A NEW CABLE PULLING FRICTION MEASUREMENT METHOD AND RESULTS

J. M. Fee, Member, IEEE

D. J. Quist

American Polywater Corporation
11222 - 60th Street North
P.O. Box 53
Stillwater, Minnesota 55082

Abstract - Cable pulling friction coefficients are determined using a specially designed, multiple conduit bend apparatus. The theory of the "multi-bend" method is described. Measurements covering variations in lubrication, cable jacket, cable/conduit size ratio (fill), number of cables, and sidewall pressure are presented. An effective coefficient of friction is determined for cable pulled on top of in-place cable. The data should provide a better understanding of the variables which produce cable pulling tension. Better estimates of tension may also be made possible.

INTRODUCTION

The tension exerted on cables as they are pulled into conduit is a major concern in cable installation. Recent research has focused on how much tension or sidewall pressure cables could safely tolerate, and how tension could be predicted.

Most of the recent research[1][2][3] treats tension as solely a result of the friction of the cable rubbing on the conduit wall. Such research takes measurements of tension and uses these measurements to calculate coefficients of friction. The intent is to provide measured coefficients which can be used for more accurate tension estimation . . . in other conduit systems. In some of this research, a single cable was pulled into straight conduit, and the coefficient of friction was simply calculated from the pulling-tension-to-cable-weight ratio.

$$f = \frac{T_m}{W} \qquad (1)$$

Where:

T_m = Measured Pulling Tension (lbs.)
W = Weight of the Cable (lbs.)
(including add-on "piggyback" weight)
f = Coefficient of Friction (dimensionless)

In other studies, tensions have been measured through conduit systems with bends, and the determination of friction coefficient is a more complicated set of calculations based on the pulling equations developed by Riffenberg and others[4]. When multiple cables were pulled, the occupancy (or weight correction) factor was a part of the coefficient calculation. This occupancy factor has almost universal acceptance in the pulling equations as used today (references [5], [6], [7] and [8]).

Such "calculated" coefficients of friction may include fallacies or omissions in the theory. No attempt has been made to include factors like cable bending forces (stiffness). While there is superb logic in using field-measured tensions (versus lab sled tests, etc.) to determine friction coefficient, we must remain aware of how the coefficients were developed. In this paper, such calculated friction coefficients will be called "effective coefficient of friction ," to remind the reader of their origin.

There are areas of agreement in the cited research.[1][2][3] Common are conclusions on the dependence of the effective coefficient of friction on:

conduit type
cable jacket type
lubricant presence and type
cable normal pressure or sidewall pressure

There is disagreement on any dependence of the effective coefficient of friction on pulling speed. Dependence of the effective coefficient of friction on number of cables[1], temperature[1], and conduit fill[3] is not researched in more than one cited study, so agreement cannot be determined.

All of the studies indicate that greater normal forces between cable and conduit produce lower effective coefficients of friction.

One method proposed to handle this "normal force factor" in tension calculations is to use two different coefficients of friction, one for "high bearing pressures" (>150 lbs./ft. sidewall pressure), and one for "low bearing pressures" (<150 lbs./ft.).[1] The HSBP (high sidewall bearing pressure) coefficient of friction is used only in bends with a small enough radius and high enough exit tension to produce 150 lbs./ft. sidewall pressure or more (defined as exit tension divided by bend radius).

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To expand and clarify this previous research, a unique new testing method was developed. The method was used to evaluate a number of parameters, including the dependence of effective coefficient of friction on normal pressure, conduit fill, jacket type, and number of cables. The results and conclusions can help cable installers better understand the variables producing cable tension, and may lead to better estimates of pulling tension for improved field operations.

BODY

Theory of Multiple Bend Tester

The multi-bend device shown in Figure 1 is simple in concept. It pulls cable through consecutive conduit bends, which produces rapidly increasing tension. One of the limitations of previous pulling research was the enormous time and expense of laying conduit for a single test. On the multi-bend device, conduit and cable could be changed and a series of pulls done at different incoming tensions in about four hours.

