Trenchless Excavation Construction Methods: Classification and Evaluation

By the Committee on Construction Equipment and Techniques

Abstract: Traditionally, trenchless excavation construction (TEC) methods have been considered only in congested and critical conditions as an alternative to open cutting. As more utilities are placed underground, the demand for these methods has increased. It is common practice in Japan and in European countries to specify the installation of the complete system by TEC methods. This is a growing trend in the United States. For the project to be designed and constructed with minimal delays and disputes, it is important that the major project decision makers (i.e., owner, regulatory-agency representative, architect/engineer, and contractor) be familiar with the available TEC methods and the basic principles of operation. The purpose of this paper is to present a classification system and a comparative analysis on the specific methods.

Introduction

Trenchless excavation construction (TEC) methods include all methods of installing utility systems below grade without direct installation into an open-cut trench. These methods are differentiated from the large-diameter tunnels by several factors, such as purpose or use, diameter of excavation, type of contract, project duration, and design data.

Because of the rapid development of new methods and significant innovations in traditional methods, considerable confusion exists in the industry regarding a classification system and the principles and practices associated with these methods. The purpose of this paper is to present a classification system and a summary of the basic characteristics associated with specific methods.

Classification System

Fig. 1 illustrates a classification system for TEC methods. This system segments the industry into three major categories: (1) Horizontal earth boring (HEB); (2) pipe jacking (PJ); and (3) utility tunneling (UT).

Horizontal earth boring (HEB) includes methods in which the bore-hole excavation is accomplished by mechanical means without workers inside the bore hole. Both PJ and UT techniques require workers inside the bore hole during the excavation and casing installation process. However, PJ is differentiated from UT by the support structure. PJ methods employ prefabricated pipe sections. New pipe sections are installed in the pit when the jacks are in a retracted position so the complete string of pipe can be jacked forward. UT techniques may use the same excavation equipment, but the support structure is constructed at the face end. Normally, this will be accomplished in the tail end of a tunneling shield. This support structure typically consists of traditional tunnel liner plates or steel ribs with wooden lagging.

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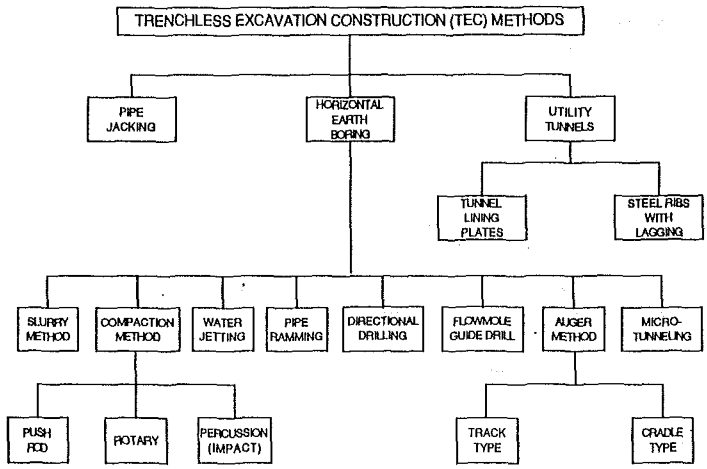

FIG. 1. TEC Classification System

TEC methods traditionally have been associated with alternatives to open cutting for roadways, railroads, and other sensitive areas that cannot tolerate the disruption and destruction that results from open-cutting technique. As surface areas become more congested, TEC methods are being specified for the installation of complete systems. Thus, the smaller diameter sizes, diameters less than 1,050 mm (42 in.), have received a disproportionate amount of research and development. This size range includes the majority of piping networks used for utility systems (i.e., gas, electric, water, petroleum products, sanitary and storm sewers), and the larger sizes are necessary for sanitary sewer and storm-water outfall systems.

