or eliminated by enforcement of proper construction procedures by other parties, including contacting the local one-call center and implementation of subsurface utility engineering procedures, the inability to conveniently add new cables is a more fundamental problem. This limitation is the motivation for the belowground cable network alternatives, as described in Chapter 5.

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4

CABLE INSTALLATION METHODS IN DUCT

There are three basic methods for placing utility cables within ducts that have previously been installed in the field:

- pulling,
- pushing, and
- blown cable.

All three methods have been applied in industry, and each has its advantages, limitations, and range of application. The methods continue to evolve, with innovations based on the cable characteristics and newly introduced products. Some techniques and equipment combine elements of these categories. Additional information for placing cables in conduit is provided in *The Plastics Pipe Institute Handbook of Polyethylene Pipe* (PPI 2006).

Another alternative to placing the cable in the field after installation of the duct is the use of preinstalled cable within HDPE duct (sometimes called "cable-in-duct"). In all methods, the allowable bending radius of the cable must be observed. For example, copper cables should typically not be bent to a radius of less than 10 times the cable diameter, and fiber-optic cables should typically not be bent to a radius of less than 20 times the cable diameter when under tension or 10 times the cable diameter otherwise (Telcordia 1998; RUS 2001).

4.1 PULLING

The most obvious and direct method for installing a cable within a duct, or any cavity, is to connect a rope or pull line to the leading end of the cable, using an appropriate type of grip, and to then pull the cable into the path. Mechanized equipment is typically used because the required pull force is often significant. The force imposes a tensile load on the cable, which must not exceed its allowable tensile capability. Each cable type (e.g., electric power cable, copper pair, optical fiber, or coaxial CATV) is characterized by its own tensile strength. The strength of metallic cables is determined by the metallic conductors providing the transmission path, in combination with additional strength members, including metallic shields, if present. For fiber cables, the strength capability is provided by metallic or nonmetallic (e.g., Kevlar) strength members. The allowable strength of metallic cables therefore varies widely. In comparison, fiber-optic communication cables typically have an allowable tensile load of 600 lb, as specified in industry requirements (Telcordia 1998).

The initial step is usually to provide a pull line in the duct or cavity of interest. This step may be accomplished in various ways, including 1, preinstalling it in the duct (e.g., for continuous HDPE innerduct), 2, blowing it through with (positive or negative) low air pressure applied to a chute towing a lightweight line, used to subsequently pull in a heavier duty rope or pull line, or 3, by inserting a push rod that installs a pull line during its retraction, or which may directly pull the cable itself. One variation that avoids the need to install a pull line is the use of relatively high air pressure (e.g., 100 lb/in.^{2} gauge) with a tight-fitting "piston" to apply a tensile force to a relatively lightweight cable, accomplishing the cable placement (see Section 4.3).

Figure 4-1 shows cable-pulling equipment, and Fig. 4-2 illustrates several typical equipment configurations for pulling cable.

The primary advantage of the pulling technique is its general applicability to any type of cable. The major disadvantage relates to possible placement distances, which are limited by the tension buildup as the cable traverses the route. The tension or pull force at the leading end of the cable is required to offset the drag (resistive) forces that accumulate along the length of the cable. For the simple case of a cable resting on the bottom of a straight duct path, as illustrated in Fig. 4-3, the required tension, T, is given by

$$T = wL\mu \tag{4-1}$$

where w is the weight of the cable per unit length, L is the length of the cable within the duct, and μ is the coefficient of friction between the cable and duct surfaces. This formula is based on the commonly used Coulomb friction model, in which the local frictional drag is proportional to the local normal pressure, such as that resulting from the weight of the cable. Equation 4-1 also assumes that there is no significant restraining load at

Figure 4-1. Cable-Pulling Equipment (Courtesy of HIS Business Mfg. Co.).

the trailing end, such as a load caused by reel resistance. Such resistance, or tail load, T_0, would result in an equivalent increased load at the leading end.

