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Synthesis of Trenchless Technologies

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Abstract:

The purpose of this study was to examine the current state of the practice of state highway agencies regarding methods and specifications for using trenchless technologies. From the perspective of the Virginia Department of Transportation (VDOT), the paramount concern associated with trenchless construction is the safety of the traveling public. Since such construction typically takes place without the re-routing of traffic, any sudden and substantial surface displacement of the overlying roadway has the potential for catastrophic consequences. Surface monitoring during and after construction is a critical activity to ensure successful installation.

The study focused on the most commonly used trenchless methods for new construction, including the selection of the most appropriate trenchless technology for specific applications, the identification of minimum geotechnical investigation requirements, design considerations, construction monitoring, costs, and performance. The study did not address all potentially available methods of utility construction and rehabilitation.

To achieve the study objective, two tasks were performed: (1) the literature on the current state of the practice with respect to the use of trenchless technology in other states was reviewed, and (2) identified specifications and design guidelines of various state transportation agencies were analyzed and examined for potential applicability to trenchless construction activities administered by VDOT.

The study concluded that trenchless technologies have been widely adopted but design guidelines and construction specifications vary significantly. Accurate subsurface characterization is critical to the selection of the most appropriate technology for a specific project. Obstructions pose a significant risk for all types of trenchless work. In general, the risk of using the directional drilling method increases with pipe diameter. The opposite is usually the case for microtunneling. Unguided trenchless methods are suitable only for short drives. Monitoring of trenchless construction is usually limited to observations of installation procedures and surface monitoring. For the most part, a high level of expertise is required for operators of trenchless equipment.

The study recommends that VDOT's Materials Division, Location and Design Division, and Construction Division jointly develop and approve the criteria for selection of trenchless technologies. Specific technical recommendations for inclusion in VDOT special provisions and the VDOT Materials Division *Manual of Instructions* are enumerated.

FINAL REPORT

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Virginia Center for Transportation Innovation and Research
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ABSTRACT

The purpose of this study was to examine the current state of the practice of state highway agencies regarding methods and specifications for using trenchless technologies. From the perspective of the Virginia Department of Transportation (VDOT), the paramount concern associated with trenchless construction is the safety of the traveling public. Since such construction typically takes place without the re-routing of traffic, any sudden and substantial surface displacement of the overlying roadway has the potential for catastrophic consequences. Surface monitoring during and after construction is a critical activity to ensure successful installation.

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INTRODUCTION

Trenchless technologies involve methods of new pipe installation with minimum surface and environmental disruptions. Construction can be carried out under a busy highway without closing it to traffic. Traffic congestion is significantly reduced, resulting in less air and noise pollution. Trenchless projects are also less hazardous to workers, as the process can be controlled from the surface. In many densely populated urban areas, open-cut excavations are simply not practical and the social costs are too great. In addition, open-cut excavations tend to increase pavement failures and can result in damage to adjacent structures (Davis, 2008). Trenchless construction lends itself to many infrastructure applications, including gas, water, sewer, pipelines, power, and communications.

The use of trenchless technologies within the Virginia Department of Transportation (VDOT) right of way has been steadily increasing over the years, particularly in densely populated urban areas. For the most part, qualified contractors complete these projects successfully, but sometimes failures occur, as shown in Figure 1. The majority of problems can be traced to inadequate subsurface exploration, changes in subsurface conditions, obstructions, and unexpected deviations from line and grade during construction.

PURPOSE AND SCOPE

The purpose of this study was to examine the current state of the practice of state highway agencies regarding methods and specifications for using trenchless technologies. From VDOT's perspective, the paramount concern associated with trenchless construction is the safety of the traveling public. Since such construction typically takes place without the re-routing of traffic, any sudden and substantial surface displacement of the overlying roadway has the potential for catastrophic consequences. Surface monitoring during and after construction is a critical activity to ensure successful installation.

Figure 1. Roadway Subsidence After Trenchless Construction in Northern Virginia

Trenchless technologies most commonly used in Virginia include jack and bore, microtunneling, and horizontal directional drilling (HDD). In this study, pipe jacking was also examined. The study focused on the most commonly used trenchless methods for new construction, including the selection of the most appropriate trenchless technology for specific applications, the identification of minimum geotechnical investigation requirements, design considerations, construction monitoring, costs, and performance. The study did not address all potentially available methods of utility construction and rehabilitation.

METHODS

To achieve the study objective, two tasks were conducted:

1. *The literature on the current state of the practice with respect to the use of trenchless technology in other states was reviewed.* The review focused on soil applications for specific technologies, although many of these methods are also suitable for rock excavation. The literature search focused on peer-reviewed publications. Search tools included Engineering Index, TRISWorld, Mechanical and Transportation Engineering Abstracts, and VDOT OneSearch databases.

2. *Identified specifications and design guidelines of various agencies were analyzed and examined for potential applicability to trenchless construction activities administered by VDOT.*

RESULTS AND DISCUSSION

The following trenchless technologies were examined:

- jack and bore
- microtunneling
- HDD
- pipe jacking.

Jack and Bore

Overview

Jack and bore, also known as auger boring, is one of the most popular methods of trenchless technology. It has been used in the United States for more than 50 years (Iseley and Gokhale, 1997). Jack and bore is a process of simultaneously jacking casing while removing the spoil material by means of an auger. A rotating cutting head is attached to the leading edge of the auger string. The spoil is transported back by the rotation of auger flights within the steel pipe casing being placed.

How It Works

The most common type of jack and bore for transportation applications is the track system (Iseley and Gokhale, 1997). The main parts of the track system include the supporting track, boring machine, casing pipe, cutting head, and augers. Optional components include a casing lubrication system. Lubricants are typically bentonite and polymer mixtures.

Once launched, jack and bore is typically unguided. Subsurface obstructions can cause large deflections. Recent technological improvements allow significantly greater accuracy for shorter drives. According to the Oregon Department of Transportation (ODOT) (2005), with the steering head and water-level grade monitoring system, an accuracy of 1% of the length of drive can be achieved in vertical grade. Horizontal alignment is generally not controlled.

One of the main benefits of jack and bore is that workers are not required to enter the shaft during trenchless construction. The rotating auger brings the spoil material back to the machine. Hydraulic jacks at the boring machine are used to advance the casing. The track system must be positioned on the same line and grade as the bore (Iseley and Gokhale, 1997). This is usually the most critical part of the project. Jack and bore requires a relatively high skill level of the operator to achieve good results.

A properly constructed drive shaft is important for the success of a track-type auger boring project. The shaft requires a stable foundation and an adequate thrust block. The thrust block transmits the horizontal jacking forces from the tracks to the ground at the rear of the drive shaft. It must be designed to distribute the jacking force over sufficient area so that the allowable compressive strength of the soil is not exceeded.

Conditions for Use

The jack and bore system may be used for crossings of all types. The New York State Department of Transportation (NYSDOT) (2007a) considers jack and bore compatible with a variety of soil conditions, although it should not be used below the groundwater table, in running sands, or in soils with large boulders.

Typical Applications

A summary of typical jack and bore applications is shown in Table 1.

Table 1. Typical Jack and Bore Applications

Applications	Depth	Length	Diameter	Pipe Type	Working Space	Soil	Operator Skill
Storm sewers, utilities	Varies	40-500 ft	8-60 in	Concrete, steel	Entry and exit bore pits: Length: 25-35 ft Width: 10-12 ft	Varies	High

Soil

Suitable soil types include sands and clays (ODOT, 2005). Jack and bore should not be used below the groundwater table, in running sands, or in soils with large boulders.

Pipe

The typical material is steel because the pipe must resist abrasion caused by the rotating augers (Iseley and Gokhale, 1997), although concrete pipe may also be used. The most common length of a casing segment is 10 ft. Pipes with a diameter of 8 to 60 in and drive lengths of 40 up to 500 ft can be used (California Department of Transportation [Caltrans], 2010).

Jacking and Receiving Pits

The recommended dimensions for jacking and receiving pits are a length of 25 to 35 ft and a width of 10 to 12 ft, with sufficient room for material storage (Caltrans, 2010). The drive shaft is a critical part of the process that must be designed and constructed properly. The foundation must be designed to support the jacking process. VDOT's *Special Provision for Section 302.03(A)1 - Jack and Bore for Design Build Projects* (VDOT, 2009a) requires that "the jacking equipment installed shall have a jacking capacity that is at least 150% of the maximum calculated allowable jacking load required to install the pipe." The thrust block should be designed so that the allowable compressive strength of the soil is not exceeded. It must remain stationary to maintain the alignment accuracy. The operator must be able to adjust the location of the cutting head if soil conditions change.

Accuracy

This technique has limited steering ability, which can affect the line and grade accuracy. Horizontal grade is usually not monitored, but if a water-level grade monitoring system is used along with a steering head, an accuracy of 1% of the bore length can be achieved (ODOT, 2005). Surface subsidence and heave during construction can pose major problems. Subsidence occurs when overexcavation is permitted, and heaving occurs when excessive force is applied to the excavation face (Iseley and Gokhale, 1997). The outcome is largely dependent on the operator's skills and the contractor's experience.

Production Rate

A typical production rate for a 24-in steel casing project is 100 ft in an 8-hour shift (NYSDOT, 2007a).

Depth of Cover

Adequate depth of cover above the pipe can minimize ground displacement. The New Hampshire Department of Transportation (DOT) (2010) specifies that the minimum cover of jack and bore installations shall be 5 ft on secondary roads and 10 ft on primary and freeway roadways. ODOT (2005) specifications require that the minimum depth of cover not be less than 2 ft. The German Association for Water, Wastewater, and Waste (DWA) (2008) Standard DWA-A 125 E stipulates 1.5 times the exterior pipe diameter, with a minimum of 2.5 ft.

Costs

All costs listed in this report are based on the time value of money–scaled (U.S. Bureau of Labor Statistics, 2014) Midwest Consumer Price Indices for 1996 (Iseley and Gokhale, 1997) and include costs of installation, mobilization, demobilization, and planning. These average costs do not include casing / carrier pipe materials, preparation of entry/exit pits and shafts, or dewatering.