No one TEC method is best suited for all conditions. It is important that the installer, designer, and regulatory agencies involved with TEC methods be familiar with the capabilities of the available methods, since some methods provide more flexibility than others. Because of the increasingly critical nature of installations of utility systems in congested areas, the need for monitoring and control systems has increased. In many situations it has become necessary that systems be installed with a high degree of precision. However, conditions vary from project to project, therefore the methods permitted should be based on an evaluation of the specific project. Methods considered acceptable in stable clay might not be suitable in wet sand, and the required precision for a sanitary gravity sewer line is not necessary, in most cases, for pressure systems or cables.

At critical locations involving public health and safety, it becomes the responsibility of the designer and the regulatory agency to limit proposed methods to only those compatible with the conditions. This should be accomplished with adequate, complete specifications prepared with an understanding of the operating principles of available methods.

To assist in the development of an understanding of the various methods outlined in Fig. 1, each is defined and described.

Auger Horizontal Earth Boring (HEB)

The auger horizontal earth boring (HEB) method uses the process of si-

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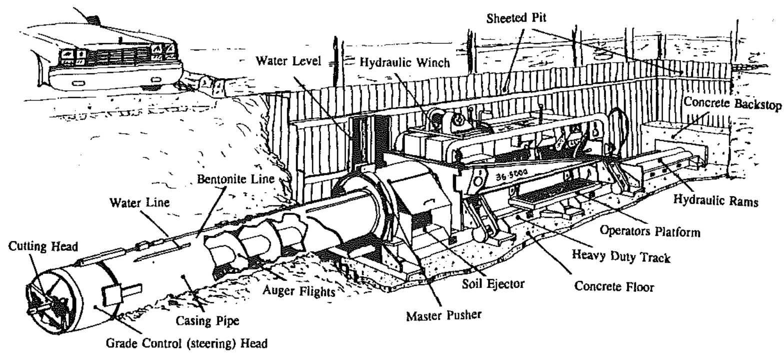

FIG. 2. Track-Type Horizontal Earth Boring

multaneously jacking the casing through the earth while removing the spoil inside the encasement by means of a continuously rotating flight auger (*Horizontal Earth Boring* 1981, 1986). The auger is a flighted drive tube with couplings at each end. The auger transmits torque to the cutting head from the power source in the bore pit and transfers spoil back to the machine.

The auger HEB method is traditionally classified as: (1) Track-type or; (2) cradle-type.

Major components of the track-type methods include the track system, machine, casing pipe, cutting head, and augers. In addition to these major components, many optional components are available, including a bentonite lubrication system, a steering head, a casing leading-edge band, and a dutch water-level indicator. Fig. 2 illustrates typical track-type auger horizontal earth-boring equipment.

Two factors that affect auger boring are attempts to minimize torque and thrust. The torque is created by the power source, which can be pneumatic, hydraulic, or an internal combustion engine through a mechanical gearbox (Winney 1988). The torque rotates the auger and cutting head. The casing remains stationary by being temporarily attached to the boring machine. The thrust is created by one or more hydraulic thrust rams at the rear of the machine. One end of each ram is attached to the machine, the other end to lugs that lock into the track system. When torque or thrust increases or decreases significantly, it is an indication of developing problems.

Soil-test borings, soil classification, and ground-water–level determination should be provided for all significant projects. The contractor should excavate test pits prior to bidding; however, this does not preclude the possibility of changed conditions or obstacles during execution of the boring operation. All reasonable efforts should be made to ensure that conditions can be handled safely.

Enough room must be provided for safe loading and unloading of equipment and materials, as well as for removing spoil. Accidents are less likely to occur on sites that are kept open and clear of debris (*Technical Manual* 1987). Job-site drainage and bore-pit dewatering must be taken into consideration. Since the major boring equipment will be in the pit during the boring operation, water entering the pit should be routed to a sump for expulsion by an adequate pumping system. Since the pit will remain open for an extended period of time to house men and equipment, it is important that it be protected and safe during the operation.

The probability of success depends, to a great extent, on the quality of the original setup. The vertical direction of the cutting head can be steered to some degree by the installation of a grade control head. Horizontal alignment can be corrected to a small degree on larger casing by pulling the augers and having a man crawl through the casing to the leading edge to manually excavate on the appropriate side and use wedges.

