measuring the resulting electrical signal. It is estimated that designers could come up with

a simple method off applying a torque to the motor frame with a torque wrench and measuring the electrical output. This calibration would be performed while the system is not running, likely on an annual basis, during system maintenance.

(4) Pros:

- Incorporating C-faced torque transducers into a new or existing system can be easily performed if gearbox and motor are set up for C-Face mounting.
- C-faced torque transducers do not have moving parts such as bearings that have a higher likelihood of encountering problems over time.
- Torque applied by the motor can be very accurately measured.
- Lag time is relatively short compared to other devices. This minimizes the amount of additional load applied to the system after the undesirable torque is measured.
- C-faced torque transducers can be recalibrated using simple methods.
- Minimal additions to the motor control circuit are required, which keeps the design non-complex, easy to maintain and troubleshoot, and increases or maintains existing reliability.

(5) Cons:

- C-faced torque transducer are reactionary devices. An undesirable torque needs to be applied before it can be measured and a shutdown sequence initiated.
- Devices are most commonly used indoors. MFRs recommended additional weather protection (not provided by the MFR) for outdoor use.
- MFRs estimate of operational life is 20-30 years. This is less than the 50-year design life commonly used for spillway gates.
- C-faced torque transducers do not measure the load applied directly to the gate structure. The device measure the torque applied to the system by the motor. Equipment efficiencies need to be accurately estimated to determine an accurate load applied to the gate structure.
- There is a lag time between when the overtorque occurs and the motor comes to a stop.

(6) Estimated Cost:

- Purchase Price: ~ $4,000 per transducer, $2,000 for electrical control components.
- Not included: additional weather protection.

(7) Considerations:

- Weather Protection – Both C-faced torque transducer MFRs the team talked to recommended that at a minimum a “doghouse” style enclosure is provided over the device if used outdoors. This would be weather protection that keeps the device mostly protected from the major elements (wind, rain, hail, snow, sun, etc.).

- Space constraints for installation at facilities not requiring new machinery may affect the difficulty of using these devices.

d. In-Line Torque Transducer. In-line torque transducers are mounted in the drive train of the operating machinery, typically between the motor and the primary reducer. In-line torque transducers have a shaft that rotates with and carries the torque of the drive train. Standard styles of flex couplings are used on the input and output sides of the rotating shaft to transfer torque between adjacent components. Torsional strain is measured with strain gauges mounted to the rotating shaft. The device is then calibrated to output the corresponding torque. The transducer housing is stationary and is typically rigidly foot mounted. The housing supports roller or ball bearings that hold the shaft in tight alignment. The strain gauge signal measured from the rotating shaft is transferred to the stationary housing electrical output via a rotary transformer or slip rings. These devices are available with various output signal options, i.e., ±10VDC, which can be used to drive a control relay to drop out the motor control circuit on an overtorque condition. The additional equipment needed to be added to the electrical control system are an external power supply (10VDC), and a control relay, both of which are very reliable for a high number of operations. See Figures D-4, D-5, and D-6.

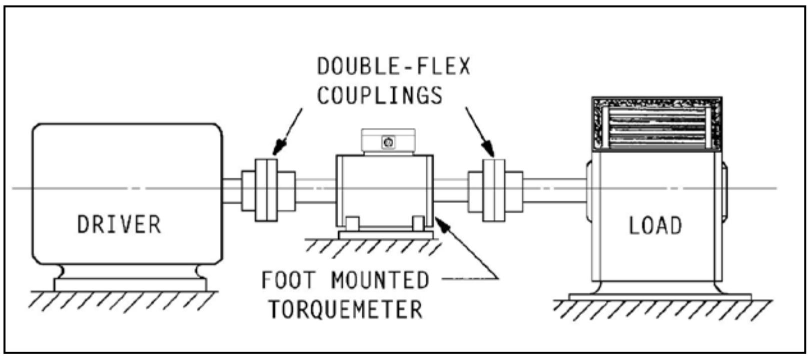


Figure D-4. In-Line Torque Transducer.

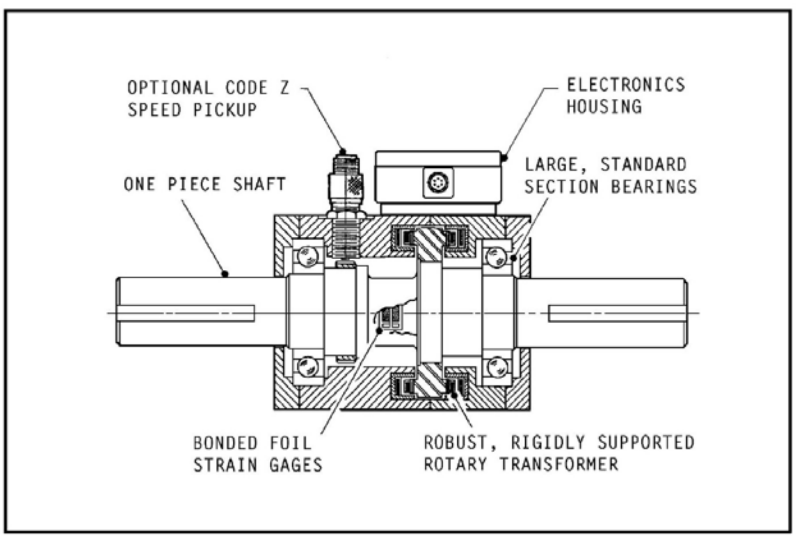


Figure D-5. Cross Section of In-Line Torque Transducer.

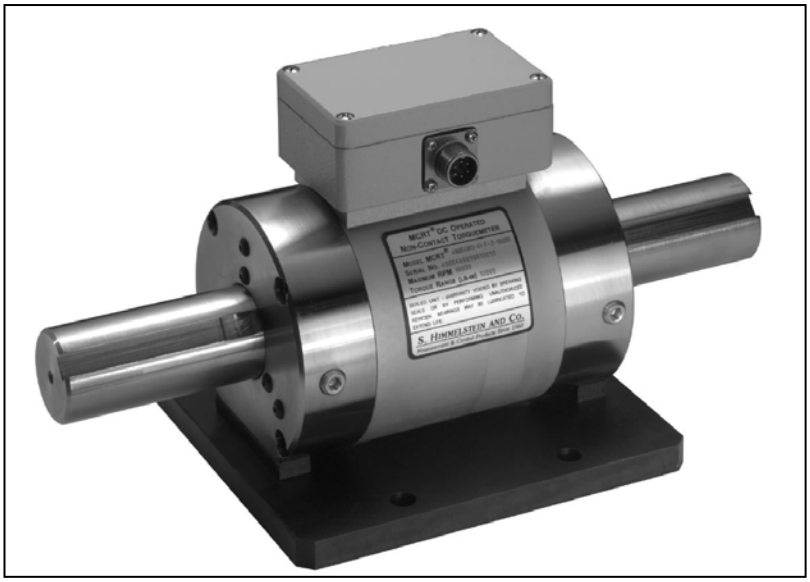


Figure D-6. In-Line Torque Transducer.

(1) Lag Time. Torque transducers are reactionary devices. This means that an undesirable torque needs to be applied to the system before the device can measure the undesirable torque and shut the system down. The total lag time of in-line torque transducers is a function of the sampling rate of the electronic equipment plus the lag time of the relay(s) used in the control circuit. The estimated worst case lag time from when the overtorque occurs to when the motor circuit is opened is 41 ms (lag time is calculated based on refresh rate of device and pick-up/dropout time of control circuit relay). See the attached sample of how to quantify the force increase experienced at the gate structure due to device lag time.

(2) Accuracy. Manufacturers quote in-line torque transducers to be +/-0.07% accurate for the enhanced version and +/-0.1% accurate for the standard version based on torque measured vs.. actual applied torque.

(3) Calibration. In-line torque transducer MFRs recommended recalibrating the devices on a regular basis. Calibration of a torque transducer is performed by applying a known torque to the device and measuring the resulting electrical signal. It is estimated that designers could come up with a simple method off applying a torque to the transducer shaft with a torque wrench and measuring the electrical output. This calibration would be performed while the system is not running, likely on an annual basis, during system maintenance.

(4) Pros:

- In-line torque transducers can be incorporated into a system using standard couplings and mounting arrangements.
- Torque applied by the motor can be very accurately measured.
- Lag time is relatively short compared to other devices. This minimizes the amount of additional load applied to the system after the undesirable torque is measured.
- In-line torque transducers can be recalibrated using simple methods.

- Minimal additions to the motor control circuit are required, which keeps the design non-complex, easy to maintain and troubleshoot, and increases or maintains existing reliability.

(5) Cons:

- The device has bearings and other moving parts that add to the complexity of the machinery system.
- Torque transducers are reactionary devices. An undesirable torque needs to be applied before it can be measured and a shutdown sequence initiated.
- Devices are most commonly used indoors. MFRs recommended additional weather protection (not provided by the MFR) for outdoor use.
- MFRs estimate of operational life was 20-30 years. This is less than the 50-year design life commonly used for spillway gates.
- In-line torque transducers do not measure the load applied directly to the gate structure. The device measures the torque applied to the system by the motor (or wherever it is mounted in the machinery system). Equipment efficiencies need to be accurately estimated to determine an accurate load applied to the gate structure.
- There is a lag time between when the overtorque occurs and the motor comes to a stop.

(6) Estimated Cost:

- Purchase Price: ~ $4,000 per transducer, $2,000 for electrical control components.
- Not included: additional weather protection.

(7) Considerations:

- Weather Protection – Both in-line torque transducer MFRs the team talked to recommended that at a minimum a “doghouse” style enclosure is provided over the device if used outdoors (devices are not typically NEMA 4X rated). This would be weather protection that keeps the device mostly protected from direct exposure to the elements (wind, rain, hail, snow, sun, etc.).
- Space constraints for installation at facilities not requiring new machinery may affect the difficulty of using these devices.

e. Variable Frequency Drive.