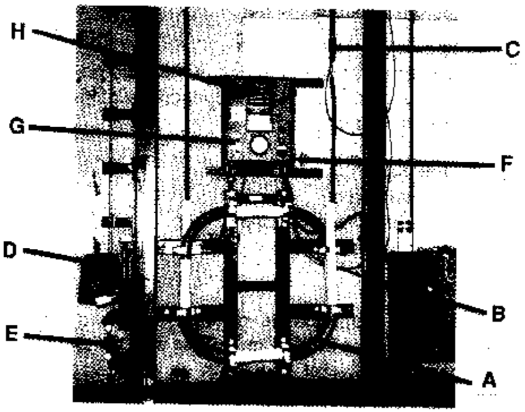

Figure 1. Multi-bend pulling device

On the multi-bend device, the conduit bends (A) are effectively consecutive. As pictured, the conduit has a total of 540° of bend in a one-and-one-half-circle configuration. "Back" tension on the cable entering the conduit is produced with a pneumatic pressure brake (B), and measured with load cell (C). The pulling winch (D) pulls the cable through the bends and the pulling tension is measured with load cell (E).

The device is automatic with a regulator (F) to control the pressure on the back tension brake, switches (G) to control the winch, and digital readouts (H) for the incoming and outgoing tension load cells.

Cable type, conduit type, conduit size, lubricant type, and number of cables could be varied easily on the device. Number of bends and radius of bends also could be varied within limits. Note that sidewall pressure could be indirectly controlled via incoming tension. Higher incoming tension produced higher sidewall pressures throughout the system.

The theory behind the multi-bend device is straightforward. By measuring the incoming and outgoing tensions, the coefficient of friction can be backcalculated from:

$$COF = \frac{2}{Wn\pi} \ln\left(\frac{Tout}{Tin}\right)^{*} \qquad (2)$$

Where:

COF = Effective Coefficient of Friction
n = Number of Bends
Tout = Measured Pulling Tension (Lbs.)
Tin = Measured Incoming Tension (Lbs.)
W = Occupancy or Weight Correction Factor

The machine, as configured in Figure 1, has a winch with a 1,000 lb. capacity. However, the practical limit on pulling tension was 600-800 lbs. On standard 2" and smaller conduits this could produce sidewall pressures in excess of 1,000 lbs./ft. On non-lubricated 600V feeder cables, this could tear the jacket off the cable. While a heavier winch could be incorporated to produce higher tensions, 600-800 lbs. was the limit for the experiments described in this paper.

The machine can hold conduit with an effective cross distance of 3.5 feet. This limits the radius of the bends and the size of the conduit. All of the work described herein was done in 2" and smaller commercially available conduits with standard factory bends.

There are also limits on the size and stiffness of cable(s) that can practically be threaded and pulled around the conduit loop. Very stiff or large diameter cables were not practical. The work described involves cable with OD's from .3 to 1 inch, mostly 600V feeder cable or multi-conductor control cable.

Operating Procedure

The conduit was mounted on the machine, the cable (lubricated or unlubricated) threaded through the conduit and attached to the winch line, the back tension pneumatic brake set at predetermined pressures, and the winch activated. The measured back tension and the pulling tension were recorded. Effective coefficient of friction was calculated from Equation (2).

For each data point, five or six consecutive pulls were done (cable fed back and immediately repulled). The calculated effective coefficient of friction and the incoming tension plotted represent the average. The agreement among the consecutive pulls was very good with usual variations of only a few percent.

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* *Note that this equation is for horizontal bends where cable weight times radius is small compared to entering tension. Comparison calculations with the more elaborate vertical concave bend equations showed no difference in effective coefficient of friction to the third decimal place.*

Consistency

The first series of experiments was to determine the consistency of the machine and of its results. Remember that each data point represents the average reading from at least five consecutive pulls. Figure 2 presents data from "identical" pulls done using the same conduit, same cable, and same lubricant. The first test was done, the conduit disassembled and cleaned, the cable cleaned, and the whole thing reassembled for test #2.