It is important to ensure that the pit foundation is secure. For unstable conditions, a concrete slab may be necessary. However, the most common foundation construction is of crushed stone. An adequately designed and constructed track-system foundation and thrust-reaction structure are essential for all auger bores.

Once the pit has been prepared, the track system is positioned. Alignment and grade must be carefully monitored during the installation process. The boring machine is then placed on the track system.

Prior to casing and auger installation, much consideration must be given to measures to be taken to minimize torque and thrust; and to ensure specified line and grade tolerances. Proper casing preparation eliminates blind risk. Use of optional components must be determined before the casing is placed in the bore pit.

In stable conditions, it is standard practice to operate with the cutting head leading the casing by several inches and using cutting head wing cutters to overexcavate approximately 1 to 2 in. to minimize casing skin friction, thus minimizing jacking thrust. If the cutting head is not advanced far enough, the wing cutters could contact the casing, creating a bind. If the cutting head is leading the casing too far, a void is created before the casing is jacked into position. If the stand-up time is less than the time the void is left exposed, then the bore-hole crown will be lost.

The only way to maintain a specified clearance between the rear of the cutting head and the leading edge of the casing is to ensure that the length of the casing is the same as the length of the auger being used. Major problems and failures have developed because the contractor didn't know the cutting-head location.

Bentonite applied near the leading edge of the casing has been proven to effectively reduce skin friction and aid in restricting sloughing and caving.

Fig. 3 illustrates a banded casing. The use of the partial band at the leading end of the casing has proven to be effective for compacting the soil and decreasing the skin friction. The banding process is most effective in unstable soil conditions, where wing cutters are not used.

When the lead casing section has been properly prepared, it is then placed in the bore pit, with the auger securely placed inside. The leading end of the casing is placed in a cradle. After necessary fabrication and hookups have been made, the boring operation can begin.

Collaring is the first operation of the bore. The objective of collaring is to start the cutting head into the embankment without allowing the casing to be lifted out of the temporary casing-support saddle. Collaring is accomplished by rotating the cutting head at low RPM and using a slow thrust advance. To a large extent, the success of the bore depends upon the line and grade established on the first section of the casing (*Technical Manual* 1987).

The casing is installed by a sequence of cyclic operations. As the cutting

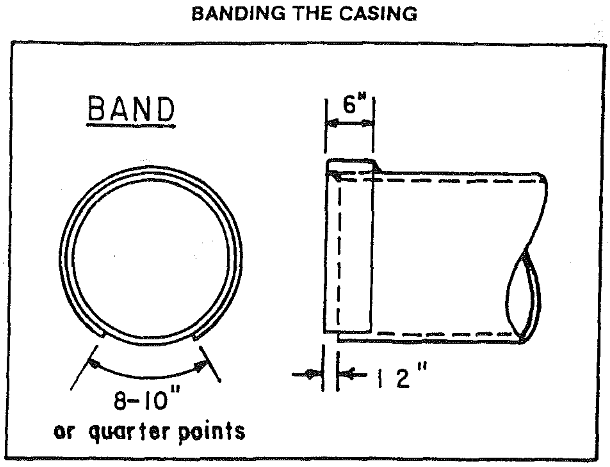

FIG. 3. Casing Leading-Edge Band Detail for Auger HEB

head and auger are rotated, forward advancement is achieved by extending the hydraulic cylinders, thrust rams, against thrust blocks in the bore pit to the limit of their stroke. The lugs that fit into prefabricated slots in the track system are then retracted and the hydraulic rams are retracted until the lugs lock into slots nearest the machine. The operation is repeated until the entire casing has been installed.

In stable ground conditions, the augers are rotated several revolutions to clean the spoil out of the casing. The auger is then disconnected at the machine. The machine is then moved to the rear of the track and another casing-auger unit is placed into position. The new unit is aligned and the two casings are welded together, the auger-to-machine connection is made, the casing-to-machine connection is made, and the auger rotation is begun along with the jacking operation.

