

Application of Horizontal Directional Drilling and Other Trenchless Methods to Electric Power Cable Installations

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SUMMARY

Underground power cables have been installed predominantly using “open cut” excavations from the surface in which conduits or pipes are installed and encased in specialized granular, engineered fluidized (flowable) backfills, or concrete backfills or where cables are directly buried and covered with low-thermal resistivity granular materials. As the use of insulated power cables has increased world-wide in more challenging installation locations, methods that avoid open-cut trenching including horizontal directional drilling (HDD), pipe-jacking and microtunneling are utilized for portions of the underground installation because surface conditions, environmental factors or regulatory guidelines would not otherwise permit conventional open-cut excavation construction methods. The types of situations where trenchless methods can be utilized include locations with soil contamination, archeologic sites, unique obstacles such as water crossings, and entry and exit to submarine installations. The expectations on the current state-of-the-art for the respective technologies are summarized. Pipe-jacking is constrained to straight alignments although an elevation change may be possible, while microtunneling and, to a greater extent, horizontal directional drilling allow vertical and lateral changes in direction. The associated characteristics of the product pipe to be installed are relevant; pipe jacking and micro-tunneling require materials that can withstand compressive forces while horizontal directional drilling requires the use of materials that have high tensile strength limits.

The design and installation of cables using the types of infrastructure constructed with these types of specialized “trenchless” methods require consideration of civil and electrical engineering design elements that impact the selection of casing and conduit materials, cable ratings, alignment (drill path), cable installation and pull distances, limits of disturbance for construction, mobilization and laydown space, and construction schedule. The construction method must consider the available materials and their respective characteristics from the standpoints of both cable design and selection, number of power cables to be installed, shared space for other utilities, and cable ampacity. For civil design elements, the mechanical features of the civil installation must also consider the characteristics of casing materials, special handling, minimum bending radii of casings and inner conduits, heat transfer properties from the standpoint of conducting heat away from the cables, and the design considerations and application of grout

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materials to use for installation. Cable ampacity is impacted by these design choices, with some design elements resulting in conflicts between civil and electrical design goals including the selection of grout materials.

This paper summarizes the various technical details for construction characteristics of each of the trenchless methods that could be considered most appropriate for cable systems, the characteristics of the materials involved (high-density polyethylene, fusible PVC, steel, and resin-reinforced fiberglass, reinforced concrete pipe), an overview of the impact of deep cable installations on ampacity from the standpoint of native soil characteristics, groundwater elevation, burial depth and ambient soil temperature, and locations where trenchless methods are most appropriate to apply. A summary of the known maximum lengths where trenchless methods have been applied will also be provided to illustrate the current status within the industry. The geological characteristics (sand, rock, cobbles, etc.) that constrain the use of certain trenchless methods is also be provided, along with strategies for performing geological surveys and soil boring location selection. Relevant references will be included in a bibliography for further reading.

KEYWORDS

installation, trenchless, directional drilling, cable, design, civil, construction methods

INTRODUCTION AND BACKGROUND

Trenchless installation methods require careful coordination between the electrical engineer designing and specifying the power cables and the civil engineer that is designing and specifying the trenchless construction method and layout. Some of the preferred design characteristics for the electrical engineer conflict with those preferred by the civil engineer. Unless the electrical engineer is aware of the options for trenchless methods and the implications for the selection of the methods, the cable system may not be accurately designed and specified, or the desired power transfer capacity may not be satisfied.

This paper identifies the major factors that are of concern to the civil engineer in developing a trenchless installation method for use with power cables and relates the various options to the implications for the electrical design. The intent is to provide the reader with enough information to proceed with the design calculations and have access to further reading for more thorough analyses of the methods.

TYPES OF TRENCHLESS TECHNOLOGIES

Trenchless methods are those that do not require open excavation along the construction segment with the exception of the end points of the segment and are used for a wide range of underground utility types such as water, sewer and natural gas lines as well as electric power cables. The trenchless construction is achieved without the use of a conventional trench. The reasons for applying these types of civil construction methods are focused on the conditions – either surface or soil – that prevent the use of conventional open-cut methods (excavator, back hoe, trencher, etc.). Trenchless methods are generally more costly than open-cut methods, although they may be competitive with submarine cable laying alternatives. By utilizing one of the trenchless methods, an opening is created through the ground in which the power cables can be installed, either directly within a casing (generically called “product pipe” regardless of material) or with a set of inner conduits or pipes for the cables; more details of this will be discussed later.