For jack and bore, the cost is $3 to $4 per inch of pipe diameter per linear foot if line and grade are not critical. The cost is $4 to $6 per inch of pipe diameter per linear foot if line and grade are critical (Iseley and Gokhale, 1997). Adjusted for inflation, 2014 costs are approximately $4.50 to $6 per inch of pipe diameter per linear foot if line and grade are not critical and $6 to $9 per inch of pipe diameter per linear foot if line and grade are critical.

Microtunneling

Overview

Microtunneling technology was first implemented in Japan in 1975. The following year, Iseki, Inc., developed their first machine that made tunneling operations in soft unstable soils possible. In 1981, Iseki developed technology that allowed the microtunneling head to crush boulders up to 20% of the outside diameter of the pipe being installed (Abraham et al., 2002). Three years later, microtunneling technology was implemented in North America. It was used for the Miami-Dade Water and Sewer Authority for the installation of a 615-ft-long pipe, 72 in in diameter, under I-95 in Miami, Florida. In 1987, the River Oaks Project in Houston, Texas, led to the wider acceptance of microtunneling technology. This project involved the installation of 3.8 miles of sewer lines, with varying diameters of 10, 18, and 21 in (American Society of Civil Engineers [ASCE], 2001). The main advantages of microtunneling include earth pressure balance at the face of the excavation and better accuracy on line and grade compared to conventional jack and bore.

How It Works

Microtunneling is defined as a remotely controlled and guided pipe jacking technique that provides continuous support to the excavation face and does not require personnel entry into the tunnel (Abraham et al., 2002). Full support at the excavation face is a feature that differentiates it from traditional open-shield pipe jacking methods. The construction method is a cyclic pipe jacking process that is used to install pipelines under highways, railroads, runways, harbors, rivers, and environmentally sensitive areas (International Society for Trenchless Technology [ISTT], 2012). With a precise automated guidance, microtunneling can be used in a wide variety of soil conditions while maintaining very close tolerances to line and grade. There are two types of microtunneling techniques: the slurry type and the auger type (ASCE, 2001). The slurry method is the more commonly used approach to remove spoils.

Microtunneling requires significant ground excavation to construct launching and receiving shafts at the entry and exit points. The equipment, as shown in Figure 2, includes a hydraulic jacking system, closed-loop slurry system, slurry separation unit to remove the soil from the slurry mixture, lubrication system to lubricate the exterior of the pipe string, laser guidance system, crane to hoist pipe sections into the jacking shaft, and control room (ISTT, 2012).

The microtunneling boring machine (MTBM) is advanced through the ground by a hydraulic jacking rig that is mounted and aligned in the launching shaft. The jacking capacity of the rig depends on the length and diameter of the bore and the soil conditions. Typical jacking capacities range from 100 to more than 1,000 tons (Abraham et al., 2002).

The rotating cutting head on the MTBM excavates the soil. The head typically overcuts the soil by 0.5 in to reduce friction on the advancing pipe. Some obstructions can be overcome by reverse rotation. The soil excavated at the face is extruded to the rear of the MTBM face into a mixing chamber within the MTBM head. Inside the chamber, the soil is mixed with clean water and bentonite from a separation unit above ground to create a mixture with suitable consistency to pump. This mixture is then transported through the discharge cables into the separation system. The entire process is a closed system because the slurry is always recycled. Bentonite allows the water to transport heavy particles to the separation tanks, which then allow the particles to settle out of the slurry mixture. The filtered slurry is then sent to storage tanks to be recirculated (Abraham et al., 2002).

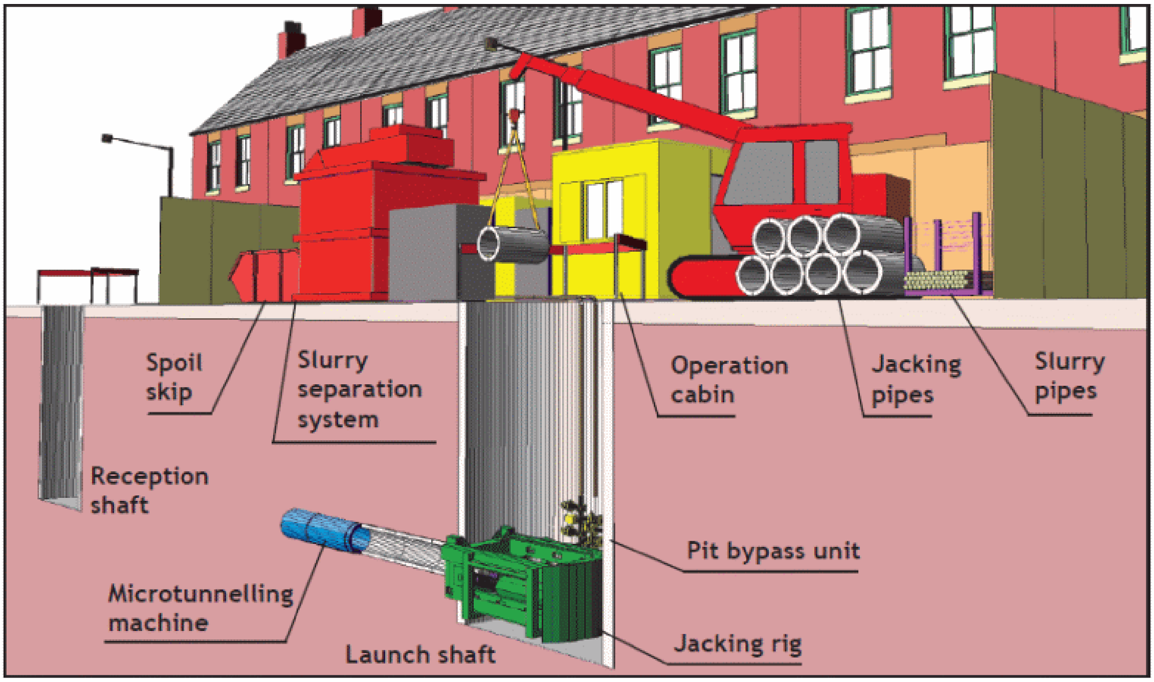

Figure 2. Microtunneling Setup (Iseki Microtunneling, 2009)

Once the MTBM is launched, the jacks are pulled back and the slurry cables and discharge cables are disconnected. A pipe section is lowered into the shaft and placed between the jacking frame and the MTBM. The slurry lines and the discharge lines are reconnected, and the pipe section is jacked into the soil as the MTBM advances in the ground excavating the soil. The jacks are retracted and the cables are disconnected once again to repeat the process with the next pipe section. This process is repeated until the MTBM reaches the receiving shaft. Contact grouting is sometimes performed at the end of the drive to fill the overcut with a cement/bentonite grout to minimize post-construction settlement.

For precise guidance control, a reference laser is mounted on the jacking shaft. The laser beam is aimed at a target located inside the MTBM. This signal is transmitted to the control cabin and enables the operator to make line and grade corrections during construction.

Typical Applications

A summary of typical microtunneling applications is shown in Table 2.

Table 2. Typical Microtunneling Applications

Primary Applications	Depth	Length	Diameter	Pipe Type	Working Space	Soil	Operator Skill
Sanitary sewers, storm sewers, other pipelines	Varies	100-1,000 ft	12–120 in	Steel, reinforced concrete, clay	Jacking pit 20-40 ft wide 50-100 ft long, smaller retrieval pit	Wet sands for slurry method to sandy clays for auger method	High skill level required to operate sophisticated equipment

Soil

Microtunneling can be used in a wide range of soil conditions for a variety of pipe diameters and materials. The slurry microtunneling method is best used in wet sands, and the auger microtunneling is more suitable for stable sandy clay. With the cutter head, microtunneling can also be used in soil conditions where boulders are present. The MTBM can typically cut through boulders that are 20% to 30% of the machine diameter (Abraham et al., 2002). Larger obstructions can pose significant problems, sometimes necessitating excavation of a rescue shaft if the obstruction cannot be overcome.

Pipe

Typical pipe diameters used for microtunneling can range from 12 to 120 in. In practice, the most common diameters are from 24 to 48 in. The maximum size of what is generally regarded as a microtunneling machine is a 60-in internal diameter. Above this size, tunneling machines are regarded as tunnel boring machines (The Highways Agency, 2008). Typically, the materials used for pipes are steel, reinforced concrete, vitrified clay, and glass-fiber reinforced plastic. Microtunneling can be used to install a variety of lengths of pipelines. The most common drive lengths are 500 to 1,000 ft for the slurry microtunneling method and 200 to 400 ft for the auger microtunneling systems (Abraham et al., 2002).

Jacking and Receiving Pits

Microtunneling requires that adequate work space be provided for the jacking equipment. The size of the pit is dependent on the dimensions of the drive shaft. The size typically ranges from 20 to 40 ft wide and 50 to 100 ft long. Circular pits are also a viable option.

Accuracy

Microtunneling work can be extremely accurate. Typically, positional accuracy within 1 in can be achieved along the entire pipe run. This high level of accuracy makes microtunneling particularly suitable for construction of large-diameter gravity sewers and for use in unstable soils.

Production Rate

The typical production rate is 30 to 60 ft in an 8-hour shift (NYSDOT, 2007a).

Depth of Cover

A minimum cover of 5 ft or 3 times the pipe diameter is recommended to minimize displacement of the surface (Abraham et al., 2002). The Unified Facilities Guide Specifications (UFGS) (2006) call for 6 ft or 1.5 times the pipe diameter, whichever is greater.

Costs

Based on the Midwest Cost Indices for 1996, microtunneling costs $13 to $20 per inch of pipe diameter per linear foot (Iseley and Gokhale, 1997). Adjusted for inflation, the corresponding 2014 costs are $20 to $30 per inch of pipe diameter per linear foot.