A variable frequency drive (VFD) is an electronic device that is installed between the normal power line and an AC motor (Figure D-7). It can operate the motor at variable speeds by controlling the frequency of the power applied to the motor. Since a motor is an inductive device, the current through the motor increases with decreasing frequency. The VFD decreases the applied voltage with decreasing frequency to keep the motor current within the motor’s capability. Full motor torque is achieved at full motor current and can be achieved at any speed up to nominal.

Sophisticated units can also control motor torque at less than rated operation by further limiting the applied voltage, which in turn controls the current. Current sensing devices can enable the VFD to directly monitor current and resulting torque, or current and torque can be inferred from an algorithm that uses applied voltage, frequency, and motor parametric data. It is this torque control capability that enables the VFD to act as a load limiting device. Models are available with programmable torque and current limits.

Many other operating features are available, such as controlling the system brake to ensure that the motor is producing sufficient torque before it is released.

Figure D-7. Variable Frequency Drive.

(1) Lag Time. In discussion with a manufacturer (Rockwell), the overload detection is programmable and if exceeded, the drive can be programmed to halt and set an output. Response time is on the order of 5-10 ms.

(2) Accuracy. Manufacturer states a torque control accuracy of +/- 2% if an optional positional encoder is used. If an encoder is not used then the accuracy is +/- 5%.

(3) Calibration for Reliability:

- VFDs can run for thousands of hours between failures. VFDs used for gate duty can be expected to be idle most of the time, but be on-call for decades. This aspect of reliability has not yet been fully characterized by the existing user base.
- VFDs should be powered up every few months to maintain DC capacitance. Capacitors can be re-formed by applying input power for ½ hour, even after 5 years.
- VFDs are field repairable and spares have historically been available for 20-30 years. Current models are well supported by the factory.

(4) Pros:

- The accuracy is +/- 2% with encoder and +/- 5% without an encoder.

- VFDs are very configurable with many features such as self-diagnostics.
- Well supported by manufacturer.
- VFDs are now often a commodity product where many different manufactures devices can be swapped into an existing control system.
- VFDs will continue to evolve, but will provide a fairly long term standard electrical interface to other electrical systems, in addition to adding new interface and standards and capabilities.

(5) Cons:

- Most features that are available will not likely be useful to spillway gate applications.
- VFDs can be complex due to the number of features that are available.
- Rapidly advancing technology with risk of future obsolescence and rapid turnover of product lines such as cell phones. Older models will likely become unsupported during their anticipated lifetime. Rockwell advises a service life of 20 years. Replacement would likely be with a newer model.
- Support hardware and software will likely become obsolete. Interfaces are evolving rapidly as well as PC operating systems. This may require maintenance of legacy computers and operating systems to run maintenance software and connect to associated hardware interface.
- Like all torque measuring devices, VFDs do not measure the load applied directly to the gate structure. Efficiencies of power train elements between the motor and the gate need to be accurately estimated to determine an accurate load applied to the gate structure.
- Require that power be applied on a regular basis. This need not be continuous, every few months will suffice.
- Environmentally sensitive – limited temperature and humidity range requires an enclosure with thermostatically controlled heater. The unit could be overheated in a cabinet in the summer sun.

(6) Estimated Cost:

- Purchase Price: ~ $2600.00 (Rockwell Powerflex 700 or 755, for 10 HP, 480Vac motor).
- VFD rated motor: ~ $4000.00 (weatherproof, with heater and encoder).
- Not Included: Configuration/support/programming hardware and software, enclosure and heater.

(7) Considerations:

- The specific vulnerabilities mentioned above suggest that a backup device be of a different technology to preclude simultaneous failures.

- Long term obsolescence concern with programming interface suggests use of the front panel interface and forgoing any PC/software.

f. Running Line Tensionometer.

Running line tensionometers are used to measure tension in a moving or static rope. The device consists of a rigid three sheave assembly with a load pin as the axle for the center sheave. The rope passes through the device and then bends around the center sheave at a fixed wrap angle. Reference Figures D-8, D-9, D-10, and D-11.

Figure D-8. Running Line Tensionometer.

Figure D-9. Running Line Tensionometer.

Figure D-10. Running Line Tensionometer.

Figure D-11. Running Line Tensionometer.

(1) Lag Time. Running line tensionometers are reactionary devices. A load approaching the overload limit must to be applied before the load is sensed and the motor control circuit dropped out. According to the manufacturer, there is no discernible lag time for the running line tensionometer itself (time between load applied and output signal). However total lag time for a running line tensionometer system is a function of the response time of the electronic equipment plus the lag time of the relay(s) used in the control circuit. Estimated worst case lag time is 41 ms (lag time is calculated based on refresh rate of device and pick-up/dropout time of control circuit relay). See attached sample of how to quantify the force increased experienced at the gate structure due to device lag time.

(2) Accuracy. According to manufacturer accuracy of a running line tensionometer is +/-1% of full scale.

(3) Calibration. Manufacturer recommends checking calibration yearly. Calibration would typically only be required on initial installation and after an overload condition. Calibration is performed by applying a known load to the device and measuring the resulting electrical signal. The weight of the gate could be used as a known load to check the calibration, but it would likely be necessary to remove the device from the wire rope and calibrate in a shop if it is determined that testing up to the overload condition is necessary. The calibration check would be performed during annual system maintenance.

(4) Pros:

- Running Line Tensionometers directly measure the force being applied to the gate structure. Efficiency of drive train components does not affect measurement.
- Lag time is relatively short compared to other devices. This minimizes the amount of additional load applied to the system after the overload threshold is reached.

(5) Cons:

- Running Line Tensionometers are reactionary devices so an overload line pull must to be applied before the overload is sensed and the motor is shut off.
- Moving components (sheave bearings) in outdoor environment require periodic lubrication.
- Custom design would be required for device to fit over closely spaced multiple ropes on a hoist.
- Running Line Tensionometer would be required for each set of hoist wire ropes to ensure overload is sensed during single sided hoisting condition.
- Potential size and weight of device may make design installation within existing space constraints challenging.
- There is a lag time between when the overload occurs and the motor comes to a stop.
- A Running Line Tensionometer will not work for an hoist system configured with chains and is intended for wire rope like hoist systems.

(6) Estimated Cost. An estimated cost is $22,000. This is a rough engineering estimate based on average of two manufacturers cost for standard devices, then considering how much more a custom unit for multiple wire ropes would cost. Also assumes that two running line tensionometer assemblies required (one for each set of hoist wire ropes)

(7) Considerations:

- Weather Protection – As these devices are exposed to the environment corrosion resistant materials and coatings should be considered.
- Space constraints for installation at facilities not requiring new machinery may affect the difficulty of using these devices.

g. Custom Wound Motor. Custom wound motors are fabricated by the motor manufacturer with a custom winding design that can change the torque vs.. speed characteristics of the motor. Manufacturers can often custom design the motor windings to limit the overload characteristics of the motor. Other than a winding design that does not match the standard NEMA design types, custom wound motors are essentially standard motors. Since the overload properties are limited by the winding design no additional electrical devices (relays, PLCs, etc.) are needed to operate the load limiting function. Reference Figure D-12.

Figure D-12. Custom Wound Motor (same appearance as typical hoist motors)

(1) Lag Time. Custom wound motors have no lag time. The inherent overload properties are limited to never produce more than the designed maximum torque (the breakdown or locked rotor torque is lowered).

(2) Accuracy. The accuracy of the overload characteristics is a function of the motor supply voltage.

(3) Calibration. Custom wound motors should be shop tested by the manufacturer to verify the desired overload properties are provided. No additional calibration should be required as the windings providing the overload limit are not modified as a result of operation.

(4) Pros:

- Custom wound motors can be easily incorporated into existing and new systems. No additional devices are needed other than the custom wound motor. These can replace standard motors typically without additional space required.
- Custom wound motors have the least impact to the reliability of a system. No additional components or points of failure are added to the system.
- Custom wound motors have no lag time.

- Custom wound motors eliminate the need for ongoing calibration checks.

(5) Cons:

- Custom wound motor need to be designed by the manufacturer on a case-by-case basis to meet the needed overload limits.
- Designers need to coordinate with the manufacturer during the design to verify that their specific overload limit requirements can be met.
- Sizes of motor housing/frames sometimes need to increase to accommodate heat dissipation requirements to provide continuous operation.
- Replacing motors in the future requires matching the custom winding requirements.
- Appropriate sizing of custom wound motors requires either measuring the system loads or accurate calculation of the needed motor operating loads. As with any LLD this includes estimates of overload conditions. Appropriate uncertainty factors should also be used to account for unexpected loading. Inaccurate estimating of operating loads can result in a motor that stalls out too early.

(6) Estimated Cost. Custom motors for a spillway Tainter gate in NWP have been purchased from Baldor. The motor was designed to reach locked rotor torque at 140% of full load torque. The 7.5 hp, 1,725 rpm motors were purchased for approximately $3,000.

(7) Considerations. If the overload characteristics of custom wound motors are reduced, there is less allowance for accommodating unknown loads. Design loads (torque and power) of custom wound motors need to be accurately estimated. This should include calculating overload conditions such as gate ice and mud gravity loads. Designers should consider using uncertainty factors when loads are not fully known. The accuracy of the performance of these motors is sensitive to the motor supply voltage. The motor manufacturer recommends these motors be supplied by a source that is constant to +/-3% of nominal voltage. If the power fluctuates more than +/- 3% it is recommended to install a constant voltage transformer to the motor supply circuit to ensure that these motors are performing per design.

h. Torque Switch.

(1) General Description.

A torque switch can be regarded as a shaft coupling comprising of two opposing plates that are pressed together axially by a spring, magnetic coil, or pneumatic pressure (Figure D-13). They are coupled through balls residing in detents in the face of the plates. During an over-torque condition the balls roll out of the detents, separating the plates enough to trigger a limit switch or proximity sensor shuts down the system.

There are both load holding and non-load holding torque switches. Load holding devices will continue to transmit torque upon overload. Non-load-holding devices will release the load. In hoisting applications, only load-holding LLDs should be used.