This process is repeated until the entire length of casing has been placed. Then the augers are removed from the casing and the casing is cleaned.

Cradle-type auger horizontal earth boring is suitable for projects that have adequate room. The bore-pit size is a function of the bore diameter and the desired length of the bore. This method is commonly used on petroleum products pipeline projects where large rights-of-way are essential. The bore-pit design and construction are not as critical in the cradle-type boring operation as in the track-type method, because the boring machine and the complete casing-auger system is held in suspension by construction equipment as the boring process is executed. Thus, the cradle-type method is often referred to as a side boom or swinging method.

The advantage of this method is that all preparatory work can be performed at ground level rather than in the bore pit. No foundation or thrust-reaction structures are needed; however, a jacking lug (dead man) must be securely installed at the bore entrance embankment. Another advantage is that workers are not required to go in the pit.

Figs. 4 and 5 illustrate typical cradle-type auger-bore equipment, setup, and procedures. After all casing for the entire bore is welded together, the

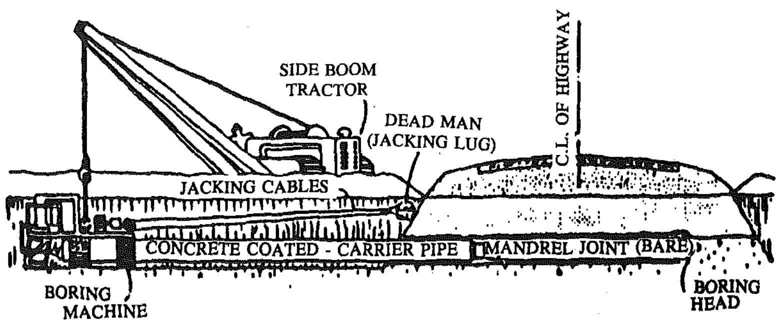

FIG. 4. Direct Installation of Carrier Pipe with Cradle-Type Auger HEB

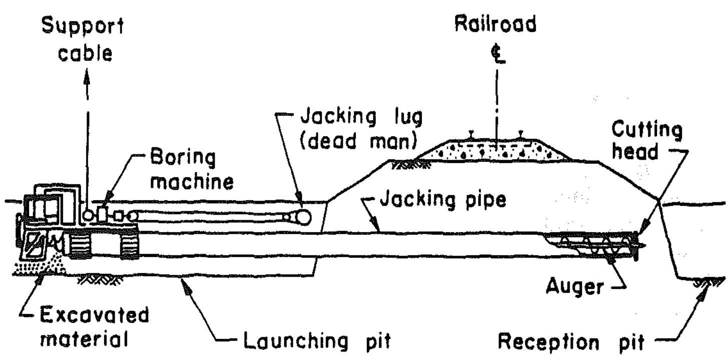

FIG. 5. Direct Installation of Casing Pipe with Cradle-Type Auger HEB

auger-cutting head unit is placed in the casing. The cradle-boring machine is attached to the trailing end of the casing, and the auger-to-machine connection is made. The total system is then suspended and moved into position in the bore pit. The operator's station is on the machine, secured to the end of the casing. The winch cable is attached to the deadman, and the cutting head properly positioned at the initial point of entry for the bore.

When the desired line and grade of the casing have been established, the boring process is initiated and is a continuous operation until completed.

A grade control head and the water-level sensing device, as used with the track-type auger-bore method, are not appropriate for this method. This method is suitable for pressure systems.

Compaction Method

The compaction method forms the bore hole by compressing the earth that immediately surrounds the compacting device. Therefore, spoil is displaced rather than removed. This method is restricted to relatively small diameter lines (i.e., 2–6 in.) in compressible soil conditions. The compaction method is divided into three subclassifications: the push-rod method, the rotary method, or the percussion (impact) method. These methods are commonly referred to as expansive installation techniques, because the earth surrounding the bore hole is displaced by the expanding effect (O'Rourke 1985).