Horizontal Directional Drilling

Overview

HDD, also known as directional boring, is a method of installing pipes underground using a steerable arc-drilling rig. The bore path can be monitored and adjusted according to the location of the proposed utility or obstacles that are encountered. A variety of pipe diameters can be installed, depending on the type of HDD used. HDD is surface launched, resulting in a safer environment for construction workers since no jacking and receiving pits are required (Doherty, 2011). A big advantage of HDD is the ability to control movement of the reamer and redirect it throughout the bore (Hashash, 2011).

How It Works

HDD is a three-phase process, as shown in Figure 3. First, a drill bit tool creates a pilot hole approximately 1 to 5 in in diameter from the entry to the receiving locations at an angle of 5 to 30 degrees from the ground surface (Iseley and Gokhale, 1997). The second phase is reaming, which enlarges the hole by approximately 50% and prepares it for the pipe placement. A reamer tool replaces the drill bit and is pulled back or pushed forward by the HDD machinery to expand the pilot hole. The third phase is pipe pullback, where the product pipe is attached to the reamer and pulled through the HDD borehole into place (Hashash, 2011).

Drilling fluid is used to suspend and remove soil cuttings. It is also used to stabilize the hole, reduce friction, cool and lubricate the drill bit, and control soil pressures below the surface (Caltrans, 2008). Typically, drilling fluid consists of a mixture of water, bentonite, soda ash, and chemicals that assist in preventing swelling (Hashash, 2011). The slurries most commonly used are bentonite-based.

Conditions for Use

HDD is divided into three classes: maxi-HDD, midi-HDD, and mini-HDD. Maxi-HDD is the method for installing the largest diameter pipeline and is typically used to cross major rivers and highways. Midi-HDD is used to construct medium-diameter pipes under rivers and smaller roadways. Mini-HDD, also known as guided boring, is used to install small-diameter pipes, telephone, power, and gas lines (Iseley and Gokhale, 1997).

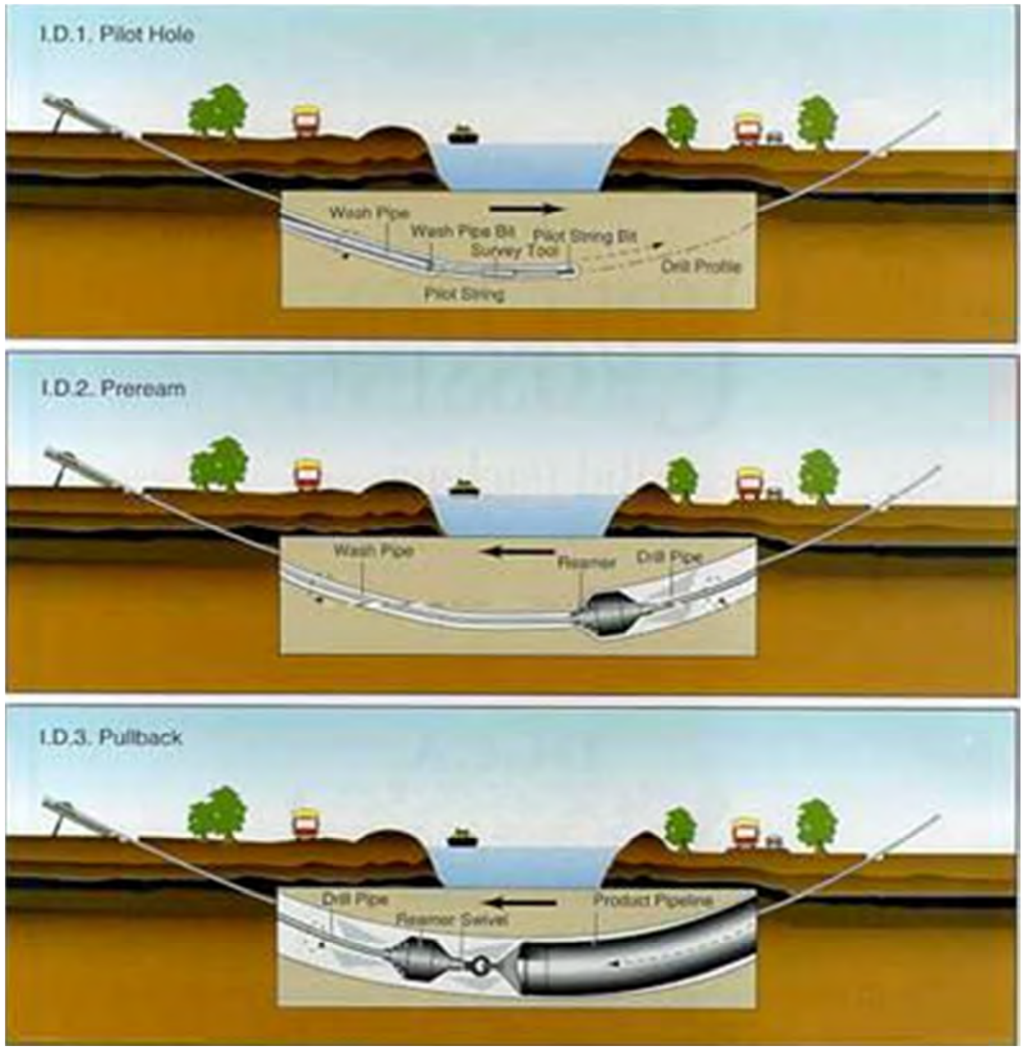

Figure 3. Pipe Installation Under Water Using Horizontal Directional Drilling (Apollo Trenchless Inc., 2013)

Typical Applications

A summary of typical HDD applications is shown in Table 3.

Table 3. Typical HDD Applications

Primary Applications	Depth	Length	Diameter	Pipe Type	Working Space	Soil	Operator Skill
Utility lines, wide range of pipe sizes	Varies, based on pipe size	Up to 6,000 ft	2–48 in	HDPE, steel, PVC, clay, FRP	No entry and receiving pits are required. A work space should be provided at both ends for storage and equipment (Oregon Department of Transportation, 2005).	Varies	High

HDD = horizontal directional drilling; HDPE = high-density polyethylene pipe; PVC = polyvinyl chloride pipe; FRP = fiberglass pipe.

Soil

Directional drilling is best suited for clays. Soft to hard clays are the preferred soils for HDD applications, although its use in cohesionless fine sands and silts is also acceptable (Iseley and Gokhale, 1997). Soils containing more than 50% gravel or loose soils are generally unsuitable (Hair, 1994). Directional boring should not be conducted in soils that contain material with particle diameters greater than 3 in, since these particles are too large to be suspended in the drilling fluid (Gelinas et al., 2010). HDD can be used successfully underwater, in saturated soils, under permafrost, and in a soil that is likely to erode (Hashash, 2011).

Pipe

High-density polyethylene pipe (HDPE) is the most common pipe material used in all three HDD methods (Carpenter, 2009). Pipes can be installed with diameters from 2 to 48 in and lengths of up to 6,000 ft. Table 4 shows typical HDD pipe characteristics for various methods.

Table 4. Typical HDD Pipe Characteristics

Method	Diameter	Length	Material
Maxi-HDD	24-48 in	6,000 ft	HDPE, steel
Midi-HDD	12-24 in	1,000 ft	HDPE, steel, ductile/iron
Mini-HDD	2-12 in	600 ft	HDPE, steel, PVC, clay, FRP

Source: Salem et al. (2008).
HDD = horizontal directional drilling; HDPE = high-density polyethylene pipe; PVC = polyvinyl chloride pipe; FRP = fiberglass pipe.

Jacking and Receiving Pits

Pits are not required for HDD because it is surface launched.

Accuracy

Placement accuracy of HDD methods varies widely and is dependent on the operator's skills. The method is fully steerable, but until recently the accuracy has not been sufficient for gravity sewer installations. Recent technological advances allow more precise control.

Production Rate

Directional drilling has the fastest boring rate among all the trenchless methods. In suitable conditions, up to 500 ft of pipeline can be installed in 1 day (ODOT, 2005).

Depth of Cover

Generally, the recommended depth of cover increases with pipe diameter to reduce the amount of settlement or heave that could potentially occur. Table 5 lists the depths of cover recommended by Caltrans. They are generally in excess of five pipe diameters.

The North Carolina Department of Transportation (NCDOT) (2012) specifies the minimum depth of cover based on the bore diameter and the type of HDD construction, as indicated in Table 6.

The Florida Department of Transportation (FDOT) (2007) specifies the minimum cover depth of 10 times the bore size when the utility is installed under the FDOT pavement and the minimum required soil Standard Penetration Test [SPT] N value of 30 in the area of installation.

Table 5. HDD Depth of Cover Recommended by California Department of Transportation

Diameter	Depth of Cover
2-6 in	4 ft
8-14 in	6 ft
15-24 in	10 ft
25-48 in	15 ft

Source: California Department of Transportation (2008).
HDD = horizontal directional drilling.

Table 6. HDD Depth of Cover Recommended by North Carolina Department of Transportation

Drilled Hole Diameter	Single Pass Reaming	Multiple Pass Reaming
2-6 in	4 ft	4 ft
>6-22 in	8 times the hole diameter	12 times the hole diameter
>22-32 in	15 ft	25 ft

Source: North Carolina Department of Transportation (2012).
HDD = horizontal directional drilling.

Overcut

The borehole should be oversized to facilitate pipe installation. The general rule of thumb is that the back ream should have a diameter that is 1.5 times the diameter of the pipe being installed. However, if the soil has the potential to swell or there are cobbles present, the diameter should be increased by 25% (Hashash, 2011). The Georgia Department of Transportation (GDOT) (2009) specifications stipulate that HDD reamers should not be greater than 1.5 times the pipe diameter. National Driller (2010) recommends that the HDD final bore should be the lesser of the diameter plus 12 in or 1.5 times the diameter, with at least 2 in annular space provided for pipes 8 in or less in diameter.

FDOT provides specific guidance for back reaming, designed to limit the ratio of bore size to product pipe diameter, as shown in Table 7.