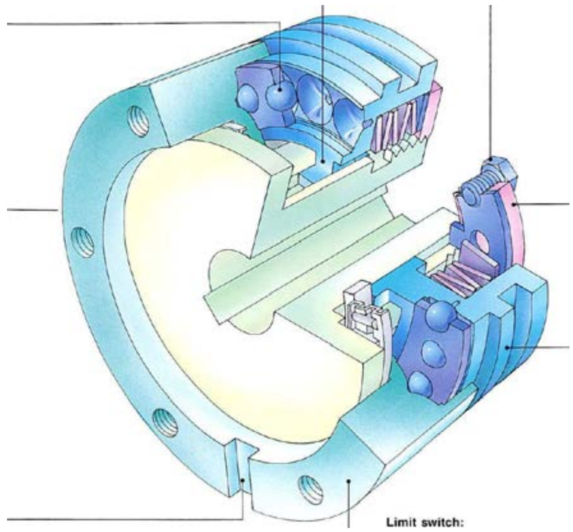


Figure D-13. Torque Switch.

(2) Lag Time.

Device lag time is stated by one manufacturer to be 3ms. It commences upon onset of overload, when relative rotation and separation between the two halves begins. It continues until they separate sufficiently far to trigger the switch or proximity sensor to open a circuit or assert a stop signal. The estimated worst case lag time from when the overtorque occurs to when the motor circuit is opened is 41 ms (lag time is calculated based on refresh rate of device and pick-up/dropout time of control circuit relay). The load does not increase during this time because of this relative rotation. (Note that the load holding devices will resume transmitting load once the relative rotation has completed.)

All other delays arise from the time it takes the hoist system to respond to the output of the device.

(3) Accuracy. One manufacturer quotes ±5% of setting. Because of its simplicity (spring loaded balls in detents), available sealed construction and binary (on/off, go/no-go, etc.) output characteristic, there is little to cause drift in the triggering torque of the device.

(4) Calibration. Applying torque to the shaft with a torque wrench and an appropriate adapter can be done to measure triggering torque as desired. This can allow precise setting of the device during initial installation and confirmation or during subsequent maintenance. This will also confirm proper activation of the limit switch or proximity sensor.

(5) Reliability. Most ball-detent torque switches are good for about 1,000 to 2,000 overloads. Stainless steel and sealed units are available, making them suitable for outdoor use.

(6) Pros:

- Reasonably accurate.
- Stable calibration.

- User settable.
- Setting is easily checked with simple tools and methods.
- Robust.
- Fast responding among reactionary devices.
- Simple.
- Minimal additions to the motor control circuit.

(7) Cons:

- As opposed to a torque limiting motor, the torque switch is a reactionary device. Like all reactionary devices, torque excess must be applied before it can be sensed and signaled, resulting in the unavoidable latent delays in the hoist system shutdown process.
- Weather protection MAY be needed for the limit switch or proximity sensor.
- Torque switches do not measure the load applied directly to the gate structure. They measure the torque applied to the system at one point in the power train. Efficiencies of power train elements between the switch and the gate need to be accurately estimated to determine an accurate load applied to the gate structure.

(8) Estimated Cost. Cost for stainless steel sealed units at a representative torque rating was quoted in 2013 at $3200 and $3600 for non-load holding and load holding devices respectively. (Not included: limit switch or proximity sensor, cabling, weather protection dog house, and interposing relay).

(9) Considerations:

- Weather Protection – The limit switch or proximity sensor may need some weather protection, such as a “doghouse” to protect from precipitation, ice, and sun if used outdoors.
- The device will require a few inches of accessible shaft that drives both sides of the gate. If none exists, a more costly alternative might be to use a device on each side of the gate.
- Though very robust, the device is not likely repairable if welded/sealed. The user will want to keep spares on-hand.

i. Overload Device.

(1) General Description. Typically overload devices offer load protection by monitoring current, when an overload condition is detected the overload would drop out the motor contactor stopping the motor. Figure D-14 shows an example of an overload device. There are overload devices that have the ability to calculate and monitor power running to a specific load, and also have several protective functions that the relay can be programmed to protect against, i.e., thermal overload, jam protection, current imbalance, current phase loss, and others. The protection that would

be used for this discussion is jam protection. When the motor starts up, the overload disables the jam protection until the motor is in its “run” state, which is a specific amount of time based on the motor parameters, at which time the protection is enabled. This protection is programmed in the relay as a percentage of full load current of the motor. When this percentage of current is reached, the relay is programmed to open a relay output contact thus removing power from the motor control circuit, stopping the motor and setting the brake to hold the load.

Figure D-14. Example of Eaton C441 Motor Insight Overload.

(2) Lag Time. These overload device jam protection features are programmed from (1-10 sec) in the relay. This means that the minimum amount of time an overtorque condition must be met before the relay contact will open is 1 second, which in itself may be able to be designed around if known during the design phase of a project. The issue of the jam protection feature being disabled on startup until the motor has reached the “run” state is unacceptable for these purposes. If the gate is jammed and the operator tried to open the gate, the motor would overload immediately and continue until the run state has been reached, the overload detected, and finally the relay contact opens.

(3) Accuracy. The accuracy of the overload limit can be impacted by the motor overload device. The advertised accuracy is +/-2%, but this can be affected by incorrect settings programmed into the device, motor parameter change over time due to degradation, and other factors.

(4) Calibration. These overload devices should be shop tested by the manufacturer to verify the desired overload properties are provided. A relay test bench that can provide 480V and 120V power is required to shop test the protection features of this device. There is no easy way to test the relay installed in the control cabinet, and no way to test the motor running characteristics or protection features of this relay in the field.

(5) Pros:

- Easily integrates into existing control schemes.
- Replaces standard thermal overload.
- Many protective features available.
- A variety of communication modules is available if there is a need to monitor/protect a remotely operated device.

(6) Cons:

- No jam protection on startup.
- Lag time is 1 second minimum, plus any lag time for other devices (control relays) that would be needed to completely integrate this device into the motor controls.

(7) Estimated Cost. The estimated cost for the device is $1200, plus the cost of additional electrical control components.

(8) Considerations:

- No protection on startup is largest issue for this device. This leaves all of the systems vulnerable—a risk this organization if unwilling to take. This device will not meet design criteria.
- Space constraints for installation at facilities in existing control cabinets may affect the difficulty of using these devices.

D-8. Evaluation Matrix.

a. General.

An evaluation matrix was developed that served to rank to the various LLDs. Evaluation factors and sub-factors were chosen by the committee and then weighted. The purpose of weighting was to delineate the importance between installing the LLD into a new design or retrofitting it into an existing design, which may be more difficult. The evaluation factors chosen are:

- Cost.
- Lag time.
- Accuracy.
- Reliability.
- Maintenance.
- Weatherability.
- Complexity.

Each LLD was rated by each committee member against each evaluation sub-factor. Then, the LLD was given an overall rating by each committee member. These ratings were then averaged to come up with an overall rating for each device. This overall rating was then used with weighting factors.

b. Completed Evaluation Matrix. Figures D-15 to D-18 show the completed Evaluation Matrix.

LLD Committee Evaluation Matrix

Weight Factors New	Weight Factors Retro	Evaluation Factors	In-Line Torque Transd'r BF	DH	MH	AN	ST	C-Faced Torque Transd'r BF	DH	MH	AN	ST	VFD BF	DH	MH	AN	ST	Custom Wound Motor BF	DH	MH	AN	ST
		OVERALL RATING	New	8.8		Retro	12.2	New	9.9		Retro	13.4	New	8.6		Retro	11.4	New	13.1		Retro	17.0
1.0	3.0	**Cost** Overall Quantitative Average			4.0					3.8					3.0					5.0		
		Overall Qualitative	VG	VG	VG	VG	VG	VG	G	VG	VG	VG	G	G	G	G	G	E	E	E	E	E
		Sub-Factors initial purchase price			6k					9k					8k					2k		
		Initial purchase. Quantitative.	VG	VG	VG	VG	VG	G	G	G	G	G	G	G	G	G	G	E	E	E	E	E
		Design and installation time. Qualitative.	VG	G	G	G	G	VG	G	VG	VG	VG	G	S	G	G	S	E	E	E	E	E
		Routine maintenance costs. Qualitative.	E	E	VG	VG	E	E	VG	VG	VG	E	E	E	VG	VG	VG	E	E	E	E	E
3.0	4.0	**Lag time** Overall Quantitative Average			3.0					3.0					4.0					5.0		
		Overall	G	G	G	G	G	G	G	G	G	G	VG	VG	VG	VG	VG	E	E	E	E	E
		Sub-Factors (and lag time)			41ms					41ms					20ms					0ms		
		Lag time: short lagtime[1] is excellent. Quantitative.	G	G	G	G	G	G	G	G	G	G	VG	VG	VG	VG	VG	E	E	E	E	E
2.0	3.8	**Accuracy** Overall Quantitative Average			5.0					5.0					3.0					3.0		
		Overall	E	E	E	E	E	E	E	E	E	E	G	G	G	G	G	G	G	G	G	G
		Sub-Factors (and accuracy)			+/- .1%					+/- .1%					+/- 2 to 5%					+/- 3%		
		Accuracy. Quantitative.	E	E	E	E	E	E	E	E	E	E	G	G	G	G	G	G	G	G	G	G
5.0	5.0	**Reliability** Overall Quantitative Average			3.0					3.8					3.0					5.0		
		Overall	G	G	G	G	G	VG	VG	VG	G	VG	VG	VG	G	S	S	E	E	E	E	E
		Sub-Factors			6					7					2					0		
		# components that make up whole LLD. Quanti.	G	G	G	G	G	G	G	G	G	G	VG	VG	VG	VG	VG	E	E	E	E	E
		device robustness, qualitative. Weight heavier.	G	G	G	S	S	VG	VG	VG	G	VG	VG	VG	G	S	G	E	E	E	E	E
		tolerance from neglect (high is better)	VG	VG	VG	VG	VG	VG	VG	VG	VG	VG	G	M	M	M	M	E	E	E	E	E
		This LLD doesn't increase #/components in system.																				
4.0	4.0	**Maintenance** Overall Quantitative Avg			3.0					3.0					3.4					4.0		
			G	G	G	G	G	G	G	G	G	G	VG	VG	G	G	G	VG	VG	VG	VG	VG
		Sub-Factors																				
		User friend fix/replace? If so, excellent. Qualitative.	G	G	G	G	G	G	G	G	G	G	VG	G	S	S	M	VG	VG	VG	E	E
		User friend to trbl shoot?If so, excellent. Qualitative.	G	G	G	G	G	G	G	G	G	G	G	G	S	S	S	VG	VG	VG	VG	E
		Access, once installed. Readily accessible is excellent. Qualitative.	G	G	G	G	G	VG	G	G	VG	G	E	E	E	E	E	VG	VG	VG	VG	VG
		Routine calibration/maintenance needed? No routine calibration/maintenance is excellent. Annual is good. Qualitative.	G	G	G	G	G	G	G	G	G	G	E	E	E	E	VG	E	E	E	E	E
		Testing. An easy to test device is excellent. Qualitative.	VG	VG	G	G	G	VG	VG	G	G	VG	VG	G	VG	G	VG	VG	G	VG	G	VG
		Lead time for replacement. Discreet.	VG	VG	VG	VG	VG	VG	VG	VG	VG	VG	VG	VG	VG	VG	VG	G	G	G	G	G
		Lead time			1-2 weeks					1-2 weeks					1-2 weeks					3 weeks		