Locations where trenchless methods would be considered for application are:

- High density of “shallow” utilities or other infrastructure that makes finding a lane for surface excavation difficult or impossible.
- Construction would be too disruptive to stakeholders along the route such as along roads with commercial businesses, public facilities, emergency services or crossing major roadways.
- Significant soil contamination might make excavation, spoils disposal, or cleaning of equipment would be prohibitively expensive.
- Archaeological artefacts or sites would be disrupted.
- Shore area get-away for submarine cable installations.
- Environmentally sensitive areas including wetlands would be disrupted such that achieving permitting would be difficult.
- Water crossings within the range of the selected trenchless technology

An assessment is usually done to consider conventional trenching methods with the trenchless alternatives considering both technical and economic factors. Other references [1] provide details of the trenchless methods. A summary of the characteristics of each method are summarized below.

Pipe-Jacking

With pipe-jacking, or sometimes called “jack and bore”, “launching” and “receiving” pits are excavated on either side of the installation segment down to the expected installation depth. The pit is then configured with the equipment to advance a casing. The face of the opening can be excavated using an auger or other mechanical equipment or by hand digging with spoils

removed from the sending pit. For power cables, pipe-jacking is on the order of 0.7-2.0m in diameter for most electric power projects (Figure 1). The casing must be made of a suitable material, usually steel but also “reinforced concrete pipe” (RCP), that can withstand the compressive forces applied as the casing is advanced. Resin and sand reinforced fiberglass is also used. Although an elevation difference between the sending and receiving pits is possible, changes in direction during the bore are difficult. Because the face of the excavation is essentially open, pipe-jacking must be done above the water table or with active de-watering of the work site during construction. The length is limited by the frictional forces that develop between the outer casing surface and the surrounding soil and typically not longer than 100-150m.



Figure 1 – Pipe jacking launching pit with steel casing

Microtunneling

Microtunneling is similar to pipe jacking in the sense that pits or shafts are excavated on either side of construction segment and a method to advance the casing is utilized while the face of the boring is excavated. However, the process is entirely mechanical and essentially provides a seal to the surrounding soil, including in areas below the water table, as construction progresses. This allows this method to be used in areas below the water table without active de-watering, potentially avoiding the need to collect the water and treat it before disposal.



Figure 2 – Example of microtunnel launch pit

Spoils from excavation are removed as a slurry or auger similar to a large-scale tunnel boring machine. Casing materials used for microtunneling include steel, concrete, CCFRPM, and clay. The typical construction diameter (0.4-2.5m) is somewhat similar than for pipe-jacking. The frictional forces of the advancing casing also limit the installation distances, but the ability to lubricate the bore hole with the slurry for the cuttings means that the total frictional forces are lower, allowing for a longer distance than pipe-jacking up to 400m.

Box Culvert Adit

A box culvert is sometimes installed by an open cut excavation from the surface when conditions allow and is not necessarily a common method for construction with underground power cables. However, in areas where there is need to achieve a relatively short crossing of one or more obstacles nearer to the surface, such as other utilities, and there is concerns about disturbing the utilities at a higher elevation, a pit can be excavated on either side of the obstacle and an excavation is created below, usually by hand digging. The excavation is braced open – essentially an adit – using sheeting and mechanical supports such as timbers. The benefit of this type of excavation is that it may be done in areas with confined space that would otherwise not permit pipe-jacking. Filling the free space within the box culvert with a flowable grout and also leaving the timbers in the opening are both considerations for heat transfer and power cable ratings.

Horizontal Directional Drilling

Horizontal directional drilling (“HDD”) is based on technology used for petroleum and natural gas drilling except with the general orientation changed from mostly vertical to mostly horizontal. In comparison to the other trenchless methods, horizontal directional drilling has the advantage that the drill path can be changed in the course of the drill. Usually, the focus is on drilling on one side of a crossing to a lower elevation sufficiently below a given obstacle, traversing horizontally to cross under the obstacle, and then drilling to a higher elevation back to the surface. After careful design activities are performed, the boring “**set back**” (distance from start of the crossing) is selected, and the **drill path** is designed, a **pilot bore hole** is created from one side of the crossing by advancing 5-10m lengths of drill stem pipe using while pumping drilling fluid (“mud”) through the drill stem which lubricates the drill stem while stabilizing the bore hole. The hole is enlarged by successive **reaming** passes until the opening is approximately 1.5 times the expected casing pipe diameter. The entry and exit angles of the drill are typically 10-18 degrees from horizontal. The drill path selection is an important design parameter for horizontal directional drilling (abbreviated “HDD”). The overall process is illustrated in Figure 3.