Table 7. Maximum HDD Overcut Recommended by Florida Department of Transportation

Nominal Inside Pipe Diameter	Maximum Reamer Bit Diameter
2 in	4 in
3 in	6 in
4 in	8 in
6 in	10 in
8 in	12 in
10 in	14 in
12 in and greater	Maximum product OD + 6 in

Source: Florida Department of Transportation (2010).
HDD = horizontal directional drilling; OD = outside diameter.

Drilling Fluid

At longer distances, polymer-based slurry and bentonite are recommended to stabilize the hole during construction. Drilling mud washes out spoils and reduces the amount of friction. In coarse-grained soils, the fluid removes cuttings and prevents cave-in. In fine-grained soils, it also prevents swelling (Hashash, 2011). Drilling mud can be left in place to solidify and support the pipe.

Costs

Based on the Midwest Cost Indices for 1996, maxi-HDD costs $200 to $500 per linear foot, midi-HDD costs $50 to $200 per linear foot, and mini-HDD costs $5 to $50 per linear foot (Iseley and Gokhale, 1997). Adjusted for inflation, 2014 costs for maxi-HDD are $300 to $760 per linear foot, midi-HDD costs are $75 to $300 per linear foot, and mini-HDD costs are $7.50 to $75 per linear foot.

Pipe Jacking

Overview

Pipe jacking is a trenchless technology method similar in principle to microtunneling. It has been used for the past 100 years (Iseley and Gokhale, 1997). The method uses a horizontal jacking force to advance the pipe. Unlike microtunneling, pipe jacking requires personnel entry inside the pipe to carry out excavation and spoil removal (URS, 2002). The method is best suited to large-diameter pipes in order to provide adequate space and ventilation for workers (Iseley and Gokhale, 1997).

How It Works

Pipe jacking is a cyclic method that uses thrust to force pipes through the ground. After each pipe segment has been installed, the ram of the jack is retracted so that another pipe segment can be placed in position and the jacking cycle can begin again (Iseley and Gokhale, 1997). Once the jacking process is started, it should not be interrupted to prevent the pipes from freezing in place. Pipe ends must be parallel to assure uniform distribution of forces (Caltrans, 2010). The spoil material is transported to the inside of the pipe (Iseley and Gokhale, 1997). Spoil removal can be accomplished manually or mechanically. Spoil conveyance systems include wheeled carts or skips, belt or chain conveyors, slurry systems, auger systems, and vacuum extraction systems (ODOT, 2005).

Soil is removed by hand mining or mechanical excavation within a shield or by a tunnel boring machine. If there is a possibility of the excavation face collapsing, various soil stabilization techniques, including dewatering and grouting, may be required. For personnel safety, the minimum pipe diameter of 42 in is recommended.

Optional equipment includes a pipe lubrication system and intermediate jacking stations. A pipe lubrication system applies bentonite or polymer slurry to the external surface of the pipe to reduce frictional resistance and to decrease jacking forces by 20% to 50% (Iseley and Gokhale, 1997). Intermediate jacking stations redistribute the total required jacking force and are located between the drive shaft and jacking shield. They are used for pipes that are at least 48 in in diameter. The stations are pushed along with the pipes, and when the jacks reach 80% of the design load, the jacking force on the pipe behind the intermediate jacking systems is held constant and the jacks in the intermediate jacking station are activated to propel the forward section of the pipeline (Iseley and Gokhale, 1997).

Conditions for Use

The primary applications of pipe jacking include sanitary sewer and pressure lines (Caltrans, 2010). Pipe jacking is also an effective and low-cost method for installing non-sewer underground pipelines, drainage culverts, and utilities (Rahjoo et al., 2012). The allowable depth of excavation varies, and the method is generally applicable to stable granular and cohesive soils.

Typical Applications

A summary of typical pipe jacking applications is shown in Table 11.

Table 11. Typical Pipe Jacking Applications

Primary Applications	Depth	Length	Diameter	Pipe Type	Working Space	Soil	Operator Skill
Sewers, pressure lines, crossings	Varies	No theoretical limit	42-120 in	RCP, steel, fiberglass	Entry and exit bore pits: Length: 25 to 35 ft Width: 10 to 12 ft	Sandy clay, varies	High

RCP = reinforced concrete pipe.

Soil

Sandy clay is the most favorable soil condition for pipe jacking installation, but most any cohesive soil is acceptable (Rahjoo et al., 2012). Unstable sands below the groundwater table and soils with large boulders are not suitable (Caltrans, 2010).

Pipe

The type of pipe material typically includes steel, fiberglass, and reinforced concrete. Although diameters as small as 42 in may be used, because of the required worker entry, it is generally recommended that pipe diameters be larger than 4 ft (URS, 2002). The quality of pipe material is very important. A cushion, such as plywood, is typically placed between pipe segments to distribute jacking loads evenly through the system (Iseley and Gokhale, 1997).

Jacking and Receiving Pits

The jacking pit is governed by the pipe size. Typical pit sizes are shown in Table 11. The design of the jacking shaft is important because the weight of the pipes must be supported by the floor and thrust structure (Iseley and Gokhale, 1997). The working space must be adequate for workers, material storage, and handling of the pipe and spoils. Typical working space is 4 to 10 ft wider than the pipe diameter and from 10 to 25 ft longer than the length of the pipe sections being installed (ODOT, 2005).

Accuracy

Typically, there is a tolerance of ±3 in for alignment and ±2 in for grade (Iseley and Gokhale, 1997).

Production Rate

The typical range is 30 to 100 ft per shift (NYSDOT, 2007a).

Depth of Cover

The minimum depth of cover should be the greater of 6 ft or 3 times the outside diameter of the pipe (Michigan Department of Transportation [MDOT], 2006). The DWA (2008) German Standard DWA-A 125E stipulates 10 times the outside pipe diameter for horizontal jacking with expander (bore enlarged by soil displacement).

Costs

Based on the Midwest Cost Indices for 1996, pipe jacking costs $5 to $15 per inch of pipe diameter per linear foot (Iseley and Gokhale, 1997). Adjusted for inflation, 2014 costs are $7.50 to $25 per inch of pipe diameter per linear foot.

Some Existing Guidelines and Specifications

Trenchless design guidelines and construction specifications adopted by transportation agencies vary significantly. In many instances, the state of the practice is developed through periodic feedback from local projects, reflecting the regional soil conditions and construction methods.

Example guidelines and specifications are as follows:

- ASCE (2001) developed a set of comprehensive guidelines for microtunneling work. These guidelines address planning aspects, materials and methods, site investigation, contract documents, and contractor prequalification.

- Trenchless excavation using microtunneling is addressed in Section 33 of the UFGS (2006).

- The Washington Suburban Sanitary Commission (2011) developed standard specifications for microtunneling. This comprehensive set of specifications includes a detail for subsurface settlement indicator.

- The City of Baton Rouge (2012) developed specifications for jacked and bored pipe / casing (Section 817) and microtunneling and pipe-jacked tunnels (Section 819).

- The City of Sanger (2008) *Standard Specifications for Public Construction* contain references to boring and jacking (Section 37).

- FDOT (2010) *Standard Specifications for Road and Bridge Construction* include Section 555, addressing directional bore (HDD) and Section 556, addressing jack and bore. Section 556 also refers to microtunneling work as being in the same category as jack and bore for purposes of specifications.

- NYSDOT *Design Guidance for Trenchless Installation of Casing* (2007a) addresses multiple types of trenchless technologies and includes a revised version of Section 650 (2007b). Geotechnical planning for proposed projects is in Chapter 2 of the NYSDOT *Geotechnical Manual* (2013), and geotechnical design specific to pipe installation is in Chapter 21 (2012).

- Section 716 of Indiana Department of Transportation (INDOT) (2012) *Standard Specifications* covers trenchless pipe installation. This specification is written fairly broadly, as it includes "auger boring, guided boring, horizontal directional drilling, micro-tunneling, pipe jacking, and pipe ramming. Other methods may be utilized when approved."

- Section 1550 of NCDOT (2012) *Standard Specifications for Roads and Bridges* addresses trenchless installation of utilities. It covers specifically jack and bore, directional drilling, tunneling, and pipe ramming, allowing other methods to be considered on a case-by-case basis.

- Item 476 of the Texas Department of Transportation (TxDOT) (2004) *Standard Specification for Construction and Maintenance of Highways, Streets, and Bridges* describes "Jacking, Boring, or Tunneling Pipe or Box." It provides construction guidance for jacking and operations.

- The Australasian Society for Trenchless Technology (2009) developed *Specification for Microtunneling and Pipe Jacking.*

- The Highways Agency (2008) issued *Design Manual for Roads and Bridges* for the United Kingdom. Volume 4, Section 1, Part 8, of the manual gives guidance on trenchless installation of pipe beneath roadways, and Volume 4, Section 1, Part 2, discusses the geotechnical subsurface investigations needed to manage certain geotechnical risks.

- European Standard EN 12889 (European Committee for Standardization, 2000) addresses trenchless construction and testing of drains and sewers. It specifies procedures for testing gravity pipelines.

- The DWA (2008) German Standard DWA-A 125E covers the underground installation of prefabricated pipes. It applies to all pipe jacking and related techniques, whereas European Standard EN 12889 (European Committee for Standardization, 2000) applies only to drains and sewers.

Current VDOT Practice

Currently, the only trenchless construction methods included in VDOT specifications are jack and bore and microtunneling as follows:

- Section 302 (Drainage Structures) of the 2007 VDOT *Road and Bridge Specifications* (VDOT, 2007), which includes jack and bore and tunneling (general)

- *Special Provision for Section 302.03(A)1 - Jack and Bore for Design Build Projects* (VDOT, 2009a)

- *Special Provisions for Section 302.03(A)3 - Micro-Tunneling for Design Build Projects* (VDOT, 2009b).

Special Provision for Section 302.03(A)1 - Jack and Bore for Design Build Projects (VDOT, 2009a), developed by VDOT's Northern Virginia District, contains the following requirements:

- *Performance:* Settlement or heave of the ground surface and existing utilities over or adjacent to the alignment of the pipe or adjacent to temporary excavation support systems at jack and bore access/egress locations shall not exceed 0.5 in.