Figure D-15. Evaluation Matrix Page 1.

LLD Committee Evaluation Matrix

Weight Factors New	Weight Factors Retro	Evaluation Factors	LLD's: In-Line Torque Transd'r (Evaluators)					C-Faced Torque Transd'r (Evaluators)					VFD (Evaluators)					Custom Wound Motor (Evaluators)				
			BF	DH	MH	AN	ST	BF	DH	MH	AN	ST	BF	DH	MH	AN	ST	BF	DH	MH	AN	ST
3.5	3.5	Weatherability Overall Quantitative Avg	2.2					3.0					2.0					5.0				
		Overall	S	G	S	S	S	G	G	G	G	G	G	S	G	M	M	E	E	E	E	E
		Sub-Factors																				
		Does the LLD need substantial weather protection or none? None is excellent.	S	G	S	S	S	G	G	G	G	G	G	S	G	M	M	E	E	E	E	E
1.5	3.0	Complexity Overall Quantitative Avg	2.6					3.4					2.6					4.8				
		Overall	S	S	G	G	G	G	G	VG	G	VG	G	G	G	S	S	VG	E	E	E	E
		Sub-Factors																				
		Easy to add to existing or new design req'd? Min effort is excellent.	S	S	G	G	G	G	G	VG	G	VG	G	G	G	S	S	VG	E	E	E	E
		Overall																				
		Sub-Factors																				

Key	
Excellent	E
Very Good	VG
Good	G
Satisfactory	S
Marginal	M
Unsatisfactory	U

Footnotes

1. A short lag time that would be considered acceptable would be a lag time that does not appreciably add to the force in the wire ropes. Currently, the maximum force in the wire ropes is equal to the amount of force required to lift the gate in a single-sided hoisting configuration multiplied by a hoisting reliability factor of 10%. What is the additional force added to the wire ropes per ms of lag time? Lag time is from when an overload is applied to when the system shuts down and no additional load is being applied to the wire ropes.
2. No protection at start-up. Jam protection only after motor meets run state.

Figure D-16. Evaluation Matrix Page 2.

LLD Committee Evaluation Matrix

		Evaluation Factors	LLD's																			
			Running Line Tension'tr					Torque Switch					Overload Device									
			Evaluators					Evaluators					Evaluators					Evaluators				
Weight Factors New	Retro		BF	DH	MH	AN	ST	BF	DH	MH	AN	ST	BF	DH	MH	AN	ST	BF	DH	MH	AN	ST
		OVERALL RATING	New	8.9		Retro	11.1	New	9.6		Retro	12.6	New	0.0		Retro	0.0					
1.0	3.0	Cost Overall Quantitative Average			1.0					4.0					4.0							
		Overall Qualitative	M	M	M	M	M	VG	VG	VG	VG	VG	VG	VG	VG	VG	VG	VG	VG	VG	VG	VG
		Sub-Factors																				
		initial purchase price			22k					5k					1.5k							
		Initial purchase. Quantitative.	M	M	M	M	M	VG	VG	VG	VG	VG	E	E	E	E	E					
		Design and installation time. Qualitative.	M	S	M	M	M	G	G	VG	VG	VG	VG	VG	VG	VG	VG					
		Routine maintenance costs. Qualitative.	VG	E	G	VG	G	E	E	VG	VG	E	VG	VG	VG	VG	VG					
3.0	4.0	Lag time Overall Quantitative Average			3.0					3.0					0.0							
		Overall	G	G	G	G	G	G	G	G	G	G	U	U	U	U	U					
		Sub-Factors (and lag time)			41ms					41ms					1040ms*							
		Lag time: short lagtime1 is excellent. Quantitative.	G	G	G	G	G	G	G	G	G	G	U	U	U	U	U					
		See note 2.																				
2.0	3.8	Accuracy Overall Quantitative Average			4.0					3.0					4.0							
		Overall	VG	VG	VG	VG	VG	G	G	G	G	G	VG	VG	VG	VG	VG					
		Sub-Factors (and accuracy)			+/- 1%					+/- 5%					+/- 2%							
		Accuracy. Quantitative.	VG	VG	VG	VG	VG	G	G	G	G	G	VG	VG	VG	VG	VG					
5.0	5.0	Reliability Overall Quantitative Average			3.0					4.0					5.0							
		Overall	G	G	G	G	G	VG	VG	VG	VG	VG	E	E	E	E	E					
		Sub-Factors			4					3					0							
		# components that make up whole LLD. Quanti.	G	G	G	G	G	VG	VG	VG	VG	VG	E	E	E	E	E					
		device robustness, qualitative. Weight heavier.	G	G	G	G	G	VG	VG	VG	VG	VG	E	E	VG	VG	E					
		tolerance from neglect (high is better)	M	G	G	S	G	VG	VG	VG	VG	E	E	E	E	E	E					
		This LLD doesn't increase #/components in system.																				
4.0	4.0	Maintenance Overall Quantitative Avg			2.2					3.2					3.8							
			S	S	G	S	S	G	G	G	G	VG	VG	VG	VG	G	VG					
		Sub-Factors																				
		User friend fix/replace? If so, excellent. Qualitative.	S	S	G	S	M	G	G	G	G	G	VG	VG	VG	VG	VG					
		User friend to trbl shoot?If so, excellent. Qualitative.	G	VG	G	G	G	VG	VG	VG	VG	VG	VG	G	VG	G	G					
		Access, once installed. Readily accessible is excellent. Qualitative.	M	S	S	M	M	G	G	G	G	G	E	E	E	E	E					
		Routine calibration/maintenance needed? No routine calibration/maintenance is excellent. Annual is good. Qualitative.	G	G	G	G	G	G	VG	G	G	VG	G	G	VG	G	G					
		Testing. An easy to test device is excellent. Qualitative.	VG	VG	VG	VG	G	VG	VG	G	VG	E	VG	G	VG	G	G					
		Lead time for replacement. Discreet.	M	M	M	M	M	S	S	S	S	S	VG	VG	VG	VG	VG					
		Lead time			8-10 weeks					4-5 weeks					1-2 weeks							

Figure D-17. Evaluation Matrix Page 3.

LLD Committee Evaluation Matrix

Weight Factors		Evaluation Factors	LLD's																			
			Running Line Tension'tr					Torque Switch					Overload Device									
			Evaluators					Evaluators					Evaluators					Evaluators				
New	Retro		BF	DH	MH	AN	ST	BF	DH	MH	AN	ST	BF	DH	MH	AN	ST	BF	DH	MH	AN	ST
3.5	3.5	**Weatherability Overall Quantitative Avg**	4.8					3.2					4.4									
		Overall	E	E	E	VG	E	G	G	G	G	VG	E	VG	VG	VG	E					
		Sub-Factors																				
		Does the LLD need substantial weather protection or none? None is excellent.	E	E	E	VG	E	G	G	G	G	VG	E	VG	VG	VG	E					
1.5	3.0	**Complexity Overall Quantitative Avg**	2.4					3.0					4.0									
		Overall	S	G	G	S	S	G	G	G	G	G	VG	VG	VG	VG	VG					
		Sub-Factors																				
		Easy to add to existing or new design req'd? Min effort is excellent.	S	G	G	S	S	G	G	G	G	G	VG	VG	VG	VG	VG					
		Overall																				
		Sub-Factors																				

Key	
Excellent	E
Very Good	VG
Good	G
Satisfactory	S
Marginal	M
Unsatisfactory	U

Figure D-18. Evaluation Matrix Page 4.

c. LLD Ranking. The data in Table D-2 summarize the results of the Evaluation Matrix.

Table D-2. LLD Evaluation Matrix Score and Ranking Summary.

LLD	Score		Ranking	
	New Installation	Retrofit Installation	New Installation	Retrofit Installation
In-Line Torque Transducer	8.8	12.2	5	4
C- Faced Torque Transducer	9.9	13.4	2	2
VFD	8.6	11.4	6 (worst)	5
Custom Wound Motor	13.1	17.0	1 (best)	1 (best)
Running Line Tensionometer	8.9	11.1	4	6 (worst)
Torque Switch	9.6	12.6	3	3

d. Load Limiting Devices Not Evaluated. The following devices were not evaluated since they did not meet specific minimum requirements.

(1) Speed Sensor. During start up there is no protection from this device. Therefore, this device does not meet design criteria.