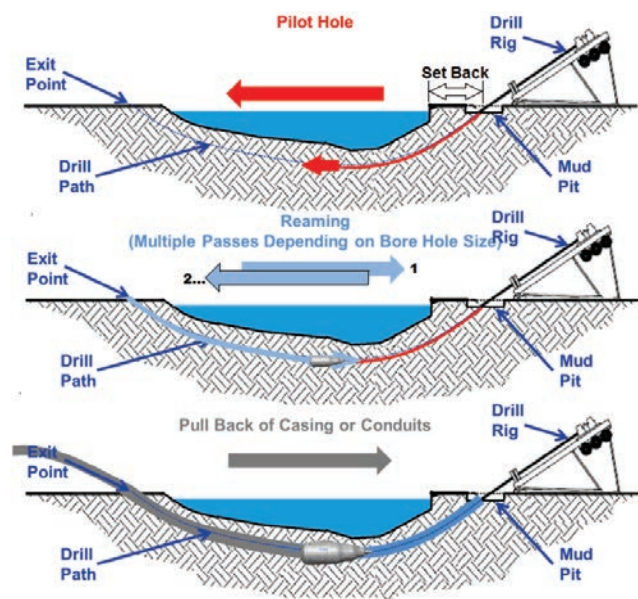


Figure 3 – Directional drilling process (top) and drill rig and control trailer (bottom)

Pipe Bursting

Pipe bursting is a novel trenchless technology applied for power cables that utilizes an existing installed pipe as a path to install a new casing pipe. The pipe bursting method fractures the existing pipe and replaces it with a new pipe or casing. An “expander head” (or “bursting head”) is smaller than the existing pipe on one end and larger on the opposite end; the expander head may have fins or other protrusions that are designed to fracture or crack open the existing pipe as it is pulled through the existing pipe. A winch or other equipment is used to pull the expander

head through the existing pipe while new conduit or casing pipe is pulled behind. Pits are excavated on either side of the existing pipe segment. As the expander head and new pipe are pulled through the existing pipe, the expander will follow the existing pipe that is to be replaced. The technology is limited to installation along segments that are 100-200m in length, which is often shorter than most transmission cable installation segments, and there are some limitations as to the minimum radii of bends in the existing pipe. A pulling device using a winch or rods is connected to the expander head and incrementally advanced, bursting the pipe or conduit and installing the new pipe or conduit as the operation proceeds. This is illustrated in Figure 4.

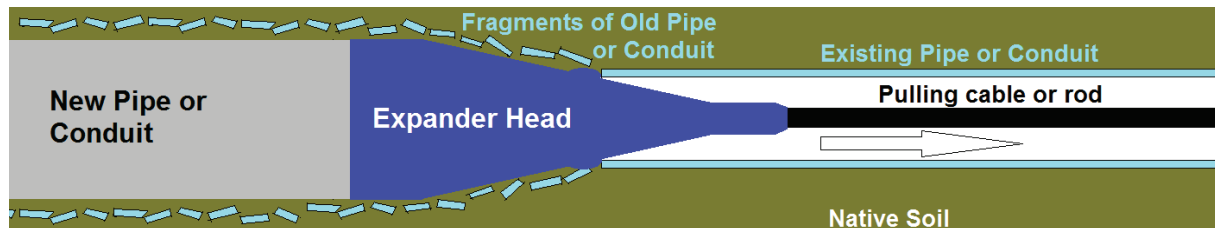


Figure 4 – Illustration of pipe-bursting

CASING AND INNER-CONDUIT MATERIAL SELECTION AND CHARACTERISTICS

From a civil engineering standpoint, the casing material with suitable tensile strength and (for HDD and pipe bursting) bending radius must be selected. For cable design, the casing material must be suitably selected to allow the selected cables to be installed and to achieve the necessary cable rating (ampacity). The geometry and separation of the cables and (if present) inner conduits, the burial depth and the environmental characteristics of the surrounding soil have an impact on the cable ratings and also the size of the trenchless opening and outer casing. The properties of the casing impact the ratings and the civil design. In some cases, the type of casing is dictated by the governing authority for the obstacle being crossed. For example, some highway departments or railroad operators have standards that require certain casing materials, such as steel or concrete, and that the crossings be perpendicular to the roadway.