The Coulomb proportionality factor, the coefficient of friction, μ, depends on the inherent mutual surface characteristics. The coefficient of friction may be reduced to more desirable levels by surface treatment, including the addition of lubricants. Such lubricants may be added to the duct immediately before cable installation, although various (HDPE) products are available with lubricant integrated into the plastic compound, or extruded as an additional interior lining. Figure 4-4 shows an externally added lubricant for facilitating the cable installation process.

Based on Eq. 4-1, a lightweight fiber or coaxial cable, with the typically low-friction combination of a polyethylene cable jacket and an HDPE duct, would be predicted to require minimal pull loads, corresponding to relatively large placement distances. For example, a fiber communication

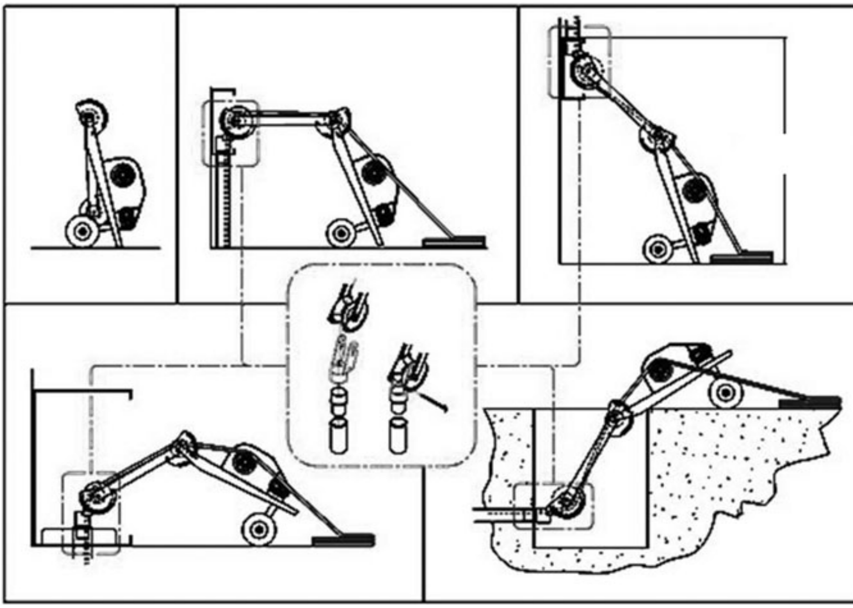

Figure 4-2. Typical Cable-Pulling Setups (Courtesy of HIS Business Mfg. Co.).

cable weighing approximately 0.15 lb/ft, with a coefficient of friction, without lubrication, of 0.35 (Telcordia 1995) when pulled into an HDPE duct, would be predicted by Eq. 4-1 to require only 0.0525 lb/ft. The required tensile strength of 600 lb would therefore suggest potential placement distances of approximately 11,000–12,000 ft—or more than 2 miles. Such predictions greatly overestimate the practical placement distances of considerably less than a mile, on the order of 1,000 ft, and they occur essentially because of effects not considered in the simplified model of Fig. 4-3 and Eq. 4-1.

To better reflect reality, a more complete model must be considered, which includes the aggravating effect of tension at duct bends and curvature. Figure 4-5 illustrates a cable, under tension, pulled around a discrete (local) bend. The tension vectors on the cable, acting at the opposite ends of the bend, are not collinear and therefore result in reaction pressure along the curved surface because the cable is effectively pulled snug against the inside of the bend. This pressure results in increased drag and may be shown to result in a greater tension at the exit of the bend. Thus, for a tension, or tail load, T_0, at the entry, the tension at the exit, or head tension T_1, is given by

$$T_1 = T_0 e^{\mu\theta} \tag{4-2}$$

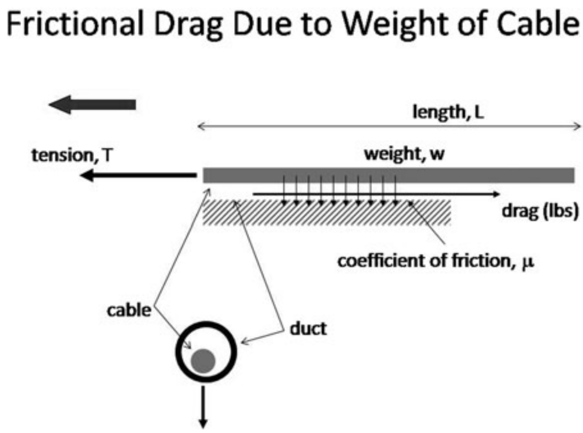

Figure 4-3. Basic Cable-Pulling Mechanism (for a Straight Path) (Courtesy of Outside Plant Consulting Services).