(2) Current Limiting Devices. There are several current limiting devices that were discussed.

(3) Circuit Breaker. This device is not desirable since:

- It has no adjustment.
- It has a slow response time.
- It does not perform well for torque control.

(4) Power Resistor. This device is not desirable since:

- The manufacturer does not think it would be good for this application.
- This device is meant to perform at start-up not for continuous operation.

e. Load Limiting Devices for non-Radial Gate Applications. This section includes LLDs that may have an application for non-radial gates such as vertical lift gates. They are included here for reference.

(1) Spring at Dead End of Rope.

Walla Walla District (NWW) uses a spring as a LLD for their vertical spillway lift gates at McNary Lock and Dam. The spring is attached to the dead end of the wire rope system that lifts the gate. Attached to the spring is a trip arm which mechanically trips a limit switch when the spring is compressed beyond a set limit. Reference Figure D-19. NWW does not have any type of LLD on their Tainter gates.

Figure D-19. McNary Dam Vertical Lift Spillway Gate LLD (spring)

This system would not work well with these spillway gates, which are primarily Tainter gates. Currently, the dead end of the wire rope is located at the gate lug, which is usually submerged. If the gate's lifting system were to be retrofitted and the dead end relocated on the deck as shown in Figure D-19, then a relative large diameter sheave would need to be placed at the gate lug, which would be problematic due to its size. These devices may have an application for vertical lift spillway gates.

(2) Load Pin at Gate Lug.

Rock Island District uses this type of LLD for their vertical lift gates. Consider a shackle that is used for rigging (Figure D-20). A strain gage is attached to the pin of the shackle which can be used to determine load. The load can then be sent to a PLC to ultimately de-energize the hoisting system.

It was agreed that this LLD probably would not work for these Tainter gates since there is a submerged condition at the dead end of the wire ropes. Electrical connections would not be reliable in a submerged condition. High flow velocities and debris impact could also affect the reliability of these types of LLDs on these Tainter gates. These devices may have an application for vertical lift spillway gates.

Figure D-20. Typical Lifting Shackle.

APPENDIX E

Inspection Record of Wire Rope and Accessories for Gate-Lifting Devices

E-1. Inspection Record Form.

1.0 IDENTIFICATION DATA

1.1 Project ____

1.2 Location ____

1.3 Gate Type ____

____

1.4 Gate Location ____

____

1.5 Gate Number ____

1.6 Application/Service/Environment ______________________________

1.7 Wire Rope Number/Location ________________________________

1.8 Multi Part Wire Rope – Yes or No ____________________________

1.9 Date Inspection ____

1.10 Inspector ____

2.0 WIRE ROPE DESIGN

2.1 Rope Design and Construction (For example 6x37 IWRC, EIPS) ____________

____

2.2 Material ____

2.3 Nominal Diameter (in service) ________________________________

2.4 Effective Diameter (new) ____________________________________

2.5 Tensile Strength (new) ______________________________________

2.6 Rope Length (new) ______________________________________

2.7 Lay of Rope (left, right, lang, regular) __________________________

2.8 Termination Connection Design ________________________________

2.9 Working Hours/Years of Service/Age ____________________________

2.10 Multi Part Wire Rope Equal Tension Verified Yes or No ______________

3.0 CONDITION OF WIRE ROPE

3.1 Which Rope(s)? ____

____

3.2 Diameter Reduction. What is the rope's current diameter? (Under constant load & at the reference location, graph time vs. reduction.)

____

____

3.3 Stretch. How much has the rope stretched? (Under constant load, graph time vs. stretch.) ____

____

____

3.4 Abrasion. How much (percent) reduction in outer diameter?

____

____

____

3.5 Broken Wires. Maximum number per lay and per strand? Describe any valley breaks or crown breaks. ____

____

____

3.6 Corrosion. Describe any corrosion, and give locations. Describe any area(s) of pitting corrosion. Include photographs and sketches. _______________________________________

____

____

____

3.7 Other Damage. Is there any evidence of peening, scrubbing, kinks, bird caging, or any other damage occurring in a localized area, and if so, describe?

____

____

____

____

3.8 Lubrication. Describe if the wire rope is lubricated or has been regularly lubricated. ___

____

____

3.9 Rope Jacket (if applicable). Describe condition of outer rope jacket or coating – provide condition of galvanizing if applicable

3.10 Potential Overstressing. Have any incidents occurred which could have stressed the wire rope above its design limits? Describe and give details

____
____
____

3.11 Check tension in Multi Part Wire Ropes – Note Measurements

____
____
____

3.12 Category I, Category II, Category III deficiencies. Describe and note specifically any deficiencies in these categories. Note exact location and type of deficiency.__________
____
____

4.0 WIRE ROPE FITTINGS

4.1 Which Fittings? ____
____
____

4.2. Wear. Describe any wear.____
____
____

4.3 Cracks. Are there any cracks? ____
____
____

4.4 Broken Wires. Has more than one wire failed adjacent to any fitting?

____
____

4.5 Corrosion. Check for corrosion at the wire rope to termination fitting interface. Describe ____

____

5.0 SHEAVES, PULLEYS, & DRUMS

5.1 Which one(s)? ____

____

____

5.2 Groove Diameters. Are the groove diameters within tolerance? (Measure with "go/no-go" gauges and groove gauges – grooves need to be within tolerance of wire rope diameter.) Note specific measurements. ____________________

____

____

____

5.3 Wear Patterns. Describe any wear patterns in the grooves. Does the wire rope over the drum grooves show any abnormal wear? Does the wire rope fit properly in the drum grooves? ____

____

____

____

5.4 Other. Are there any broken flanges, wobble in the bearings, broken flanges, flat spots, or off center groove wear? ____________________________

____

____

Notes: (1) Reference: Chapter 8 of EM 1110-2- 3200 – minimum wire rope inspection requirement is once per year for all USACE civil works facilities. (2) The condition of the wire rope and its accessories should be assessed both in absolute terms and in comparison to previous inspections. (3) Attach photographs, sketches, or additional sheets if more room is needed. (4) Include additional discussion and photographs of any Category I, Category II, or Category III deficiency

WIRE ROPE INSPECTION SUMMARY SHEET

Gate Number: ____

Wire Rope Location: ____

Year Installed: ____

Diameter New: ____

Wire Construction and Material: ______________________________

Position of Measurement	Wire Breaks	Abrasion	Corrosion/Pitting	Diameter Reduction %	Crushing	Other

Attach photographs as necessary

____

____

____

Final Assessment: Provide discussion and write up below

____

____

____

Date and Signature of Inspector

____

____

E-2. OSHA Fact Sheet, Cranes and Derricks in Construction: Wire Rope — Inspection.

OSHA® FactSheet

Subpart CC – Cranes and Derricks in Construction: Wire Rope – Inspection

This fact sheet describes the inspection requirements of subpart CC – Cranes and Derricks in Construction, as specified in 29 CFR 1926.1413. These provisions are effective November 8, 2010. This document is intended to assist wire rope inspectors and supervisors.

Inspection Trigger	Inspection Details	Performed by	Documentation
Each shift	See list below, visual inspection must begin prior to each shift in which the equipment is used.	Competent Person	Not required
Monthly	See details below.	Competent Person	Required. Must be signed by the person who conducted the inspection and retained for a minimum of 3 months.
Annual	See details below.	Qualified Person	Required. Must be signed by the person who conducted the inspection and retained for a minimum of 12 months.

- The annual/comprehensive and monthly inspections must be documented according to 1926.1412(f)(7) and 1916.1412(e)(3), respectively.
- Rope lubricants of the type that hinder inspection must not be used.
- All documents produced under this section must be available, during the applicable document retention period, to all persons who conduct inspections under this section.

Shift Inspection

Shift inspections are visual inspections that a competent person must begin prior to each shift during which the equipment is used. Shift inspections do not require untwisting (opening) of wire ropes or booming down. The inspection must consist of observation of wire ropes (running and standing) that are likely to be in use during the shift for apparent deficiencies, including the following:

Apparent Deficiencies – Category I	Removal from Service Criteria
• Significant distortion of the wire rope structure such as kinking, crushing, unstranding, birdcaging, signs of core failure, or steel core protrusion between the outer strands. • Significant corrosion. • Electric arc damage (from a source other than power lines) or heat damage. • Improperly applied end connections. • Significantly corroded, cracked, bent, or worn end connections (such as from severe service).	If a Category I deficiency is identified, the competent person must immediately determine whether it constitutes a safety hazard. If the deficiency is determined to be a safety hazard, all operations involving use of the wire rope in question must be prohibited until: • The wire rope is replaced. (See 1926.1417), or • If the deficiency is localized, the problem is corrected by severing the wire rope in two; the undamaged portion may continue to be used. Joining lengths of wire rope by splicing is prohibited. If a rope is shortened under this paragraph, the employer must ensure that the drum will still have two wraps of wire when the load and/or boom is in its lowest position.

Apparent Deficiencies – Category II	Removal from Service Criteria

• Visible broken wires:
  ◦ In running wire ropes: six randomly distributed broken wires in one rope lay or three broken wires in one strand in one rope lay, where a rope lay is the length along the rope in which one strand makes a complete revolution around the rope.
  ◦ In rotation-resistant ropes: two randomly distributed broken wires in six rope diameters or four randomly distributed broken wires in 30 rope diameters.
  ◦ In pendants or standing wire ropes: more than two broken wires in one rope lay located in rope beyond end connections and/or more than one broken wire in a rope lay located at an end connection.
• A diameter reduction of more than 5% from nominal diameter.
	If a Category II deficiency is identified, operations involving use of the wire rope in question must be prohibited until:
	• Employer complies with the wire rope manufacturer's established criterion for removal from service, or with a different criterion that the wire rope manufacturer has approved in writing for that specific wire rope. (See 1926.1417).
	• The wire rope is replaced. (See 1926.1417), or
	• If the deficiency is localized, the problem is corrected by severing the wire rope in two; the undamaged portion may continue to be used. Joining lengths of wire rope by splicing is prohibited. If a rope is shortened under this paragraph, the employer must ensure that the drum will still have two wraps of wire when the load and/or boom is in its lowest position.