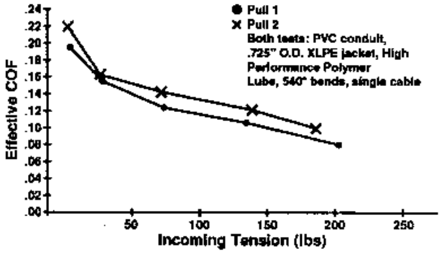

Figure 2. Results variance over two identical pulls

Note that incoming tensions measured in the two tests are not identical because a particular regulator brake setting does not produce exactly the same back tension every time. Regardless, the agreement between the two tests is good.

Coefficient of Friction Dependence on Incoming Tension

The data in Figure 2 demonstrate a universal characteristic of this testing. The effective coefficient of friction decreases as we increase incoming cable tension; in other words, as sidewall pressure in the system increases.

In a multiple bend system like this, the sidewall pressure is different out of each bend. Only a crude interpretation of a "bend" of 540° would allow a "constant" sidewall pressure, equal to the final pulling tension divided by bend radius.

A more reasonable approach is to break the system into its natural configuration of six right angle bends. The effective friction data from test #1 in Figure 2 are replotted in Figure 3 against the sidewall pressure out of the last bend. Noted in parentheses by the data point is the (last bend, first bend) sidewall pressure. Four "sidewall pressures" between these two also existed in the system.

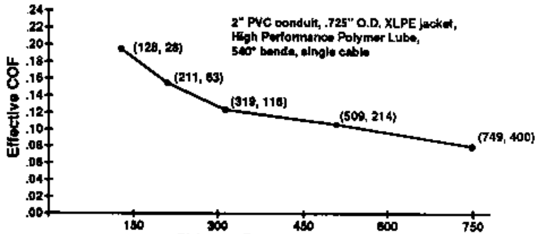

Figure 3. Pull #1 coefficients plotted against final bend sidewall pressure

The data in Figure 3, confirmed throughout this research, indicate that the change in coefficient of friction with normal pressure is continuous, and a large part of the transition occurs below 150 lbs./ft. It does appear that above some sidewall pressure the coefficient of friction levels off and becomes somewhat constant (at least up to 700 lbs./ft. sidewall pressure). It would appear that the use of a <u>single</u> LSBP (low sidewall bearing pressure) coefficient of friction under 150 lbs./ft. and a <u>single</u> HSBP (high sidewall bearing pressure) coefficient of friction over 150 lbs./ft., could lead to errors in tension estimation.

The sidewall pressure above which the effective coefficient of friction might reasonably be regarded as a constant cannot be determined in our multi-bends. A single coefficient of friction at low sidewall pressure does not look nearly as reasonable, especially when all the graphs are reviewed. While the graphs skew up at lower sidewall pressure, there is considerable inconsistency. The brake could not produce accurate back tensions under 10 lbs., which typically inflated thru six bends to 150 lbs. of pulling tension. To get better data and definition at the low end of sidewall pressure, a system with fewer bends could be tried.

Effective Friction Coefficient Dependence on Cable Jacket Type

The data plotted in Figure 4 show three different cable jackets pulled through 2" PVC conduit. At the higher incoming tensions, the PVC and XLPE are very close, but the Nylon® coating is notably higher friction.

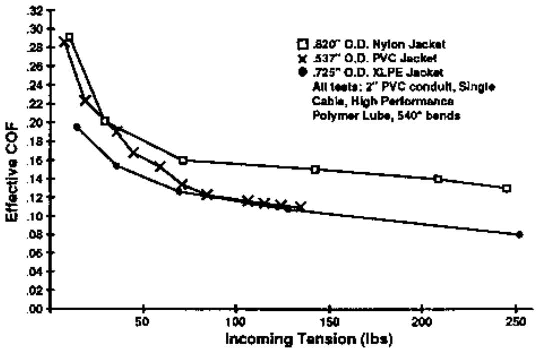

Figure 4. Three different types of cable (jacket) pulled through same conduit

Time and material availability limited this test to only a few jacket types. The observed variation of effective coefficient of friction with cable jacket type is consistent with the other studies.

Lubricated Versus Unlubricated Cable

With the 540° of bends, it was not possible to pull an <u>unlubricated</u>, single cable at all, even at the lowest incoming tension (10 lbs.). Thus, the effective coefficient of friction of unlubricated cable (PVC and XLPE jacket in PVC conduit) was above 0.45, but we don't know how much. This compares with lubricated (with a high performance polymer lube) effective coefficients of friction of .22 to .08 for these same jackets, conduits and single cables. Again, measurements with a fewer bend modification might define the upper end for unlubricated cable.