This section summarizes the characteristics of the casing materials as they impact the cable and civil design.

Steel

From a civil and mechanical engineering design standpoint, steel is one of the most preferred materials due to its high longitudinal yield strength limit (for HDD), ability to withstand compressive forces that might be applied during pipe-jacking or microtunneling, and that the casing pipes is readily available in many diameters, wall thicknesses and yield strengths.

While these characteristics are favourable, the relatively large minimum bending radius can require significant setback from an HDD crossing. Steel has very good thermal conductivity for transferring heat, but ac electrical induction can cause hysteresis and eddy current losses, generating heat, that impacts cable ratings. The steel casing itself is also susceptible to corrosion and can cause interference for cathodic protection systems on pipe within the casing.

Plastic (High Density Polyethylene, HDPE; Fusible Polyvinyl Chloride, fPVC)

Polymer (plastic) casing materials are also common. They are generally less expensive than steel and have greater flexibility allowing that smaller bore hole radii may be used. Plastic casings are not strong in compression and therefore cannot be used as a driven casing for pipe jacking and microtunneling. However, they are considered for HDD or as inner conduits to a larger casing. To accommodate the forces imparted on the casings during installation, the plastic casing wall is often thicker (50-75mm) than similar diameter steel casings. Polymers have a relatively high thermal resistivity which is a barrier to heat efficiently leaving the cables within the casing that must be factored into the cable design.

Fusible PVC is a newer material used for directional drilling as an alternative to HDPE. The material is mechanically stronger but also must be handled with somewhat greater care than HDPE because it tends to have a higher hardness and can be more brittle.

Reinforced Concrete Pipe

Reinforced concrete pipe (RCP) is a possible casing material for pipe-jacking applications. The concrete has strength in compression and is often used in pipe jacking operations. The concrete pipe has generally good thermal resistivity – similar to that of good quality thermal backfills – so it has a lower impact on cable ratings as compared to other options.

Centrifugally Cast Fiberglass Reinforced Polymer Mortar Pipe (CCFRPMP)

This material is a manufactured product that has inherently strong properties for applications in pipe-jacking and microtunneling. Unlike steel, the material is not susceptible to corrosion and does not generate heat losses when exposed to nearby ac electric current.

HDD: Casing versus No Casing

The advantage to having a casing is that the annular space between the inner conduits and the outer casing can be filled with a low thermal resistivity grout to help with conducting heat away from the cables. This also often provides lower risk to the installation of the conduit bundle (for extruded transmission cables) where each individual conduit might not be strong enough to withstand the forces of installation.

There are disadvantages to using casings. The casing itself introduces an added material cost, and the large diameter increases the minimum bending radius for applications using directional drilling. Steel casings do not have an appreciable thermal resistance to cable heat loss but introduce cable current-dependent losses, while plastic casings have a relatively high thermal resistance to heat loss. On balance, plastic is usually better than steel from a cable rating perspective. Also, when a casing is used, there generally must be some form of grout – at least water – installed in the annular space between the inner conduits and casing to enhance heat transfer. For longer installations, grouting this space can be a challenge and potentially could leave air-filled voids that create hot spots.

With no casing, a bundle of conduits can be pulled directly into the boring, provided the tensile strength limits of the smaller conduits are not exceeded and there is a reasonable expectation that forces will be shared among the individual conduits. The smaller bundle of conduits also means that the minimum bending radius of the bore hole can be smaller which may be advantageous where there are constraints on the set back from the edge of the crossing.