Apparent Deficiencies – Category III	Removal from Service Criteria
• In rotation-resistant wire rope, core protrusion or other distortion indicating core failure. • Prior electrical contact with a power line. • A broken strand.	If a Category III deficiency is identified, operations involving use of the wire rope in question must be prohibited until: • The wire rope is replaced. (See 1926.1417), or • If the deficiency (other than power line contact) is localized, the problem is corrected by severing the wire rope in two; the undamaged portion may continue to be used. Joining lengths of wire rope by splicing is prohibited. Repair of wire rope that contacted an energized power line is also prohibited. If a rope is shortened under this paragraph, the employer must ensure that the drum will still have two wraps of wire when the load and/or boom is in its lowest position.

Where a wire rope is required to be removed from service under this section, either the equipment (as a whole), or the hoist with that wire rope must be tagged-out, in accord with 1926.1417(f)(1), until the wire rope is repaired or replaced.

Critical Review Items

Particular attention must be given to all of the following:

- Rotation-resistant wire rope in use.
- Wire rope being used for boom hoists and luffing hoists, particularly at reverse bends.
- Wire rope at flange points, crossover points, and repetitive pickup points on drums.
- Wire rope at or near terminal ends.
- Wire rope in contact with saddles, equalizer sheaves or other sheaves where rope travel is limited.

Monthly Inspection

Each month an inspection must be conducted as stated under "Shift Inspection" above.

In addition to the criteria for shift inspection, monthly inspections require that:

- The inspection must include any deficiencies that the qualified person who conducts the annual inspection determines under 1926.1413(c)(3)(ii) must be monitored.
- Wire ropes on equipment must not be used until an inspection under this paragraph demonstrates that no corrective action under 1926.1413(a)(4) is required.
- The inspection must be documented according to 1926.1412(e)(3) (monthly inspection documentation).

Annual/Comprehensive Inspection

At least every 12 months, wire ropes in use on equipment must be inspected by a qualified person as stated under "Shift Inspection" above.

In addition to the criteria for shift inspection, annual inspections require that –

- The inspection must be complete and thorough, covering the surface of the entire length of the wire ropes, with particular attention given to all of the following:
  - Critical review items from 1926.1413(a)(3)–(see "Critical Review Items" above).
  - Those sections that are normally hidden during shift and monthly inspections.
  - Wire rope subject to reverse bends.
  - Wire rope passing over sheaves.

Exception

In the event an annual inspection under 1926.1413(c)(2) is not feasible due to existing set-up and configuration of the equipment (such as where an assist crane is needed) or due to site conditions (such as a dense urban setting), such inspections must be conducted as soon as it becomes feasible, but no longer than an additional 6 months for running ropes and, for standing ropes, at the time of disassembly.

- If a deficiency is determined to constitute a safety hazard, operations involving use of the wire rope in question must be prohibited until:
  - The wire rope is replaced (see 1926.1417), or
  - If the deficiency is localized, the problem is corrected by severing the wire rope in two; the undamaged portion may continue to be used. Joining wire rope by splicing is prohibited. If a rope is shortened under this paragraph, the employer must ensure that the drum will still have two wraps of wire when the load and/or boom is in its lowest position.
- If a deficiency is identified and the qualified person determines that, though not presently a safety hazard, the deficiency needs to be monitored, the employer must ensure that the deficiency is checked in the monthly inspections.

Additionally

- The inspection must be documented according to 1926.1412(f)(7).
- Rope lubricants of the type that hinder inspection must not be used.
- All documents produced under this section must be available, during the applicable document retention period, to all persons who conduct inspections under this section.

This is one in a series of informational fact sheets highlighting OSHA programs, policies or standards. It does not impose any new compliance requirements. For a comprehensive list of compliance requirements of OSHA standards or regulations, refer to Title 29 of the Code of Federal Regulations. This information will be made available to sensory-impaired individuals upon request. The voice phone is (202) 693-1999; teletypewriter (TTY) number: (877) 889-5627.

For assistance, contact us. We can help. It's confidential.

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APPENDIX F

Glossary of Terms, Acronyms, and Abbreviations

F-1. Glossary of Terms.

Abrasion
: Frictional surface wear on the wires of a wire rope.

Acceleration Stress
: The additional stress that is imposed on a wire rope as a result of an increase in the load velocity.

Actuator
: A mechanical device, like a cylinder or hydraulic motor, used to convert hydraulic energy into mechanical energy.

Aggregate Strength
: The strength derived by adding the individual breaking strengths of the elements of the strand or rope. This strength does not recognize the reduction in strength resulting from the angularity of the elements in the rope, or other factors that may affect efficiency.

Aircraft Cables
: Strands, cords and wire ropes made of special-strength wire, designed primarily for use in various aircraft industry applications.

Alternate Lay
: Lay of a wire rope in which the strands are alternately regular and Lang Lay.

Area, Metallic
: Sum of the cross-sectional areas of all the wires either in a wire rope or in a strand.

Armored Rope
: Rope with individual strands spirally wrapped with flat steel wire.

Back-Stay
: Guy used to support a boom or mast; or that section of a main cable, as on a suspension bridge, cableway, etc., leading from the tower to the anchorage.

Bail
: Either: (1) U-shaped member of a bucket, or (2) U-shaped portion of a socket or other fitting used on wire rope.

Basket of Socket
: The conical portion of a socket into which a broomed-rope-end is inserted and then secured.

Becket

An end attachment to facilitate wire rope installation.

Becket Loop

A loop of small rope or strand fastened to the end of a larger wire rope. Its function is to facilitate wire rope installation.

Bending Stress

Stress that is imposed on the wires of a strand or rope by a bending or curving action.

Birdcage

A colloquialism descriptive of the appearance of a wire rope forced into compression. The outer strands form a cage and, at times, displace the core.

Block

A term applied to a wire rope sheave (pulley) enclosed in side plates and fitted with some attachment such as a hook or shackle.

Boom Hoist Line

Wire rope that operates the boom hoist system of derricks, cranes, draglines, shovels, etc.

Boom Pendants

A non-operating rope or strand with end termination to support the boom.

Breaking Strength

Breaking Strength is the ultimate load at which a tensile failure occurs in the sample of wire rope being tested. (Note: The term "breaking strength" is synonymous with actual strength.) Minimum Acceptance Strength is that strength that is 2½% lower than the catalog or nominal strength. This tolerance is used to offset variables that occur during a sample preparation and actual physical test of a wire rope. Nominal Strength is the published (catalog) strength calculated by a standard procedure that is accepted by the wire rope industry. The wire rope manufacturer designs wire rope to this strength, and the user should consider this strength when making design calculations.

Bridge Cable

(Structural Rope or Strand) The all-metallic wire rope or strand used as the catenary and suspenders on a suspension bridge.

Bridge Socket

A wire rope or strand end termination made of forged or cast steel that is designed with baskets-having adjustable bolts-for securing rope ends. There are two styles: (1) the closed type has a U-bolt with or without a bearing block in the U of the bolt, and (2) the open type has two eye-bolts and a pin.

Bridle Sling

A two-part wire rope sling attached to a single-part line. The legs of the sling are spread to divide and equalize the load.

<u>Brinell Hardness</u>

A system to measure the hardness of metals by indentation. A hardened steel ball is pressed into a smooth surface of the metal under a fixed load and the resulting indentation is microscopically measured. With a conversion chart, This number can also be used to determine the approximate tensile strength of the same metal.

<u>Bright Rope</u>

Wire rope fabricated from wires that are not coated. The term bright refers to a wire rope manufactured with no protective coating or finish other than lubricant.

<u>Bronze Ropes</u>

Wire rope made of bronze wires.

<u>Button Conveyor Rope</u>

Wire ropes to which buttons or discs are attached at regular intervals to move material in a trough.

<u>Cable</u>

A term loosely applied to wire rope, wire strand and electrical conductors.

<u>Cable-Laid Wire Rope</u>

A type of wire rope consisting of several wire ropes laid into a single wire rope (e.g., 6x42 (6x6x7) tiller rope).

<u>Cable Tool Drilling Line</u>

The wire rope used to operate the cutting tools in the cable tool drilling method (i.e., rope drilling).

<u>Center</u>

The axial member of a strand about which the wires are laid.

<u>Centralized Lubrication</u>

A system of non-recirculating lubrication that supplies a metered amount of lubricant from a central location to individual lubrication points.

<u>Chain Lubrication</u>

A dip or splash system that uses a chain to distribute lubricant to bearings, similar, in a way, to an oil ring; or any system designed to lubricate a conveyor chain.

<u>Choker Rope</u>

A short wire rope sling that forms a slip noose around an object that is to be moved or lifted.

<u>Classification</u>

Group, or family designation based on wire rope construction and cross section with common strengths and weights listed under the broad designation.

<u>Clevis</u>

A “U” shaped fitting with a pin.

<u>Clip</u>

Fitting for clamping two parts of wire rope to each other.

<u>Closed Socket</u>

A wire rope end termination consisting of basket and bail made integral.

<u>Closer</u>

A machine that lays strands around a core to form rope.

<u>Closing Line</u>

Wire rope that performs two functions: (1) closes a clamshell or orange peel bucket, and (2) operates as a hoisting rope.

<u>Coil</u>

Circular bundle or package of wire rope that is not affixed to a reel.

<u>Come-along</u>

Device for making a temporary grip on a wire rope.

<u>Common Strand</u>

Galvanized strand made of galvanized iron wire whose grade is common iron.

<u>Conical Drum</u>

Grooved hoisting drum of tapering diameter.

<u>Consistency</u>

(Pertains to grease), describes the hardness of a grease (its resistance to deformation), indicating relative softness or hardness with the application of force. Test method ASTM D-217 measures the extent of penetration of a cone under a fixed load and for a specific interval. In general, the greater the penetration, the softer the grease. Using this method, NLGI grades the softest grease (deepest penetration) as 000, the hardest as 6.