Coefficient of Friction Dependence on Conduit Fill

For the data graphed in Figure 5, two different XLPE-jacketed, single cables (one of .725" OD and one of .370" OD) were pulled into 1" and 2" PVC conduit. This resulted in 52% and 14% conduit fill in the 1" conduit and 13% and 4% conduit fill in the 2" conduit.

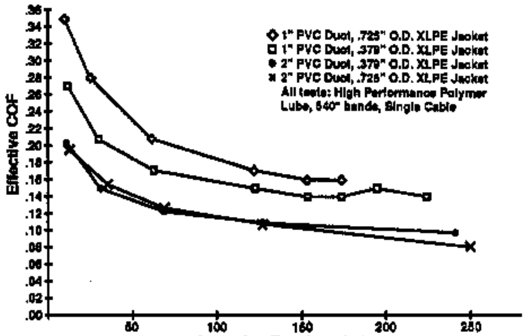

Figure 5. Pull Results from two different size cables in two different size conduits

The effective friction coefficient results are very similar for both fills (13% and 4%) of cable in the 2" conduit, but are higher and different for the 52% and 14% fill levels in the 1" conduit. It would appear that conduit fill, at least at the high end for single cables, can affect effective coefficient of friction. Conduit fill for single cables represents a relationship between cable size and conduit size.

There is also an indication that effective coefficient of friction may vary with conduit size, but this is not clear. The two sizes of conduit, while both PVC, had visibly different inside surface textures. The 2" was smooth, while the 1" was patterned and rougher. This difference might also explain the higher effective friction coefficients for the smaller conduit.

Effective Friction Coefficient Dependence on Number of Cables

Another variation of cable-to-conduit size relationships is introduced by pulling multiple cables. This conduit fill is not the only factor at work, since multiple cables have multiple rubbing surfaces as well as increased rubbing forces produced by the cables' configuration and pressures against each other.

The data graphed in Figure 6 below is the first where the weight correction or occupancy factor [see "W" in Equation (2)] was not 1. For the .765 cable pulled (first one cable, then two cables, and finally three cables), the "W" was 1, 1.27 and 1.27 respectively. The conduit fills were 15%, 29% and 44% respectively.

While the one-and-two-cable variations could be threaded thru six bends, the three-cable could not, and the conduit was modified to two bends for the three-cable pull (as noted on Figure 6). To make a more valid comparison, the "x" axis on Figure 6 represents pulling tension, rather than the incoming tension.

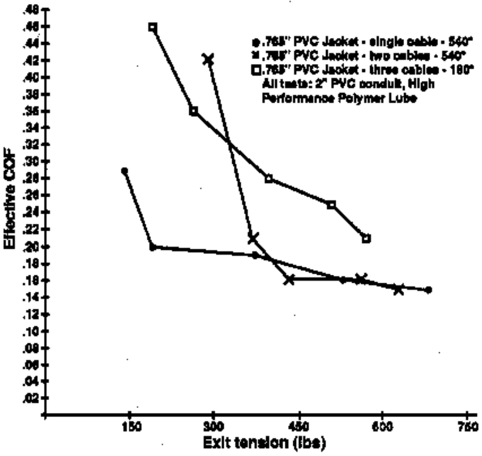

Figure 6. Pull Results for multiple cables

Figure 6 shows large differences in effective coefficient of friction at the low sidewall pressure end, with less significant differences at high sidewall pressures. In fact, the one-and-two-cable pulls are quite close at the high end. Remember that the conventional weight correction factor (vector force correction for cable configuration) is already in the effective coefficient of friction determination for the two-(and-three)-cable pulls.

It is interesting to note that the three-cable pull does show higher effective coefficients of friction across the board than the one and two. This could be a wedging/jamming phenomena and/or a fill effect. The 40% fill is well above conventional "jamming" ratios. More extensive studies are needed to answer these questions.