Figure 4-4. Cable Lubricant (Courtesy of American Polywater Corporation).

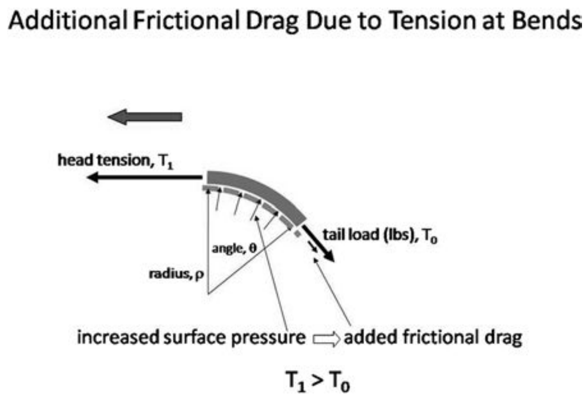

Figure 4-5. Increased Tension at a Discrete Bend (Courtesy of Outside Plant Consulting Services).

where the angle θ is expressed in radians. The exponential term has great significance, effectively acting as a cumulative, compounding effect at discrete bends along the duct path, which is independent of the cable weight, cable stiffness,[1] path radius of curvature, and direction of curvature. This phenomenon is sometimes referred to as the "capstan effect" and is the basis of the capstan winch used on boats to secure the boat to the dock. In this implementation, a rotating drum (capstan) is used to develop a high tension at one end by means of a relatively low tension at the opposite end, based on the cumulative drag around the several loops of rope on the drum (see Fig. 4-6).

For a path with distributed curvature, such as a gradual bend in a horizontal plane, the effect of cable weight plus curvature may be shown to result in the following formula for the tension at the leading end:

$$T_1 = T_0 \cosh(\mu L/\rho) + [T_0^2 + (w\rho)^2]^{1/2} \sinh(\mu L/\rho) \qquad (4\text{-}3)$$

where ρ is the radius of curvature of the horizontal bend. The mathematical cosh and sinh functions contain exponential terms similar to that of Eq. 4-2. For large radii of curvature or high values of initial tension T_0, Eq. 4-3 reduces to Eq. 4-1 or 4-2, respectively. The original analysis for this technology was performed within the power industry and also considered bends in vertical planes for which various equations were developed, depending on the quadrant of the curve (Buller 1949; Rifenberg 1953). The

[1]Cable stiffness is an additional aggravating factor but is not directly considered in the current discussion.