- *Pre-Qualification:* Contractors must have 5 years minimum experience of prior trenchless installation, and a field supervisor should be present at all times when work is being progressed.

- *Design and Calculations:* Contractors should submit construction drawings and design calculations, which will be checked and stamped by a professional engineer registered in the Commonwealth of Virginia. In addition, drawings should be submitted that describe all of the proposed equipment and procedures that will be used along with a description of the proposed line and grade control methods.

- *Surface Monitoring:* Ground movement/settlement should be monitored for all structures, roadways, and any other areas of concern within at least 25 ft on both sides of the trenchless route. When crossing beneath roadways, survey-monitoring points should be established along the centerline and at horizontal offsets of 0.5 times and 1.25 times the pipe invert depth from the pipe centerline.

- *Execution:* Jacking and receiving pits should be of adequate size to accommodate the boring machine and other necessary equipment. The contractor is also responsible for designing and maintaining an excavation support system. The use of water and other drilling liquids to facilitate spoil removal is prohibited. When voids are created outside the pipe during installation the contractor should submit a plan to fill those voids.

- *Tolerance:* Pipe alignment shall not vary from the proposed plan more than 6 in horizontally and 2 in vertically. The contractor shall conduct their installation in a manner that "minimizes settlement and/or heave of the ground and shall be responsible for damage due to settlement or heave from any construction-induced activities."

Special Provision for Section 302.03(A)3 – Micro-Tunneling for Design Build Projects (VDOT, 2009b), developed by VDOT's Northern Virginia District, contains the following requirements:

- *Performance:* Settlement or heave at the ground surface during and after construction shall not exceed 0.5 in.

- *Pre-Qualification:* Contractors must be experienced in micro-tunneling and must have completed a minimum of 5 pipeline or conduit construction projects in similar ground conditions within the last 3 years.

- *Surface Monitoring:* Not specified explicitly.

- *Execution:* Launching and receiving pits should be of a size commensurate with safe working practices.

- *Tolerance:* Pipelines should be placed within 1 in of the vertical and 1 in of the horizontal alignment shown on the plans.

Neither special provision refers to the minimum required depth of cover for underground utilities and pipelines constructed within the VDOT right of way. This issue is addressed in the *Code of Virginia,* Title 56, Chapter 10.3, § 56-265.26:1 (Utility line depth requirement). It stipulates that underground utility lines be installed at depths required by accepted industry standards. Additional requirements are detailed in the *Virginia Administrative Code*, Title 24, Chapter 151, Section 24VAC30-151-340 (Underground Utility Installations Within Nonlimited Access Highways), as follows:

All underground utilities within VDOT right-of-way will require a minimum of 36 inches of cover, except underground cables that provide cable or telecommunications services shall be at a minimum of 30 inches of cover. The district administrator's designee has the discretion to grant an exception to depth of cover requirements if the permittee encounters obstacles preventing the installation of main line facilities at the minimum depth of cover, as long as installation at the minimum depth of cover is resumed when the installation passes by the obstacle.

VDOT's *Land Use Permit Guidance Manual* (VDOT, 2013) references minimum depth of cover requirements for all underground utility installations, as articulated in Section 24VAC30-151-340 of the *Virginia Administrative Code*.

Trenchless Method Selection

One of the most widely referenced studies of trenchless technologies is *Trenchless Installation of Conduits Beneath Roadways* (Iseley and Gokhale, 1997). It covers several additional technologies that are not discussed in this report, such as steerable and non-steerable impact moling and utility tunneling.

The general suitability of various trenchless applications is summarized in Table 12. The selection criteria based on soil and rock conditions are shown in Table 13. Table 14 summarizes the applicability of various trenchless technologies when SPT N values, per ASTM D1452, are available or rock strength is known (Iseley et al., 1999).

Although jack and bore can be very economical when compared to other trenchless technologies, it provides very limited support to the excavation face. This method is not suitable for installations where running sands are expected or for operation below the water table (Dayal et al., 2011). Inappropriate use of jack and bore in poorly graded granular soils, fine sands below the water table, or unstable ground conditions can result in excessive post-construction settlement.

Generally, unguided methods should be used only for relatively short drives. For longer drives, steerable methods such as HDD and microtunneling are more suitable if the alignment accuracy is critical. The advantages of using HDD include the relatively short setup time, long installation length, and ability to move around buried obstacles (Hashash, 2011). The risks include the potential for heave or soil collapse and increased costs in difficult geologic conditions. A great advantage of microtunneling over other methods is that it provides continuous face support and balances hydrostatic conditions, thus maintaining a stable excavation heading even in very poor soils. Microtunneling presents some cost and schedule disadvantages as compared to jack and bore, such as higher operating expenses and extended project duration attributable to the longer setup time (URS, 2002).

Table 12. Overview of Trenchless Applications

Method	Range of Diameters	Primary Application
Jack and bore	8-60 in	Crossings
Microtunneling	10-120 in	Sewer installations
Horizontal directional drilling	2-48 in	Pressure lines, water, gas, cable
Pipe jacking	42-120 in	Sewers, pressure lines, crossings

Source: Iseley and Gokhale (1997).

Table 13. Applicability of Trenchless Technologies to Various Soil and Rock Conditions

Soil Conditions	Jack and Bore (Auger Boring)	Microtunneling	Horizontal Directional Drilling	Pipe Jacking
Soft to very soft clays, silts, and organic deposits	Y	Y	Y	M
Medium to very stiff clays and silts	Y	Y	Y	Y
Hard clays and highly weathered shales	Y	Y	Y	Y
Very loose to loose sands *above* the water table	M	Y	Y	M
Medium to dense sands *below* the water table	N	Y	Y	N
Medium to dense sands *above* the water table	Y	Y	Y	Y
Gravel and cobbles with a diameter less than 2 to 4 in	Y	Y	M	Y
Soils with significant cobbles, boulders, and obstructions with a diameter more than 4 to 6 in	M	M	M	M
Weathered rocks, marls, chalks, and firmly cemented soils	Y	Y	Y	M
Slightly weathered to unweathered rock	Y	M	M	N

Source: Iseley et al. (1999).
Y = generally used; M = possible but difficulties may occur; N = generally unsuitable.

Table 14. Applicability of Trenchless Technologies to Soil and Rock Types

Soil Type	N Value (Standard Penetration Test Value, per ASTM D1452)	Jack and Bore (Auger Boring)	Microtunneling	Horizontal Directional Drilling	Pipe Jacking
Cohesive soils (clay)	N < 5 (Soft)	M	Y	M	M
	N = 5-15 (Firm)	Y	Y	Y	Y
	N > 15 (Stiff – Hard)	Y	Y	Y	Y
Cohesionless soils (sand/silt)	N < 10 (Loose)	M	Y	M	M
	N = 10-30 (Medium)	Y	Y	Y	Y
	N > 30 (Dense)	Y	Y	Y	Y
	High groundwater	N	Y	M	M
Boulders/cobbles		≤33% D	≤33% D	M	M
Full-face rock		≤12 ksi	≤30 ksi	≤15 ksi	≤30 ksi

Source: Iseley et al. (1999).
Y = recommended; M = possible but difficulties may occur; N = generally unsuitable; D = size of largest boulder versus minimum casing diameter.

There are opposite trending curves for the perceived risk of using HDD and microtunneling, as shown in Figure 4. The perceived risk for HDD increases with pipe diameter; the opposite is the case for microtunneling. For HDD, the risk greatly increases with the larger pipe diameter because of the difficulty in maintaining a stable, fluid-filled borehole. For microtunneling, there is a much greater risk of subsurface obstructions stopping a small-diameter boring machine. The breakpoint for pipe diameter occurs at approximately 30 in, with microtunneling becoming a less risky option at larger diameters (Mathy et al., 2008). For HDD, there is a risk of "frac-outs" (blowout of drilling mud) resulting in potential pavement damage. The risk of a blowout increases with larger hole diameters. Blowout can be caused by fluid pressure exceeding the soil's shear strength, fractures present in soil or rock, or previous soil disturbance caused by other construction activities (The Highways Agency, 2008).

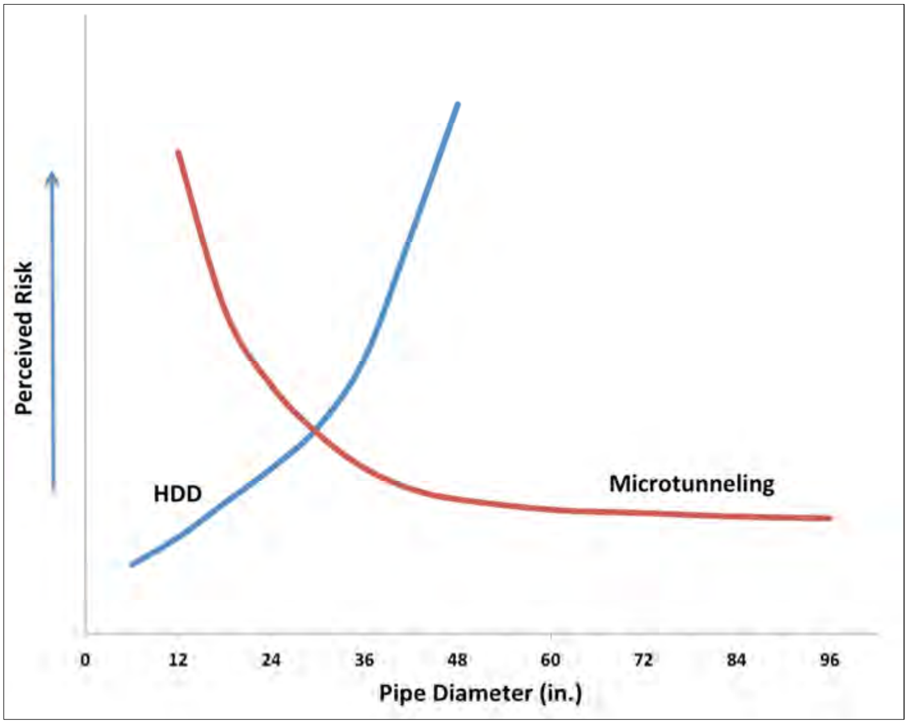

Figure 4. Perceived Risk for HDD and Microtunneling (after Mathy et al., 2008). HDD = horizontal directional drilling.