A rod pusher is a machine that will push or pull a solid rod or pipe through the earth to produce a hole by means of compaction (soil displacement) without rotation or impact. A compaction bit is literally pushed through the earth by mechanical force transmitted through rods. If the hole must be larger than the compaction bit, a reamer is pulled back through the hole by the rods.

There are several manufacturers of commercial rod-pushing machines. The most popular principle of operation consists of a large hydraulic cylinder, a reaction plate, and a rod-gripping device. If the operation requires reaming, then the reaction plate must resist forces in both directions. The hydraulic cylinder can be powered by the hydraulic manifold system of a backhoe, trencher, etc., or by a separate hydraulic power unit. The rods are usually 1.2 m (4 ft) in length and 35 mm (1.37 in.) to 45 mm (1.75 in.) in diameter. These solid rods are thrust through the ground without rotation.

The procedures consist of excavating an appropriate bore and receiving pit, placing the machine in the bore pit and connecting a power source, placing the compaction bit on the push rod, attaching the rod to the machine, making final line and grade adjustments, and executing push cycles. Each push cycle consists of several independent pushes per rod length depending on the cylinder stroke length. Accuracy is a function of the initial setup and soil conditions.

The rotary method combines the advantages of a rotating drill rod and the compaction effect developed from using a compaction bit. Power can be obtained via an attachment to a backhoe, trencher, etc., above ground, or with standard horizontal earth-boring units similar to those described for the auger-bore operation. This method is limited to small bores [i.e., less than 150 mm (6-in.)].

The percussion method uses an underground piercing tool that is self-propelled, powered by a pneumatic or hydraulic power source. The diameter and length of tools vary, but all are streamlined into bullet or missile shapes. Compressed air or hydraulic fluid is transmitted to the tool through flexible hoses, and imparts energy at a blow frequency of 400–600 strokes per minute to a reciprocating piston inside the nose of the tool. These tools are effective in most ground conditions, from loose sand to firm clay (Milliken 1987).

Percussion tools vary in outer diameter from 45 mm (1.75 in.) to 175 mm (7 in.). Percussion tools typically advance at rates of 75 mm (3 in.) per min to approximately 1.2 m (4 ft) per min with speed being a function of soil conditions, not tool size (Milliken 1987).

The boring-pit size, for the percussion operation, is a function of bore depth and size of tool selected. A sighting device is normally used to ensure satisfactory alignment. After proper alignment is obtained, the tool is collared into the embankment, power is applied, and the operation is monitored until the tool exits in the receiving pit. The tool is then removed, and the desired utility can be attached to the end of the air hose to be inserted directly into the bore hole. When rigid pipe is installed, the tool and the air hose is removed and the pipe is often pushed through the open bore hole.

When no sensing or guiding system is being used with the compaction method, the span length is usually limited to 18 m (60 ft) with 12 m (40 ft) being optimum. However, 60-m (200-ft) bores have been made successfully.

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Recently, guiding systems have been developed for the push-rod and percussion-tool method, which allows the operator to know, at all times, the alignment and depth of the device and permit adjustments to be made while advancing the device.

Slurry Horizontal Rotary Drilling Method (SRD)

This process is distinguished from horizontal auger boring in that it uses drill bits and drill tubing in lieu of augers and cutting heads. A drilling fluid, such as a bentonite slurry, water, or air, is used to facilitate the drilling process by keeping the bit clean and aiding in spoil removal. Because of this latter characteristic, it is often confused with the water-jetting method; however, unlike the water-jetting method, the SRD method does not use the drill fluid to cut the face or wash out a hole. The face is cut mechanically by the bit. Washouts are prevented by controlling the drill-fluid rate of flow and pressure.