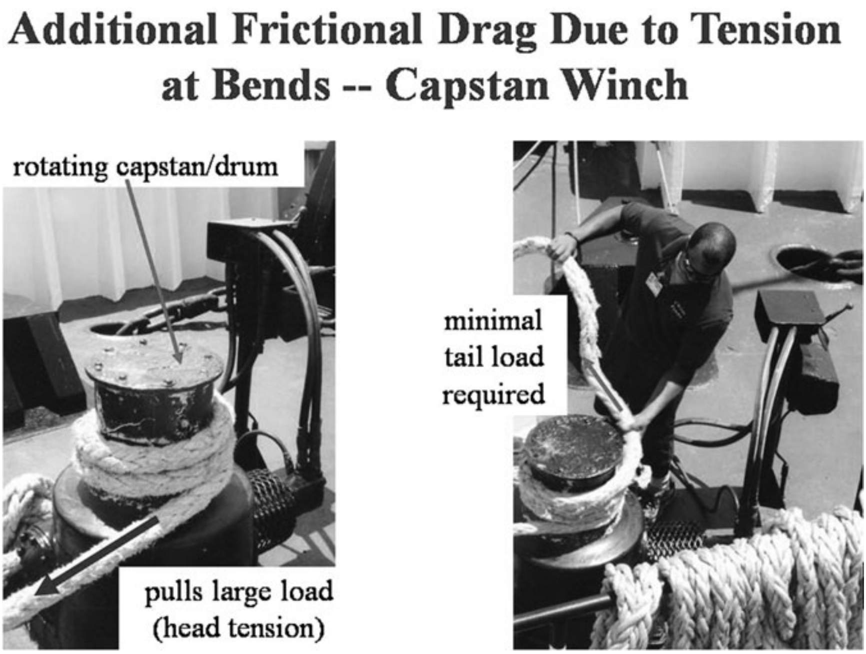

Figure 4-6. Illustration of the Capstan Effect (Courtesy of Outside Plant Consulting Services).

corresponding formulae are contained in *The Plastics Pipe Institute Handbook of Polyethylene Pipe* (PPI 2006). This theory was subsequently applied to communication cables, including more recently developed fiber-optic cable applications (Griffioen 1993).

For practical applications, nominally "straight" rigid conduit paths actually display a small degree of curvature because of some degree of flexibility and corresponding lack of straightness in the installed plastic pipe, combined with possible undulations and spiraling of innerduct placed within the conduit for the subsequent placement of fiber cable. Based on investigations at Bell Telephone Laboratories, an effective curvature of approximately 160° per 1,000 ft—i.e., almost one 90° bend per 500 ft of duct path—may be assumed, which corresponds to an effective radius of curvature ρ of approximately 360 ft.[2] Furthermore, although no tail load is deliberately applied to the cable, an effective initial tension, T_0, corresponding to the weight of 127 ft of (fiber) cable may be assumed. This

[2] Path curvature (radians per unit distance) is equal to the reciprocal of the radius of curvature ρ. One radian equals 57.3°.

assumption is also based on empirical results obtained at Bell Telephone Laboratories, and it may be considered to occur because of a combination of effects, such as coil memory and cable stiffness, resulting in increased reactive pressure at the beginning of the duct path. (A recommended procedure is to manually or mechanically turn the feeder cable reel to avoid or minimize any additional tail load.) In addition to the finite effective curvature along the nominally straight route, there are often discrete bends at sweeps into manholes or other access points, as well as at deliberate planar bends along the route. The combination of all these effects, which may be quantified via sequential application of Eqs. 4-2 and 4-3, results in greatly reduced pulling lengths.

For directly buried flexible HDPE duct (innerduct), the effective curvature would typically be significantly greater than that experienced within the relatively rigid conduit path described earlier (in Section 2.2.2.3), depending on the innerduct construction, size, and method of burial. Trenched installations tend to display the largest effective curvature, with plowed and directionally drilled installations displaying less curvature. Trenched duct may reduce placement distances to much less than 1,000 ft.

In general, the primary limitation of the traditional pulling method for installing cables within pipes is the rapid tension buildup associated with the significant cumulative compounding effects at route bends and path curvature. The need to provide or install a pull line represents an additional inconvenience. The use of air pressure and a piston does avoid the need for a separately installed pull line, but the technique is further limited by the relatively low pull force that may be safely generated by the air compressor (typically 100 lb/in.^{2} gauge) (see Section 4.3).

4.2 PUSHING

Pushing a cable from the near (reel location) end offers some advantages relative to the traditional pulling technique, including elimination of the need for a pull line. Nonetheless, the procedure inherently suffers from similar limitations in potential placement distances. In particular, a capstan effect resulting from the axial forces pushing the cable snugly against the *outside* of the bend also leads to escalating friction forces, with placement distances again severely limited by the presence of duct bends and path curvature. In general, equations analogous to those in Section 4.1 are applicable, resulting in the exponential buildup of required push force because of inevitable path curvature. However, the combination of a conventional cable puller at one end of a duct and a cable pusher at the opposite end can significantly increase the cable placement distances. Figure 4-7 illustrates cable-pushing equipment.