NYSDOT (2007a, b) specifications do not allow any trenchless methods that rely on soil displacement, including pipe ramming. These requirements were implemented based on experience.

The Massachusetts Department of Transportation (MassDOT) (1996) trenchless selection guidelines contain the following requirements:

- MassDOT will not allow auger boring if loose sand is encountered in combination with a high water table or loose embankment fill is indicated by the test borings. The contractor must use jacking methods or pre-grout the soils prior to auger boring.

- MassDOT will not permit auger boring methods if cobbles or boulders are encountered at the pipe's invert elevation or if rock fill was used to construct the highway embankments (will result in large voids). The contractor must use hand tunneling methods in this case.

- MassDOT will not permit the auger boring of casing sizes less than 30 in unless test borings indicate sand, silt, clay, or gravel free of obstructions. If a small-diameter casing is bored to an obstruction, the contractor's submitted design should state that the casing will be filled with grout and abandoned.

Design and Construction Details

General

An example of technical specifications addressing various construction details is as follows (Dulles Rail Consultants, 2012):

- Pipe Jacking: thickness of the overcut shall not extend beyond the outside diameter of the pipe by more than 0.5 inch. Deviations from line and grade shall not exceed amounts that allow the final placement of carrier pipes to within 0.5 in for sewer and drain lines, and 2 in for ducts and water mains at any point along the casing pipe.

- Jack and Bore: casing pipe deviation from line and grade shall not exceed 2 in in any direction at any point along the pipe.

- Thickness of the overcut shall not extend beyond the outside diameter of the casing pipe by more than 0.5 inch.

- The cutter head will not be allowed to advance ahead of the casing unless the Contractor can demonstrate that ground loss or settlement is less than the specified limit. In no case will the cutter head be allowed to advance more than 12 in ahead of the casing.

- The Contractor shall maintain the ground water level a minimum of 2 ft below the invert at all times during construction.

- Ground stabilization, if required, shall be performed by a contractor that has a minimum of five continuous years' experience of successfully grouting soils.

- Immediately after the jacking or auger/boring operation is complete and the casing pipe is accurately positioned and approved for line and grade, any voids between the casing pipe and the surrounding excavated material shall be completely filled by pressure grouting for the entire length of installation. Grout holes shall be filled starting at the pipe invert and moving upwards towards the crown. Grouting shall commence no later than 24 hours after the casing installation has been completed.

- If it is found that the roadway or adjacent structures need to be rebuilt due to settlement or lifting, the Contractor shall be responsible to perform all repairs and/or rebuilding of the roadway or adjacent structures in accordance with VDOT requirements.

MassDOT (1996) specifications do not allow wet boring or jetting ahead or inside of the casing to facilitate casing installation or to remove soil in jack and bore construction. In addition, the specifications require that an auger stop-ring be welded to the front of the casing to prevent the auger from extending beyond the casing and overexcavating soil. In addition, allowing the auger to rotate with no forward movement is not allowed as it will draw soil into the auger and cause settlement. Boring without the concurrent installation of a casing pipe is not permitted.

FDOT (2010) specifications for jack and bore provide the following construction details:

- The rear of the cutting head should be kept from advancing in front of the leading edge of the casing by more than 1/3 times the casing diameter and in stable cohesive soils not to advance by more than 8 inches.

- In unstable conditions, the cutting head should be retracted into the casing a distance that permits a balance between pushing pressure, pipe advancement and soil conditions.

- At least 20 feet of full diameter auger must be provided at the leading end of the casing. Subsequent auger size may be reduced but the auger diameter must be at least 75 percent of the full auger diameter.

- Water may be injected to facilitate spoil removal, but the point of injection must be no closer than 2 feet from the leading edge of the casing.

- A log of volume of spoil material removed relative to the casing advancement should be maintained.

For HDD, NCDOT (2012) specifications stipulate that for bores up to 6 in in diameter in stable ground, the hole may be drilled and reamed, followed by pulling the pipe into the hole within 8 hours. For drilled holes greater than 6 in, the contractor is required to pull the pipe or casing into the hole simultaneously as reaming occurs. Multipass reaming larger than 6 in requires a certification that the soils are self-supporting of dead and live loads. FDOT (2010) specifies that "to minimize heaving during pullback, the pullback rate is determined in order to maximize the removal of soil cuttings without building excess downhole pressure."

NCDOT (2012) specifications stipulate the use of drilling fluids under the following conditions:

- Use drilling fluid as appropriate for the soil type.
- Use drilling fluids only on the outside of pipe for lubrication or hole stabilization.
- Pump drilling fluids only while drilling or reaming.
- Monitor flow rates to match the amounts entering and leaving the bore.
- Do not increase pressure or flow to free stuck drill heads, reamers or piping.

MassDOT (1996) specifications require that all pit excavations and jacking operations be conducted in the dry. Groundwater levels must be kept at a minimum of 1 ft below the casing invert and 2 ft below the pit bottom for the duration of the project. If the groundwater level does not meet these criteria or if a loose fine-grained soil exists in conjunction with a high water table, the contractor must use a dewatering system to drain the soil before starting or continuing the work. The contractor must check the monitoring wells and record their levels daily, whether or not construction occurs that day.

For line and grade tolerance, NCDOT (2012) specifies that trenchless installation of water main may not vary more than 2% of total length from the required horizontal alignment and 1 ft from vertical alignment. Trenchless installations for grade- and alignment-dependent pipes, such as sewers, may not vary. TxDOT (2004) stipulates that the final position of the pipe or box must not vary from the line and grade shown on the plans by 1 in in 10 ft. Variations must be regular and in one direction, and the final flow line must be in the direction shown on the plans.

When a project is completed, it is important for the owner to obtain a documented record of construction. FDOT (2010) trenchless specifications require delivery of as-built plans showing locations and descriptions of all bores (successful and failed) within 30 days of completing the work. The Highways Agency (2008) requests as-built drawings, including details of the installed conduit, temporary works, permanent structures, backfill, a post-construction structures and elevation survey, construction photographs, details of any problems encountered, and corrective procedures performed.

Some agencies set minimum qualifications necessary to carry out trenchless design and construction. Caltrans (2008) specifications require that trenchless design be performed by a licensed engineer with at least 5 years of experience in substructure design. The ASCE (2001) construction guidelines recommend the following criteria for prequalifying a microtunneling contractor:

- proof of financial stability of the firm
- minimum of five construction projects of similar size and scope carried out by the project manager and superintendent
- minimum of 3,000 ft and/or 10 drives for qualified personnel operating the equipment.

Pits

Methods such as pipe jacking, microtunneling, or auger boring require construction of entry and receiving pits. Microtunneling also requires surface space for equipment and a control cabin. HDD requires surface area for pipe assembly and storage prior to pullback. Technologies that use slurry in excavation also require additional room for a slurry tank, and those technologies that result in spoil excavation will require space for excavated material. Pits should be designed and constructed to resist all applicable static and dynamic loads, including the maximum driving force.

The DWA (2008) German Standard DWA-A 125E provides general guidance for estimating the required pit sizes. For example, for pipes up to 16 in, it recommends a minimum of 8 by 6.5 ft and 6.5 by 6.5 ft for the starting and receiving pits, respectively. For pipes in the range of 42 to 68 in, it recommends 19 by 13 ft and 15 by 10 ft for the starting and receiving pits, respectively. The required pit size is governed by the type of equipment and pipe dimensions.

New Hampshire DOT (2010) specifications require that pits be placed beyond a line created by a 1.5:1 slope projected down from the shoulder break of the roadway). MassDOT (2013) requires that pits be located at least 30 ft from the edge of the nearest through traffic lane and at least 20 ft from the edge of the pavement on ramps. On low-traffic roadways and frontage roads, pits should be located at least 10 ft from the edge of pavement and at least 5 ft from the face of the curb. For interstate highways, GDOT (2009) does not allow pits in medians less than 100 ft wide. Caltrans (2008) requires that pits for jack and bore operations be located a minimum of 10 ft from the edge of pavement in rural areas, at least 5 ft beyond the curb and gutter in urban areas, and at least 5 ft beyond the toe of slope of embankments.

Although HDD does not require entry and receiving pits, some surface area must be provided to the contractor for the required material storage and mobilization. Although mini-HDD can be effectively used in very congested spaces, up to 400 by 200 ft may be required to accommodate maxi-HDD equipment. ODOT (2005) recommends a 120 by 175 ft working area for carrying out HDD operations.

Casings

Casings are typically required under roadways to protect the product pipe and provide a stable tunnel. Casings can also be used to facilitate alignment. One way of overcoming line and grade tolerance limitations of a trenchless method is to install an oversized casing and then adjust the carrier pipe within it (Dayal et al., 2011). Caltrans (2008) requires that all transverse crossings 6 in or greater be encased. Washington State Department of Transportation (WSDOT) (2010) specifications require that the casing pipe be extended 6 ft beyond the toe of fill slopes, or bottom of ditch line, or outside the curb.