The process can be executed from above ground or from a pit. The power unit can be hydraulic, gas, air, or diesel-driven, mounted on tracks, rubber tires, or hand-held. The fluid is introduced into the tubing through a water swivel tee, which allows the drill tubing to rotate. The fluid is then transferred to the cutting bit through the drill tubing. Drill bits that are compatible with the soil conditions are used to mechanically cut the bore-hole face.

A bentonite slurry drill fluid is used in unconsolidated, noncohesive soils. Bentonite consistency will vary with the soil type that is encountered. This slurry is then mixed with the bore-hole cuttings by the drill bit. While some cuttings are removed from the bore hole during the bore operation, the majority remain. This mixture of bentonite slurry and bore-hole cuttings aids in preventing bore-hole collapse by exerting a counterbalance earth pressure on bore-hole walls. The colloidal characteristic of the bentonite develops an impermeable seal on the bore-hole walls, reducing water infiltration as it facilitates spoil removal.

Since the casing or carrier-pipe installation procedures are independent of the boring operation, any currently available pipe material or cable may be installed. Types of pipes commonly installed include steel, concrete, fiberglass, plastic, corrugated metal, and ductile iron.

The SRD method is most effective for smaller-diameter bore holes, ranging from 50 mm to 300 mm (2 to 12 in.); however, in stable soil conditions, 1,200-mm (48-in.) bores have been completed successfully. SRD methods have the distinct advantage of being quick and easy to set up.

Water-Jetting Method

This method uses the principle of soil liquefaction to create the bore hole. Water pressure and flow rate create a jetting action, which places the soil in a quick condition for the purpose of eroding the bore hole.

The necessary equipment include a source of pressurized water, a flexible hose to transmit water from the source to the probe, a probe—normally a rigid, small-diameter pipe that is used to direct the water as it cuts or washes out a bore hole—and a nozzle to increase the water velocity, which aids in the jetting process. The length of the bore is controlled by adding extensions to the probe rod.

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The water-jetting process is simple, requiring no special operator skill, and the capital expenditure for equipment is minimum. There is no way to control the amount of overcut. The process results in large quantities of water and muck that must be disposed off. Ground settlement is highly probable as a result of overexcavation that occurs in creating a usable bore hole.

Pipe-Ramming Method

Pipe ramming is an innovative use of the percussion tool as a pipe-driving hammer. Holes of as much as 200 mm (8 in.) in diameter, depending on soil conditions, are obtainable with the leading end of the steel pipe closed in a wedge or missile shape. However, in most cases, if the line is larger than 150 mm (6 in.) in diameter, it is driven with the face open.

A band is installed around the leading edge of the pipe for reinforcement and to decrease the amount of friction on the following pipe sections.

The closed face uses the soil displacement principle. Therefore the pipe volume exceeds the volume of soil displaced. The open-face technique uses the same equipment and methods, but the soil is removed from within the pipe.

If room is available, the bore pit is constructed so the pipe can be driven in one piece. The percussion tool is mated to the pipe by using special adapters for each size of pipe. The tool is rigidly connected to the pipe being driven by lugs welded onto the casing, and a pushing plate is fitted to the rear of the plate.

The power source can be normally compressed air supplied from a portable compressor or hydraulic. After the alignment and grade check, the pipe is collared into the embankment and the ramming operation is begun. The leading edge of the open-face pipe cuts a bore hole the size of the pipe outer diameter. The spoil enters the pipe and is compacted as it is forced to the rear of the pipe.

Water or bentonite slurry can be applied to the outside of the casing pipe to provide lubrication. After the pipe has been rammed in place, the tool is removed and the pipe is cleaned out.

Because of the cyclic impact associated with the pipe-ramming method, the method is limited to steel pipe. It is an economic method for installing medium size casings and allows many options, but there is limited alignment control.

Directional Drilling Method

The directionally controlled horizontal drilling process, used as a horizontal boring technique for crossing under natural or manmade obstacles, is an outgrowth of the technology and methods developed for the directional drilling of oil wells. The directional drilling method was developed in the United States, and has revolutionized complicated pipeline river crossings. It also has been used to install numerous roadway-railway crossings.