<u>Construction</u>

Geometric design description of the wire rope’s cross section. This includes the number of STRANDS, the number of WIRES per strand and the pattern of wire arrangement in each STRAND.

<u>Constructional Stretch</u>

The stretch that occurs when the rope is loaded. Constructional stretch is due to the helically laid wires and strands creating a constricting action that compresses the core and generally brings all of the rope’s elements into close contact.

Continuous Bend
Reeving of wire rope over sheaves and drums so that it bends in the same direction, as opposed to reverse bend.

Cord
Term applied to small sizes of wire ropes.

Core
The axial member of a wire rope about which the strands are laid.

Coring Line
Wire rope used to operate the coring tool for taking core samples during the drilling of a well.

Corrosion
Chemical decomposition of the wires in a rope through the action of moisture, acids, alkalines or other destructive agents.

Corrosion-Resisting Steel
Chrome-nickel steel alloys designed for increased resistance to corrosion.

Corrugated
Term used to describe the grooves of a SHEAVE or DRUM after these have been worn down to a point where they show an impression of a wire rope.

Creep
The unique movement of a wire rope with respect to a drum surface or sheave surface resulting from the asymmetrical load between one side of the sheave (drum) and the other. It is not dissimilar to the action of a caterpillar moving over a flat surface. It should be distinguished from “slip,” which is yet another type of relative movement between rope and the sheave or drum surface.

Critical Diameter
The diameter of the smallest bend for a given wire rope that permits the wires and strands to adjust themselves by relative movement while remaining in their normal position.

Crowd Rope
A wire rope used to drive or force a power shovel bucket into the material that is to be handled.

Cylindrical Drum
Hoisting drum of uniform diameter.

Dead-Line
In drilling, it is the end of the rotary drilling line fastened to the anchor or dead-line clamp.

Deceleration Stress

The additional stress that is imposed on a wire rope as a result of a decrease in the load velocity.

Design Factor

In a wire rope, it is the ratio of the nominal strength to the total working load.

Diameter

A line segment that passes through the center of a circle and whose end points lie on the circle. As related to wire rope it would be the diameter of a circle that circumscribes the wire rope.

Dog-Leg

Permanent bend or kink, in a wire rope, caused by improper use or handling.

Dragline

A dragline is: (1) wire rope used for pulling excavating or drag buckets, and (2) name applied to a specific type of excavator.

Drum

A cylindrical flanged barrel, either of uniform or tapering diameter, on which rope is wound either for operation or storage; its surface may be smooth or grooved.

Dynamometer Test

A test measuring rope tension, usually during break-in.

Efficiency

Ratio of a wire rope’s actual breaking strength and the aggregate strength of all individual wires tested separately-usually expressed as a percentage.

Elastic Limit

Stress limit above which permanent deformation will take place within the material.

End Preparation

The treatment of the end of a length of wire rope designed primarily as an aid for pulling the rope through a reeving system or tight drum opening. Unlike END TERMINATIONS, these are not designed for use as a method for making a permanent connection.

End Termination

The treatment at the end or ends of a length of wire rope, usually made by forming an eye or attaching a fitting and designed to be the permanent end termination on the wire rope that connects it to the load.

Endless Rope

Rope with ends spliced together to form a single continuous loop.

Equalizing Sheave

The sheave at the center of a rope system over which no rope movement occurs other than equalizing movement. It is frequently overlooked during crane inspections, with disastrous consequences. It can be a source of severe degradation.

Equalizing Thimble

Special type of fitting used as a component part of some wire rope slings.

Extra Improved Plow, Steel Rope (EIPS)

A specific wire rope grade -higher nominal strength.

Extra High Strength Strand

A grade of galvanized or bright strand.

Eye or Eye Splice

A loop, with or without a thimble, formed at the end of a wire rope.

Factor of Safety

In the wire rope industry, this term was originally used to express the ratio of nominal strength to the total working load. The term is no longer generally used since it implies a permanent existence for this ratio when, in actuality, the rope strength begins to reduce the moment it is placed in service. See DESIGN FACTOR.

Fatigue

As applied to wire rope, the term usually refers to the process of progressive fracture resulting from the bending of individual wires. These fractures may and usually do occur at bending stresses well below the ultimate strength of the material; it is not an abnormality although it may be accelerated due to conditions in the rope such as rust or lack of lubrication.

Fiber Center

Cord or rope of vegetable or synthetic fiber used as the axial member of a strand.

Fiber Core

Cord or rope of vegetable or synthetic fiber used as the axial member of a rope.

Filler Wire

Small spacer wires within a strand that help position and support other wires. Also the name for the type of strand pattern utilizing filler wires.

Fitting

Any functional accessory attached to a wire rope.

Flat Rope

Wire rope that is made of a series of parallel, alternating right-lay and left-lay ropes, sewn together with relatively soft wires.

Flattened Strand Rope

Wire rope that is made either of oval or triangular shaped strands to form a flattened rope surface.

Fleet Angle

That angle between the rope's position at the extreme end wrap on a drum, and a line drawn perpendicular to the axis of the drum through the center of the nearest fixed sheave. See DRUM and SHEAVE.

Galvanized

Zinc coating for corrosion resistance.

Galvanized Rope

Rope made of galvanized wire.

Galvanized Strand

Strand made of galvanized wire.

Galvanized Wire

Wire coated with zinc.

Grade

Wire rope or strand classification by strength and/or type of material, i.e., Improved Plow Steel, Type 302 Stainless, Phosphor Bronze, etc. It does not imply a strength of the basic wire used to meet the rope's nominal strength.

Grades, Rope

Classification of wire rope by the wire's metallic composition and the rope's nominal strength.

Grommet

An endless circle or ring fabricated from one continuous length of strand or rope.

Grooved Drum

Drum with a grooved surface that accommodates the rope and/or wire rope and guides it for proper winding.

Grooves

Depressions-helical or parallel-in the surface of a sheave or drum that are shaped to position and support the rope.

Guard Rail Cable

A galvanized wire rope or strand erected along a highway.

Guy Line

Strand or rope, usually galvanized, for stabilizing or maintaining a structure in fixed position.

<u>Haulage Rope</u>
Wire Rope used for pulling movable devices such as cars that roll on a track.

<u>Hawser</u>
Wire rope, usually galvanized, used for towing or mooring marine vessels.

<u>High Strength Strand</u>
Grade of galvanized or bright strand.

<u>High Stranding</u>
A failure where one strand of a rope loosens and sticks out from the other strands of a rope.

<u>Holding Line</u>
Wire rope on a clamshell or orange peel bucket that suspends the bucket while the closing line is released to dump its load.

<u>Idler</u>
Sheave or roller used to guide or support a rope.

<u>Improved Plow Steel Rope</u>
A specific grade of wire rope.

<u>Independent Wire Rope Core (IWRC)</u>
A wire rope used as the axial member of a larger wire rope.

<u>Inner Wires</u>
All wires of a strand except the outer or cover wires.

<u>Internally Lubricated</u>
Wire rope or strand having all of its wire components coated with lubricants.

<u>Iron Rope</u>
A specific grade of wire rope.

<u>Kink</u>
A unique deformation of a wire rope caused by a loop of rope being pulled down tight. It represents irreparable damage to and an indeterminate loss of strength in the rope.

<u>Lagging</u>
Lagging is either: (1) External wood covering on a reel to protect the wire rope or strand, or (2) the grooved shell of a drum.

Lay

"Lay" refers to (1) The manner in which the wires in a strand or the strands in a rope are helically laid, or (2) the distance measured parallel to the axis of the rope (or strand) in which a strand (or wire) makes one complete helical convolution about the core (or center). In this connection, lay is also referred to as LAY LENGTH or PITCH.

Lay Types

Right or left lay refers to the direction in which the strands rotate around the wire rope. If the strands rotate around the rope in a clockwise direction (as the threads do in a right hand bolt), the rope is said to be right lay. When the strands rotate in a counterclockwise direction (as the threads do in a left hand bolt), the rope is left lay.

- Right Lay: The direction of strand or wire helix corresponding to that of a right hand screw thread.
- Left Lay: The direction of strand or wire helix corresponding to that of a left hand screw thread.
- Cross Lay: Rope or strand in which one or more operations are performed in opposite directions. A multiple operation product is described according to the direction of the outside layer.
- Regular Lay: The type of rope wherein the lay of the wires in the strand is in the opposite direction to the lay of the strand in the rope. The crowns of the wires appear to be parallel to the axis of the rope.
- Lang Lay: The type of rope in which the lay of the wires in the strand is in the same direction as the lay of the strand in the rope. The crowns of the wires appear to be at an angle to the axis of the rope.
- Alternate Lay: Lay of a wire rope in which the strands are alternately regular and lang lay.
- Albert's Lay: An old, rarely used term for lang lay.
- Reverse Lay: Another term for alternate lay.
- Spring Lay: This is not definable as a unique lay; more properly, it refers to a specific wire rope construction.

Lead Line

That part of a rope tackle leading from the first, or fast, sheave to the drum.

Line

Synonymous term for WIRE ROPE.

Locked Coil Strand

Smooth-surfaced strand ordinarily constructed of shaped, outer wires arranged in concentric layers around a center of round wires.

Loop
A 360 degree change of direction in the course of a wire rope, which, when pulled down tight, will result in a kink.

Lubricant
Substance interposed between two surfaces in relative motion for the purpose of reducing the friction and/ or wear between them.

Lubrication
Reduction of friction or wear between two load-bearing surfaces by the application of a lubricant; includes boundary lubrication (thin or interrupted fluid film, especially bearings where wear occurs); mixed film, where some liquid pools support the load; elastohydrodynamic (high-pressure loads increase the lubricant’s viscosity and load-carrying capacity, especially in gears); hydrodynamic (a thick fluid film lubrication, especially in journal bearings) and hydrostatic (external pump pressure used to form a thick fluid film, as in start-up of journal bearings).