Effective Friction Coefficient for Cable on Cable

A set-up was devised for pulling cable on top of cable. The two cables labeled "B" and "C" in Figure 7 were pulled and clamped tight in the conduit loop. Then "A" was pulled in the groove formed by "B" and "C".

Figure 7. Cable A was pulled on top of in-place cables B or C

While cable "A" could be pulled with back tensions up to 170 lbs., it would try to wedge itself between "B" and "C" and move them sideways. Surging began at 15 lbs. back tension, which had not happened with cable into conduit pulls.

There is also a weight correction factor for cable "A" of:

$$W = \frac{1}{\sqrt{1 - \left(\frac{d'}{d + d'}\right)^2}} \qquad (3)$$

Where:

d = diameter of "A" (inches)
d' = diameter of "B" and "C" (inches)

Figure 8 graphs the effective coefficient of friction of the cable pulled on top of cable. Even with the surging, the friction coefficients are in the same range as cable pulled into conduit (.20 to .25 at LSBP and .10 to .15 at HSBP).

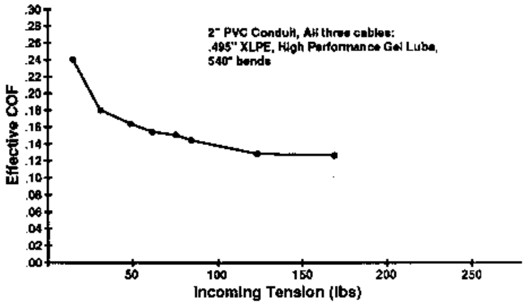

Figure 8. Effective friction coefficient pulling one cable on top of two in-place cables

It is easy to see how complicated the wedging forces could get in a complex pull-by situation. While our data indicates the effective friction coefficients of jacket-on-jacket (lubricated) are not extraordinary, the wedging and jamming factors could combine to produce unpredictable tension.

CONCLUSIONS

The research described in this paper was not extensive enough to cover all the variables affecting cable pulling tension or effective coefficient of friction. Even so, the results from the multi-bend testing indicate some new variables affecting effective coefficient of friction.

It's instructive to list the variables examined by the rough magnitude of their effect in the tests.

(1) Lubricated vs. Non-lubricated
(2) Normal/Bearing Force/Weight on the Cable
(3) Number of Cables
(4) Conduit Size (and/or Interior Condition)
(5) Conduit-to-Cable Ratio (Single Cables--Higher Fills)
(6) Cable Jacket Type

No attempt was made to evaluate different types of pulling lubricants in this work. The lubrication from the high performance polymer gel that was used was the primary (largest magnitude) tension-reducing factor evaluated.

Another important factor, which needs further study, is the influence of normal pressure on effective friction coefficient. The research shows higher friction coefficients at lower incoming tensions (sidewall pressures). However, the magnitude of these lower shear coefficients is not consistent. Additional studies, perhaps with fewer bends and/or less back tension could provide additional data and clarification. Isolating the factors that influence this low shear friction, and better quantifying its variation, could lead to much more accurate tension estimation.

The variables of conduit fill, cable jacket type, and number of cables clearly have an influence, but not as significant as the presence of lubricant and magnitude of normal pressure.

The research gives additional understanding why a coefficient of .5 may be unduly conservative in calculations. We did not see any lubricated friction coefficients (high performance lubricant) get this high. This conservatism could result in more expense in splicing and conduit access than necessary.

In the future, we hope to use the technique described to provide data on the numerous unanswered questions. Even with the great number of influencing variables, it would appear cable pulling can be further optimized and made more predictable and controllable.

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John M. Fee received a B.S. degree in chemistry from Massachusetts Institute of Technology in 1968.

He worked from 1968 to 1981 at the 3M Company, St. Paul, Minnesota, on a variety of chemical product developments. Since 1981, he has been with American Polywater, and is currently President. He has worked extensively in the area of cable pulling lubricants and theory.

Mr. Fee is a member of the ICC of the PES, and chairs a working group developing compatibility test standards for lubricants and cables.

Deborah J. Quist has an Associate Degree as a laboratory technician from Hennepin Technical Center.

She has worked at American Polywater since 1986 in various product development and evaluation functions. Ms. Quist's latest work involves measurement methods for cable/conduit/lubricant friction.