The horizontal directional drilling method is a two-stage process. The first stage consists of drilling a small-diameter pilot hole along the desired centerline of the proposed pipeline. The second stage involves enlarging the pilot hole to the desired diameter in order to accommodate the pipeline. The pilot hole is drilled with a specially built drill rig that allows the drill string

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to enter the ground at an angle of entry that can vary from 5 to 30°, with an optimum entry angle of 12°. This drill rig pushes the drill string into the ground while a bentonite drilling mud is pumped through the drill stem to a down-hole drill motor just behind the bit (Hair and Hair 1988).

The drill mud operates the down-hole motor, functions as a coolant, and facilitates spoil removal by washing the cuttings to the surface, where they settle out in a reception pit. The drill stem is approximately 75 mm (3 in.) in diameter, nonrotating, and contains a slightly bent section, called a bent housing. The bent housing (typically from 0.5–1.5°) is used to create a steering bias. A curved or straight profile is achieved by steering the drill rod as it is being pushed into the ground. The steering is controlled by the positioning of the bent housing (Hair and Shiers 1985).

The pilot-hole path is monitored by a down-hole survey system behind the bent housing. It provides data on the inclination, orientation, and azimuth of the leading end. These data are transmitted to the surface, where they are then interpreted and plotted. Normally, position readings are taken on every pipe segment, which is about every 9 m (30 ft). Should the pilot hole get off alignment, then the drill stem is pulled back and a new course is cut (Hair and Hair 1988).

During the drilling operation, a 125-mm- (5-inch-) diameter steel wash-over pipe is rotated over the pilot drill stem. The wash-over pipe relieves the friction and resisting pressure caused by the cuttings mixed with the drill mud. In addition, the wash-over pipe provides rigidity to the pilot drill stem. Bentonite slurry is pumped between the wash-over pipe and the pilot drill stem. The rotation of the wash-over pipe allows the diameter of the bore hole to be increased to approximately 275 mm (11 in.).

After the pilot hole has been constructed, the pilot drill stem is withdrawn through the wash-over pipe. Reaming devices are then attached to the wash-over pipe and pulled back through the pilot hole, enlarging it to the desired diameter. The pipe installed must be of a type that can resist the axial tensile force that develops as it is pulled through the bore hole. Steel pipe is the most common pipe used at the present time, however, high-density polyethylene pipe could be used. The flows and pressures must be monitored to prevent mud-migration problems. The rig working area should be reasonably level, firm, and suitable for the movement of rubber-tired vehicles.

Directional drilling can be accomplished for long, complicated crossings quickly and economically with minimum environmental impact. This process does not require bore or receiving pits.

FlowMole Guidedril Method

The FlowMole Guidedril Method is a proprietary system researched, designed, developed, and operated by the FlowMole Corporation, Kent, Washington. The method involves a unique steerable tunneling system, specifically designed for small-diameter lines installed at any reasonable depth and up to 120 m (400 ft) in length. A low-flow, high-pressure bentonite slurry cutting fluid is used to bore stable, long-distance, small-diameter bore holes. This process is referred to as the SoftBor process. The soil is actually cut by the small-diameter, high-pressure jets of liquefied clay (bentonite slurry) just ahead of the boring tool. The bentonite slurry mud impregnates the soil immediately around the tool, which lines the bore-hole wall, stabilizing in-

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herently unstable soils such as fine sand. The lubricating characteristics of the bentonite slurry greatly reduce the frictional drag when utility lines are being inserted in the bore hole.

The patented SoftBor process is characterized by a low-flow (1-to-2 gpm), high-pressure (1,000–4,000 psi) soil-cutting system. While the water performs the cutting action, it is differentiated from the water-jetting and the slurry-bore methods because of the pressures and the flow rates that create the cutting. Soil erosion and overcutting do not occur with the FlowMole system because the small-diameter jets that produce the required flow are designed so the cutting fluid energy dissipates rapidly. This also prevents the cutting fluid from damaging existing utility lines (*An Alternative* 1986).