Marline Spike
Tapered steel pin used in splicing wire rope.

Martensite
A brittle micro-constituent of steel formed when the steel is heated above its critical temperature and rapidly quenched. This occurs in wire rope as a result of frictional heating and the mass cooling effect of the cold metal beneath. Martensite cracks very easily, and such cracks can propagate from the surface through the entire wire.

Mild Plow Steel Rope
A specific grade of wire rope.

Milking (Sometimes Called “Ironing”)
“Milking” is the progressive movement of strands along the axis of the rope, resulting from the rope’s movement through a restricted passage such as a tight sheave.

Modulus of Elasticity
Mathematical quantity expressing the ratio, within the elastic limit, between a definite range of unit stress on a wire rope and the corresponding unit elongation.

Mooring Lines
Galvanized wire rope, usually 6x12, 6x24, or 6x37 class for holding ships to dock.

Nominal Strength
The industry accepted strength of a rope of a certain size, material, and construction.

Non-Preformed
Rope or strand that is not preformed. See PREFORMED STRANDS and PREFORMED ROPE.

Non-Rotating Wire Rope
Term, now abandoned, referring to 19 x 7 or 18 x 7 rope.

Non-Spinning Wire Rope
See ROTATION RESISTANT ROPE.

Open Socket
A wire rope fitting that consists of a basket and two ears with a pin. See FITTING.

Outer Wires
Outer layer of wires.

Part Number
The number of load bearing ropes for a sheave.

Pin
A rope guide of small diameter.

Peening
Permanent distortion resulting from cold plastic metal deformation of the outer wires. Usually caused by pounding against a sheave or machine member, or by heavy operating pressure between rope and sheave, rope and drum, or rope and adjacent wrap of rope.

Plow Steel Rope
A specific grade of wire rope. A grade of steel above traction steel, referring to its original use of pulling plows.

Preece Test
A recognized standard of testing the galvanized coating on a wire.

Preformed Strands
Strand in which the wires are permanently formed during fabrication into the helical shape they will assume in the strand.

Preformed Wire Rope
Wire rope in which the strands are permanently formed during fabrication into the helical shape they will assume in the wire rope.

Prestressing
An incorrect reference to PRESTRETCHING.

Prestretching
Subjecting a wire rope or strand to tension prior to its intended application, for an extent and over a period of time sufficient to remove most of the CONSTRUCTIONAL STRETCH.

Proportional Limit

As used in the rope industry, this term has virtually the same meaning as ELASTIC LIMIT. It is the end of the load versus elongation relationship at which an increase in load no longer produces a proportional increase in elongation and from which point recovery to the rope's original length is unlikely.

Rated Capacity

The load that a new wire rope or wire rope sling may handle under given operating conditions and at an assumed DESIGN FACTOR.

Reel

A flanged spool on which wire rope or strand is wound for storage or shipment.

Reeve

To pass a rope through a hole or around a system of sheaves.

Reserve Strength

The strength of a rope exclusive of the outer wires.

Reverse Bend

Reeving a wire rope over sheaves and drums so that it bends in opposing directions.

Rollers

Relatively small-diameter cylinders, or wide-faced sheaves, that serve as support for ropes.

Rotary Line

On a rotary drilling rig, it is the wire rope used for raising and lowering the drill pipe, as well as for controlling its position.

Rotation-Resistant Rope

A wire rope consisting of an inner layer of strand laid in one direction covered by a layer of strand laid in the opposite direction. This has the effect of counteracting torque by reducing the tendency of finished rope to rotate.

Round-Wire Track Strand

Strand composed of concentric layers of round WIRES, used as TRACK CABLE.

Safety Factor (see Design Factor)

Safe Working Load

This term is potentially misleading and is, therefore, in disfavor. Essentially, it refers to that portion of the nominal rope strength that can be applied either to move or sustain a load. It is misleading because it is only valid when the rope is new and equipment is in good condition. See RATED CAPACITY.

Sand Line

In well drilling, it is the wire rope that operates the bailer that removes water and drill cuttings.

Seale

The name for a type of strand pattern that has two adjacent layers laid in one operation with any number of uniform sized wires in the outer layer, and with the same number of uniform but smaller sized wires in the inner layer. This construction has two layers of wires around a center with the same number of wires in each layer. All wires in each layer are the same diameter. The strand is designed so that the large outer wires rest in the valleys between the smaller inner wires.

Seize

To make a secure binding at the end of a wire rope or strand with SEIZING WIRE or SEIZING STRAND.

Seizing Strand

Small strand usually of 7 wires made of soft annealed wire.

Seizing Wire

Soft annealed wire.

Serve

To cover the surface of a wire rope or strand with a fiber cord or wire wrapping.

Shackle

A “U” or anchor-shaped fitting with pin.

Sheave

A grooved pulley for wire rope.

Single Layer

The most common example of the single layer construction is a 7-wire strand. It has a single-wire center with six wires of the same diameter around it.

Sling, Wire Rope

An assembly fabricated from WIRE ROPE that connects the load to the lifting device.

Sling, Braided

A flexible sling, the body of which is made up of two or more WIRE ROPES braided together. See SLINGS.

Smooth-Faced Drum

Drum with a plain, ungrooved surface. See DRUM.

Socket

Generic name for a type of wire rope fitting.

Speltered Socket
Either a zinc- or epoxy-filled socket.

Spin Resistant
An abandoned term referring to a ROTATION-RESISTANT rope of the 8 x 19 classification.

Spiral Groove
A continuous helical groove that follows a path on and around a drum face, similar to a screw thread. See DRUM.

Splicing:
“Splicing” refers to: (1) making a loop or eye in the end of a rope by tucking the ends of the strands back into the main body of the rope, or (2) a formation of loops or eyes in a rope by means of mechanical attachments pressed onto the rope, or (3) the joining of two rope ends so as to form a long or short splice in two pieces of rope.

Stainless Steel Rope
Wire rope made up of corrosion resistant steel wires.

Steel Clad Rope
Rope with individual strands spirally wrapped with flat steel wire.

Stone Sawing Strand
A plurality of round or shaped wires helically laid about an axis.

Strand
The bundles of wires laid helically around a rope’s core.

Strander
A machine that lays wires together helically to form a strand.

Stress
The force or resistance within any solid body against alteration of form. In the case of a solid wire, it would be the load on the rope divided by the cross-section area of the wire.

Stretch
The elongation of a wire rope under load.

Swaged Fitting
Fitting into which wire rope can be inserted and then permanently attached by cold pressing (swaging) the shank that encloses the rope.

Tag Line
A small wire rope used to prevent rotation of a load.

Tapering and Welding
: Reducing the diameter of the end of a wire rope and welding it to facilitate reeving.

Tensioning
: Adjusting the tensions of the individual ropes on a multi-rope device.

Terminal Efficiency
: Strength of a rope terminal compared to that of the rope.

Thimble
: Grooved metal fitting to protect the eye, or fastening loop of a wire rope.

Tiller Rope Cable
: A very flexible operating rope, commonly made by laying six 6x7 ropes around a fiber core resulting in a 6x42 construction. As well as, a 3/32 inch 7x7 galvanized cable coated to an outside diameter of 3/16 inch with vinyl or nylon.

Tinned Wire
: Wire coated with tin.

Track Cable
: On an aerial system it is the suspended wire rope or strand along which the carriers move.

Traction Rope
: On an aerial conveyor or haulage system it is the wire rope that propels the carriages.

Traction Steel Rope
: A specific lower grade of wire rope.

Tramway
: An aerial conveying system for transporting multiple loads.

Turn
: Synonymous with the term WRAP; it signifies a single wrap around a drum.

Turnbuckle
: Device attached to wire rope for making limited adjustments in length. It consists of a barrel and right and left hand thread bolts.

Warrington
: The name for a type of strand pattern that is characterized by having one of its wire layers (usually the outer) made up of an arrangement of alternately large and small wires. This construction has two layers of wires around a center with one diameter of wire in the inner layer, and two diameters of wire alternating large and small in the outer layer. The larger outer layer wires rest in the valleys, and the smaller ones on the crowns, of the inner layer.

Wedge Socket

Wire rope fittings wherein the rope end is secured by a wedge.

Wire (Round)

A single, continuous length of metal, with a circular cross-section that is cold-drawn from rod.

Wire Rope

A plurality of wire strands helically laid about an axis.

Wire Strand Core (WSC)

A wire strand used as the axial member of a wire rope.

F-2. Acronyms and Abbreviations.

Term	Definition
AASHTO	American Association of State Highway and Transportation Officials
API	American Petroleum Institute
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
BHN	Brinell Hardness Number
BS	British Standard Institution
CECW	Directorate of Civil Works, US Army Corps of Engineers
CFR	Code of the Federal Regulations
COF	Coefficient of Friction
DIN	Deutsches Institut für Normung [the German national standards organization]
EEIPS	Extra Extra Improved Plow Stee
EIPS	Extra Improved Plow Steel
EM	Engineer Manual
EP	Extreme Pressure
ER	Engineer Regulation
FC	Fiber Core
FOS	Factor of Safety
HSS	Hydraulic Steel Structures
IPS	Improved Plow Steel
ISO	International Standards Organization
IWRC	Independent Wire Rope Core

Term	Definition
MSHA	Mine Safety and Health Administration
NDT	Non-Destructive Testing
NWD	Northwestern Division
NWDR	Northwestern Division Deviation Policy
O&M	Operations and Maintenance
OSHA	Occupational Safety and Health Administration
PE	Polyethylene
PIANC	Permanent International Association of Navigation Congresses
PLC	Programmable Logic Controller
PS	Plow Steel
SC	Strand Core
TCVM	Taut Cable Vibration Method
TS	Traction Steel
UFGS	Unified Facilities Guide Specification
UHMW	Ultra High Molecular Weight
USACE	U.S. Army Corps of Engineers
WRTB	Wire Rope Technical Board
WS	Wire Strand
WSC	Wire Strand Core