MassDOT (2013) specifies the following requirements for pipelines that may be placed under highways without casings:

- It is a welded steel pipeline.
- It is cathodically protected.
- It is coated in accordance with accepted industry standards.
- It complies with federal and state requirements and meets accepted industry standards regarding wall thickness and operating stress levels.
- The depth of the crossing is a minimum of 3 ft below the original ditch grade.
- The bores are continuous from the beginning of the installation until the leading edge of the pipeline is through the entire crossing.
- The completed pipeline crossings are all pressure tested.
- During the pipeline installation, traffic on the highway will not be restricted.
- Grouting will be done along the top of the pipe to fill all voids.
- All water lines shall be cased when crossing under the roadbed of trunk highways except service lines of 2 in diameter or less. Encasement may be omitted under entrances, depending on the type and amount of traffic and depth, condition, and maintenance responsibility

Overbreak (Overcut) and Grouting

Overbreak, or overcut, is defined as the annular gap between the excavated bore and the outer pipe wall. Overbreak is necessary to decrease jacking forces, inject lubrication, and facilitate steering, but the risk of excessive settlement increases with the amount of overbreak. The overbreak is typically specified at 0.5 to 1 in on radius. Caltrans (2008) allows up to 1 in radially for pipe jacking. The same amount is specified for microtunneling by the U.S. Army Corps of Engineers (UFGS, 2006). WSDOT (2010) and MassDOT (2013) allow the bore to be 5% larger than the diameter of the carrier for general trenchless methods. For jack and bore, MassDOT (1996) requires that the overcut not exceed the outside diameter of the pipe by more than 0.5 in.

MassDOT (1996) specifications require that upon completion of the jacking/boring operation, the contractor must grout all voids surrounding the casing. For casings 30 in in diameter or greater, the contractor should pressure grout from the interior of the casing through pre-installed grout holes or nipples. Three holes must be installed at 120-degrees spacing for every 10 ft of casing. For casings less than 30 in in diameter, the contractor should grout from the road surface. The grout should have a documented minimum 28-day compressive strength of 500 psi. After completing the grouting operation, the contractor should seal each grout hole.

The New Hampshire DOT (2010) specifications stipulate that steel jacking sleeves and jacked concrete pipe be fabricated with grout holes. A minimum of three grout holes are required per 10-ft section.

The City of Baton Rouge (2012) requires that all tunneled pipes 36 in in diameter or larger have grout injection ports built into the pipe at the 12 o'clock position for pumping slurry during the pipe installation and for grouting the annular space once the tunneling is complete.

Caltrans (2008) requires grouting on pipes with diameters of 36 in and greater. Grouting holes must be on 8-ft centers, longitudinally—offset and staggered 22 degrees from vertical. Grout pressures must not exceed 5 psi for a time required to fill all voids.

Depth of Cover

Many agencies specify a default depth of cover required over the installation. These default values are typically set irrespective of the method of trenchless construction and the pipe diameter. Sometimes the depth of cover is specified depending on the road classification, as shown in Table 15.

Table 15. Minimum Depth of Cover Recommended by Several States

Agency	Primary Roads	Secondary Roads
New Hampshire DOT (2010)	10 ft	5 ft
Montana DOT (2008)	3.5 ft below the ditch line	
New York State DOT (2007a)	>5 ft	
Georgia DOT (2009)	10 ft	4 ft

MassDOT (2013) specifications state that the depth of burial for all underground facilities crossing the highway shall be a minimum of 3 ft under ditches and a minimum of 5 ft under the pavement surface as measured from a straight line connecting the lowest points of the finished ground or pavement surface on each side of the right of way to the top of the facility at the time of the installation. Water and sewer lines must be installed with a minimum of 5.5 ft cover for highway crossings. The WSDOT (2009) utilities accommodation policy stipulates a minimum cover of 5 ft from the lowest point of finished roadway or shoulder and 3.5 ft below the ditch line. VDOT's *Land Use Permit Guidance Manual* (VDOT, 2013) specifies 3 ft as the minimum depth of cover under pavement.

It should be recognized that although the default depths are conservative for most installations, the actual cover requirements may be greater in project-specific cases. Minimum depth of cover specifications are provided in the report sections concerning various trenchless methods.

Principal risks associated with trenchless methods are heave and settlement of the overlying soil. Heave, although potentially damaging to road surface, is usually a temporary event typically resulting from applying excessive face pressure. It is difficult to quantify in advance of construction since it is mostly method rather than material dependent. Settlement is often a long term phenomenon, with consequences potentially appearing long after construction. The magnitude of post-construction settlement depends mainly on the depth of cover, size of the bore, volume of overbreak, and soil type.

Settlement can be estimated in advance of construction based on previous studies conducted on tunneling in soft ground (Aoyagi, 1995). Typically, surface settlement results from the collapse of the annular space between the jacking pipe and the bore. Wallin et al. (2008) presented a relationship between surface settlement, depth of cover, volume of the overbreak, pipe and bore diameters, and soil properties. To estimate the required depth of cover Wallin's relationship can be restated as follows:

$$h_c = \frac{\dfrac{\pi\left(d_b^2 - d_p^2\right)/4}{\Delta h_{cl}} - \left(1 + \tan\left(45 - \frac{\phi}{2}\right)\right)\frac{d_b}{2}}{\tan\left(45 - \frac{\phi}{2}\right)} \quad \text{[Eq. 1]}$$

where

h_c = required depth of cover above crown of bore
Δh_{cl} = allowable settlement at centerline of pipe
d_b = diameter of bore
d_p = exterior diameter of pipe
ϕ = friction angle of soil.

The relationship is based on the assumption that the volume of surface settlement is equal to the volume of the overbreak. The required depth of cover is directly proportional to the volume of overbreak and inversely proportional to the soil friction angle.

Monitoring

One of the most significant aspects of the DWA (2008) German Standard DWA-A 125E is the requirement for automated electronic logging of various parameters during trenchless construction, including the thrust force. Continuous logging is required in case of open shields and unstable working face. The trend toward increased use of automated logging in the industry is also evident in other equipment-intensive construction activities, such as ground improvement.

In general, transportation agencies do not specify acceptable limits for heave and settlement. A typical trenchless specification states that surface heave or settlement above the installation is not permitted. NCDOT (2012) guidelines call for ceasing all trenchless operations when the measured settlement exceeds 0.25 in. Caltrans (2010) specifies a threshold "action level" and "maximum allowed" values, as shown in Table 16.

Washington Suburban Sanitary Commission (WSSC) (2011) specifications require that surface settlement markers be located according to a grid, spaced 10 ft by 10 ft and extending as shown on construction drawings but not less than 20 ft on either side of the tunnel centerline. The same type of settlement monitoring is specified by Dulles Rail Consultants (2012).

The New Hampshire DOT (2010) requires that three lines of settlement monitoring points be constructed parallel to the centerline of the pipe, with the lines located along the pipe centerline and 15 ft on either side of the centerline. The settlement monitoring points must be established at maximum 12-ft intervals along each line and must consist of painted points on pavement and 1-ft-deep concrete monuments in unpaved areas. The contractor must monitor the settlement points on a daily basis or as directed.

NCDOT (2012) specifications call for measuring road settlement at 10-ft intervals along the centerline and at 10 ft on each side of the pipeline. A licensed land surveyor is required to monitor these points daily until the construction is complete.

MassDOT (1996) specifies survey points along the centerline of the casing, with a minimum of one point at the median, one point at the centerline of each travel lane, and one point at the top of each embankment slope. If at any time distress or settlement occurs at the paved surface, MassDOT will require testing to verify the integrity of the road subbase, subgrade, and underlying soils. The contractor is required to survey all points prior to initiating any construction to establish baseline records. Subsequent surveying is required to take place at the completion of each day, whether or not work progressed at the site that day.

Table 16. Settlements Allowed by California Department of Transportation

Settlement Monitoring Points	Action Level	Maximum Allowed
Surface	0.25 in	0.5 in
Surface–traffic lane	--------	0.25 in
Subsurface	1.5 in	2.5 in

Source: California Department of Transportation (2010).

Dulles Rail Consultants (2012) specified the following monitoring requirements:

- A pre-construction survey of all structures and utilities shall be conducted within a radius of five times the depth of trenchless crossing.
- Install shallow surface settlement indicators (#8 rebar extending at least 2 ft below the bottom of paving) at 20 ft intervals along the centerline of each crossing, at locations coinciding with the grid of surface settlement markers. Do not install indicators at locations that fall in non-paved areas.
- Prior to the start of construction, all monitoring points shall be surveyed a minimum of three times to establish baseline readings. Surveying shall be performed daily or every 50 ft of casing advancement. In addition, if settlement exceeds Limit Level 2, all monitoring points within 20 ft of the heading shall be surveyed hourly.

It is important to recognize that voids created at some depth may result in surface settlement after a substantial period of time following construction depending on the overlying soil type and pavement thickness. MassDOT (2013) contract provisions hold the contractor liable for pavement distress within 50 ft of the pipe centerline for a period of two winter/spring cycles after the completion of the project. The influence area boundary is increased 2 ft for every 1-ft depth over 20 ft, where depth is measured from the highest pavement surface to the casing invert.

A simple subsurface monitoring point consists of a length of steel rebar installed inside a cased borehole extending to some specified height above the pipe. In addition, inclinometers and multiple-point borehole extensometers can be used for subsurface displacement monitoring applications. It appears that ground-based digital photogrammetry measurements can provide a high precision of surface elevation monitoring (Lueke and Ariaratnam, 2010). LiDAR instruments and total station surveys can also be used for surface displacement monitoring. Baseline surveys should be conducted before any construction begins.

In addition to visual inspection the European Standard EN 12889 (European Committee for Standardization, 2000) specifies procedures for testing gravity pipelines for leaks using air or water methods. INDOT (2012) specifications require that when the installation is 4 in or larger and the casing is used as the carrier pipe, a video inspection shall be performed using a high-resolution color video camera and recording equipment.

Geotechnical Investigation

Prior to initiating trenchless work, contractors should investigate the following: work area requirements, existing grade/elevation data, a catalog of surface features, a map of boring and test pit locations, a catalog of waterways and wetlands, a record of all subsurface utilities, and an examination of all adjacent structures within 50 ft of the proposed trenchless excavation (Suleiman et al., 2010). Special care should be taken to establish the proposed horizontal and vertical alignments so that adequate investigation can be planned in the vicinity (Richardson et al., 2003). Test borings are the most common method for performing geotechnical investigations but other methods might be appropriate, including ground penetrating radar (for gravels and sands), acoustic sonar, test pits, and geophysical methods (Najafi, 2005). Geophysical techniques include ground penetrating radar surveys, the site uniformity borehole seismic method, and seismic tomography, which can be used in addition to drilling boreholes in order to identify possible obstructions (Klein, 2001). Regardless of the method selected, the subsurface investigation should determine the following information: nature of soil and its stratification, depth to and nature of bedrock, nature of existing fill material and any obstructions encountered, and groundwater levels. At least two exploratory borings should be drilled for short crossings, and borings should be located every 150 to 200 ft along the proposed alignments for projects greater than 1,000 ft in length (Essex, 1992).