Casing Material	Typical Diameter for Cable Projects meters (in.)	Thermal Resistivity C°-m/Watt	Causes Added A.C. Losses?	Compression Strength MPa (psi)	Density kg/m ³ (lbs/ft ³)	Minimum* Bending Radius	Longitudinal Tensile Strength MPa (psi)	Install Type*
Steel	0.5-1.2 (20-48)	0.01-0.02 (negligible)	Yes	150 (22000)	7850 (490)	1200x O.D.	250 – 500 (36000 – 70,000+)	HDD, PJ, MT
HPDE	0.5-0.9 (20-36)	2.5 – 3.5	No	Poor (N.A.)	960 (60)	110x O.D.	24 (3500)	HDD
fPVC	0.5-0.9 (20-36)	4.0 – 5.5	No	Poor (N.A.)	1480 (92)	270x O.D.	48 (7000)	HDD
RCP	0.9-1.2 (36-48)	0.5 – 1.1	No	30 (4000)	2400 (150)	N.A.	Poor (N.A.)	PJ, MT
CCFRPMP	0.5-0.9 (20-36)	0.65 – 0.75	No	72 - 90 (10500 – 13000)	2000 (125)	N.A.	10 - 15 (1400 – 2100)	PJ, MT
No Casing	N.A. (diameter of conduit bundle)	N.A. Inner conduits surrounded by drilling fluid	No	N.A. (cannot be used with pipe-jacking or microtunneling)	N.A.	Limited by inner conduit size	N.A.	HDD

*HDD = Horizontal Directional Drilling, PJ = Pipe Jacking, MT = Microtunneling, N.A. = Not Applicable, O.D. = Outer Diameter

GROUTING AND GROUT SELECTION

When a casing is installed and inner conduits are placed within the casing for the power cables, the space between the casing and inner conduits can be filled with a material; the need – and potential benefits – to do this are unique when power cables are being used within the casing. The material can mechanically stabilize the installation and conduits internal to the casing, but for power cables, the material introduced to the annular space is intended to aid heat transfer away from the power cable positions. From the cable design perspective, heat transfer is improved by maximizing the density of the grout material – for typical grouts, this means limiting water and clay or other fluidizers, and maximizing the sand content – but this is diametrically opposed by the grout installer that is concerned about pumping pressures and the distance to pump the grout without exceeding pressure limits or deforming the inner conduits.

Air has a very high thermal resistivity compared to most liquids and solids, so leaving the annular space filled with air potentially has the greatest impact on ratings because heat leaving the cable will experience more significant temperature rise through the air. If a more sophisticated solution is unavailable, filling the annular space with water would provide far better heat transfer because the thermal

Casing Annular Filling	Thermal Resistivity, K-m/Watt (typical)	Density kg/m ³
Air	40-45	1.3
Water	1.60-1.65	1000
Bentonite Clay	0.9-1.4 (wet) 3.0-5.0 (dried)	1500-2650 593
Non-Hardening Grout	0.65-0.90 (if remains wet)	2000
Concrete (~20MPa)	0.45-0.60	2400
Hardening Grout	0.60-0.85	2200
Thixotropic Grout	0.60-0.90	1600-2000

resistivity of water is approximately 4% that of air. Other materials, including hardening grout (containing cement, sand, water and sometimes small aggregate) and non-hardening grout (e.g., mix of silica flour, sand water, bentonite), including thixotropic materials have higher density and therefore better heat transfer properties but present greater challenges to the grout installer – the time to efflux for the selected grout is an important characteristic for flow through any internal spacers and around the inner conduits. The heat of hydration from cement-based grouts should be evaluated from the standpoint of softening, and potentially deforming, plastic conduits as curing occurs. The civil contractor, soil testing specialist, civil engineer and electrical engineer collaborate on this selection process.

CIVIL ENGINEERING DESIGN

Geotechnical Borings and Subsurface Investigations

Trenchless projects must carefully consider the underground conditions so that the project can be properly designed and the cable selection process can proceed. From a civil design perspective, identifying the soil characteristics is important to assess the viability of trenchless methods as well as the types of equipment that need to be selected. Borings should be located at all pit or shaft locations for pipe jacking and microtunnel installations as well as at intervals of 50 to 100 m along the alignment. Borings for HDD applications are performed in the vicinity of the planned route – but not right over the planned alignment – approximately every 100-300m and offset 10-20m. The offset is important so as not to create pathways for inadvertent returns (fracturing of drilling fluid to the surface or “frac out”). The geotechnical borings determine the strata of soil in the ground, which impacts the types of soil boring equipment to be used. The drilling design may indicate that the drill path should be deeper or shallower. The design phase of most trenchless projects is far in advance of the contractor obtaining construction permits; this makes performing the geotechnical survey a challenge in some cases, especially for installations involving the marine environment. For this reason, sometimes geotechnical borings are only obtained near the end points for the drill path with the civil engineer interpolating soil characteristics between the bore hole locations.

The geotechnical borings also affect the cable system design from the standpoint of knowing the thermal resistivity characteristics of the native soil and the elevation of the water table, which would affect the native soil thermal.