The ASCE (2001) construction guidelines recommend that exploratory borings be drilled at all pit locations and at a spacing no greater than 300 ft along microtunneling alignments. Boreholes should extend to approximately 10 ft or two pipe diameters below the proposed pipe invert. If soft compressible soils are present at this depth, some boreholes should extend into firm ground. Continuous sampling from one diameter above the pipe to one diameter below the pipe is recommended. Groundwater levels should be determined. Some of the soil and rock properties that should be identified include the following:

- grain size distribution
- unit weight
- density/consistency (typically SPT N value)
- moisture content
- plasticity index
- core recovery
- rock type, quality, hardness, unconfined compressive strength.

In addition to geotechnical exploration, areas of known or suspected contamination should be delineated and characterized. Mixed-face (soil/rock) conditions should be identified and avoided if possible in microtunneling. Some of the critical conditions that impact HDD and microtunneling performance include size and strength of cobbles and boulders, tree roots, fill debris and metal obstructions, shallow cover, mixed-face conditions (when a bore path moves along the interface between different soil formations), and changed-face conditions (when a bore path moves from one soil formation to another) (Mathy et al., 2008). Subsurface obstructions can present a significant challenge to all trenchless methods. Although locating potential obstructions may be theoretically possible using various approaches, it is often not feasible within the project constraints.

MassDOT (1996) recommends at least two exploratory borings (one at each of the proposed pit locations) for an undivided highway. The borings must penetrate to a depth at least 5 ft below the bottom elevation of the proposed pits. For a divided highway, additional boring is required at the center of the median strip.

Caltrans (2008) specifications require that a geotechnical investigation and soil analysis be carried out by a licensed geotechnical engineer or engineering geologist.

The Pipe Jacking Association (2013) advises that "under no circumstances should boreholes be sunk on the line of the tunnel. Boreholes should be sunk adjacent to shaft locations.

All boreholes should be properly backfilled and sealed. Improperly sealed boreholes drilled along the tunnel centerline can result in a frac-out during HDD construction, possibly resulting in pavement distress."

Costs

Typically, there is little relationship between the unit cost and the depth of installation. The use of trenchless technologies allows for installation of utilities in most ground conditions, often where open cut methods are not practical. Work performed under high fills is frequently more economical when using trenchless technology. Frequently, cost is not the primary factor and other considerations, such as safety, inconvenience to the motoring public, and environmental impacts, govern the choice of construction method (ODOT, 2005).

A study based on 174 trenchless projects was carried out by the National Research Council in Canada (Zhao and Rajani, 2002). The cost analysis of several trenchless methods indicated that on the average, the most expensive method is microtunneling at approximately $74 diameter inches per linear foot, followed by pipe jacking at approximately $33 diameter inches per linear foot. Horizontal drilling is one of the most economical methods. Typically, the cost of horizontal drilling is approximately 75% of the cost of the open cut excavation. In contrast, the cost of microtunneling is relatively high because of extensive support equipment required to carry out the work and the need for a skilled operator.

CONCLUSIONS

- *Trenchless technologies have been widely adopted, but design guidelines and construction specifications vary significantly.*

- *Obstructions (artificial and natural) pose a significant risk for all types of trenchless technologies, but particularly for microtunneling.*

- *In general, the risk of using HDD increases with pipe diameter. The opposite is typically the case for microtunneling. The breakpoint occurs at a pipe diameter of approximately 30 in.*

- *Accurate characterization of subsurface conditions is critical to the selection of the most appropriate trenchless technology for a specific project. It is difficult to predict representative subsurface conditions for a roadway crossing based on a limited number of test borings performed perpendicular to the direction of installation. Other factors, such as available space for launching and receiving pits, costs, schedule, traffic delays, and existing utilities, should also be considered.*

- *Unguided trenchless methods are suitable only for short drives (on the order of 50 ft or less). Steerable methods, such as HDD and microtunneling, are more applicable for longer drives and where alignment accuracy is more critical.*

- *Monitoring of trenchless construction is generally limited to observations of installation procedures and survey monitoring of the surface, particularly the roadway surface. Some geophysical techniques, such as ground penetrating radar, have been used successfully for monitoring of shallow installations.*

- *A high level of expertise is required for operators of trenchless equipment, particularly for microtunneling.*

RECOMMENDATIONS

1. *VDOT's Materials Division, Location and Design Division, and Construction Division should jointly develop and approve the criteria for selection of trenchless technologies, as well as guidance on risk, cost, space requirements, minimum cover, schedule, and limitations on use.*

2. *VDOT's Materials Division, Location and Design Division, and Construction Division should collaborate to develop a standard checklist for uniform review of contractors' trenchless project submittals for all work conducted within the VDOT right of way.*

3. *VDOT's Construction Division should retain the existing practice regarding prequalification of trenchless excavation contractors. Prospective contractors should provide proof of relevant competency and qualifications.*

4. *VDOT's Materials Division should revise Chapter 3 of the Manual of Instructions to include guidelines for geotechnical investigations for trenchless projects that may include the following minimum requirements:*

    - *SPT borings located at jacking and receiving pits*

    - *SPT borings at a maximum spacing of 100 ft along trenchless alignments*

    - *horizontal offset of SPT borings from design alignment at HDD crossings*

    - *SPT boring depth at least two pipe diameters or 10 ft below the invert elevation*

    - *continuous SPT split spoon soil sampling between 1 diameter above to 1 diameter below the pipe*

    - *laboratory classification tests on representative soil samples*

    - *rock type, rock quality designation (RQD), and percentage recovery on representative rock samples*

    - *groundwater elevation measurements upon completion and at 24 hours following the completion of SPT borings.*

5. *VDOT's Construction Division should consider a policy of not allowing any trenchless construction methods that rely on soil displacement, including pipe ramming.*

6. *VDOT's Construction Division should consider developing a Special Provision for Implementation of Trenchless Technologies to incorporate the items listed in the Appendix.*

BENEFITS AND IMPLEMENTION

This study was intended to improve the state of the practice for implementation of trenchless technologies on VDOT construction projects. The recommendations, based on practices adopted by other transportation agencies, are intended to minimize the number and severity of construction problems encountered when trenchless technologies are used. This will minimize the related schedule delays and cost impacts on active construction projects. The recommendations provided in this report will be implemented through guidelines in the VDOT Materials Division *Manual of Instructions* and issuance of revised statewide specifications. The State Materials Engineer, in coordination with VDOT's Location and Design Division and Construction Division, will facilitate the implementation efforts, which are anticipated to take effect by January 1, 2016.

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APPENDIX

RECOMMENDED CHANGES TO SPECIAL PROVISIONS FOR TRENCHLESS TECHNOLOGIES

- VDOT Special Provisions for Trenchless Technologies should require that the minimum depth of cover be at least 5 feet or 3 times the outer pipe diameter, whichever is greater, for trenchless utilities installations larger than 8-inch nominal diameter. For installations of 8-inch diameter and less, the minimum depth of cover should be 36 inches, in accordance with the VDOT *Land Use Permit Guidance Manual,* Section 24VAC30-151-340 and Section 24VAC30-151-360.

- VDOT Special Provisions for Trenchless Technologies should require that all trenchless design details and calculations, including the description of the proposed monitoring program, be prepared and sealed by a licensed professional engineer registered in the Commonwealth of Virginia with a minimum of 5 years of experience in substructure design.

- VDOT Special Provisions for Trenchless Technologies should require that the contractor submit a detailed ground surface monitoring plan and an emergency action plan for addressing potentially excessive surface deformations resulting from trenchless construction. A description should be provided of how potential ground movements will be monitored and what contingency plans will be implemented.

- VDOT Special Provisions for Trenchless Technologies should limit the allowable overbreak/overcut in trenchless construction to 0.5 inch maximum.

- VDOT Special Provisions for Trenchless Technologies should require that at least 20 feet of full diameter auger be provided at the leading end of the jack and bore casing. Subsequent auger size may be reduced, but the auger diameter at any point should not be less than 75 percent of the full auger diameter. The auger should not be allowed to rotate with no casing advancement.

- VDOT Special Provisions for Trenchless Technologies should require that the groundwater level be maintained at a minimum of 1 foot below the casing invert elevation and a minimum of 2 feet below the pit bottom elevation at all times during jack and bore construction.

- VDOT Special Provisions for Trenchless Technologies should require surface elevation monitoring for all trenchless projects constructed within the VDOT right of way. At a minimum, monitoring points should be established along the centerline of the pipe alignment, at a parallel distance of twice the height of cover from the centerline (both sides), at a parallel distance of 25 feet from the centerline, at the shoulder/mainline joints for each direction of travel, and in the median. Additional points should be located in the center of the roadway for roadways equal to or greater than 48 feet in width. Three stable baseline readings should be established prior to starting construction, with readings conducted daily or every 50 feet of casing advancement during active tunneling and every month for 3 months after completion of the crossing. Monitoring frequency should be increased if deformation limits are exceeded. All elevation readings should be performed by, or under the direction of, a licensed land surveyor.

- VDOT Special Provisions for Trenchless Technologies should require post-installation contact grouting for all trenchless installations of 42 inches in diameter and larger unless the contractor can provide satisfactory evidence that no voids are present.

- VDOT Special Provisions for Trenchless Technologies should require the contractor to submit as-built plans within 30 days of project completion. As-built plans should include details of the installed conduit, temporary works, permanent structures, backfill, post-construction structures and elevation survey, construction photographs, descriptions of any problems encountered, and corrective procedures.