From the selection of the alignment, many times the civil engineer would prefer the installation depth be deeper to get into more stable geological strata and better soil consistency. However, for the cable design, deeper burial depths can impact the cable rating by increasing the path for heat to leave the cables and also to magnify the impact of mutual heating when multiple trenchless alignments are in the same vicinity. A compromise must be found that accommodates the requirements of each concern while balancing the risks and costs of the project.

Drill or Bore Path Selection

The most critical consideration when selecting the vertical location of the conduit or casing for trenchless applications is the soil or rock characteristics. Depending on the trenchless method, the presence of high-risk materials must be identified. Very soft soils, reactive clays, gravel, cobbles, and boulders are common high-risk materials. Desirable materials are typically sands, lean clays and soft rock with favorable strength characteristics.



Figure 5 – Lay down area for HDD casing

Part of the drill path selection must consider laydown area for the assembled casings used with HDD, both from the standpoint of length and alignment with the pilot hole which could be several hundred or a few thousand meters. The steel casing pipe sections are welded together in advance, or the HDPE or fusible PVC sections fused together ideally for the full length of the crossing prior to pull back; significantly greater risk is introduced if pull back is interrupted for casing assembly, although certain conditions may require this to happen.

ELECTRICAL DESIGN CONSIDERATIONS

Cable Ratings (Ampacity)

Cable ratings for trenchless installations follow the rating methods applied for more typical installations except using appropriate adjustments to the parameters to consider the impact on ambient temperature, native soil characteristics and the unique installation geometries associated with trenchless methods, including the type of casing and grout being used. Adjustments include:

- Ambient temperature – Deeper than ~5m of installation depth, the ambient temperature approaches the average annual air (or, for undersea, water) temperature in a given area.
- Native soil thermal resistivity – A concern for conventional (shallow) trenches is that the moisture content of the soil may vary with seasonal fluctuations or due to moisture migration away from the cables, resulting in higher thermal resistivity. Trenchless installations are often deeper and end up below the water table where the moisture content tends to be greater. The soils also tend to have greater density and fewer organic components at the greater installation depths.

- Calculation method – The calculation method for deeper trenchless installations is similar to that for shallower installations although there may be allowance for the longer earth thermal time constant at the increased depth. Appropriate consideration for the unique geometry, presence of a casing as may affect heat losses or additional thermal resistance to heat flow (or both), and the variation in ratings along the drill path and adjacent areas must all be factored into determining the cable ratings and sizing the cables.
- Mutual heating – Mutual heating is a factor for consideration when the horizontal separation is within 4x to 5x of the burial depth. So, for example, mutual heating for cables buried at 1m would be a factor for consideration within 4-5m to either side of the circuit(s). This becomes magnified at the increased burial depths for trenchless installations and could mean that mutual heating becomes a more important factor.

Grounding, Bonding and Corrosion Protection

For extruded cables, the sheath and metallic screen ground and bonding scheme must be considered for trenchless sections just as is done for open-cut installations. There are similar concerns for the sheath bonding scheme in that managing losses in the metallic sheath and screen is important for achieving the necessary cable rating. For shorter trenchless segments, the segment may be part of a larger splice-to-splice segment and use one of the typical options (multiple point grounding, single point grounding or cross-bonding). For longer trenchless sections, the length may impact the ability to use cross-bonding and achieve balanced section lengths to eliminate losses, and single-point bonding may be a challenge if the standing voltage exceeds acceptable limits.

For pipe-type cables installed within a separate outer casing, the steel casing may prevent the cathodic protection system from sufficiently protecting the cable pipes. The interference caused by the casing may impact the effectiveness. This should be carefully considered for pipe-type cables.

For pipe-type cables installed without an outer casing, there can be efforts to select a more robust corrosion coating. Instead of a polyethylene extrusion or tape common to open-cut installations, a fusion-bonded epoxy and polymer concrete coating might be selected which would be more resistant to damage during pull back of the cable pipe into the bore hole.

CONCLUSIONS

There are many factors to consider when using trenchless methods in conjunction with underground power cables. This effort combines the disciplines of electrical engineering, civil engineering, geotechnical engineering, and the construction contractor. When this collaboration is executed appropriately, the cable system can be designed to meet power transfer needs using a civil engineering solution that avoids the challenges of conventional open-cut trenching.

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