The most significant feature of the SoftBor process is its remote-steering capability. The remote steering is accomplished through directing the cutting at the nose of the bore tool. A computerized electronic control system provides steering commands. This system maintains the tool on course and provides detailed data on the exact position of the tunnel so that bores can be made on a controlled path. The position of the tool can be determined within 50 mm (2 in.) both laterally and vertically (*An Alternative* 1986).

Pipe sizes compatible with this process range from 50 mm (2 in.) to approximately 350 mm (14 in.), and successful bore lengths of as much as 180 m (600 ft) have been made within specified tolerance.

Microtunneling Method

The term microtunneling is used to describe methods of horizontal earth boring, which are highly sophisticated, laser-guided, and remote-controlled. These methods permit accurate monitoring and adjusting of the alignment and grade as the work proceeds so that pipe can be installed on precise line and grade. These methods are for lines that are less than 900 mm (36 in.) in diameter. However, identical automated tunneling equipment is used on larger pipes exceeding 2,250 mm (89 in.). Basically, they are automated tunnel-boring machines (TBMs).

Microtunneling machines have been used with reinforced concrete pipe, vitrified clay pipe, glass reinforced plastic pipe, Hobas (fiberglass) pipe, steel pipe, ductile iron pipe, and asbestos cement pipe. Most microtunneling equipment is designed to operate in soft-ground soil conditions.

Microtunneling equipment can be used to install pipes to extremely accurate alignment tolerances. It can be used in very difficult ground conditions without expensive dewatering systems or compressed air. Since workers are not required to enter trenches or the tunnel, it enhances job safety.

More than 30 major manufacturers exist worldwide. However, the majority are in Japan. Microtunneling was developed in Japan during the 1970s. Only two manufacturers are marketing in the United States. No U.S. firm currently manufactures microtunneling equipment.

Microtunneling systems can be subdivided into two categories, based on spoil transportation system. These categories are: (1) Slurry spoil removal; and (2) auger spoil removal.

Fig. 6 illustrates the slurry system. It can install pipes of 375-mm (15-in.) outer diameter and more, and it can crush boulders that are as big as 30% of the shield diameter.

The basic process involves hydraulically jacking the pipe into place, fol-

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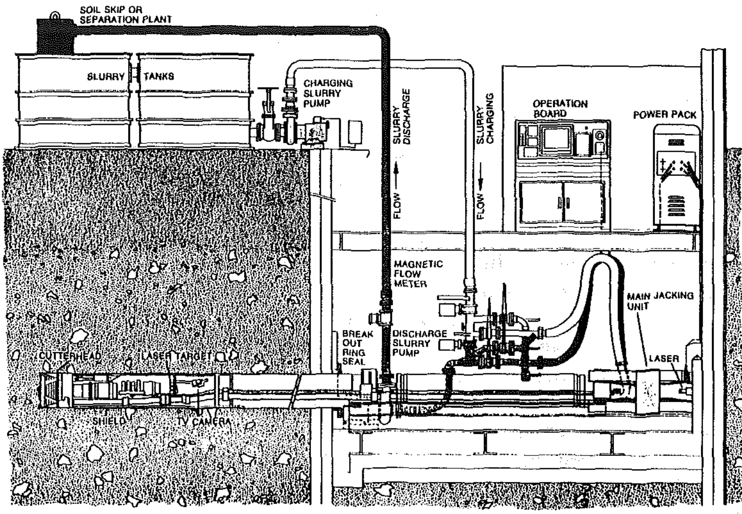

FIG. 6. Slurry-Type Microtunneling Machine

lowing the microtunnel-boring machine from a bore pit. The bore pit must be structurally stable. All systems (jacking, steering, mechanical earth-pressure counterbalance, slurry, etc.) are controlled at the operations board, which is in a job trailer at the surface of the bore pit. Also on the surface near the bore pit are the power pack and the slurry separation equipment tank (Micro-Tunneling 1987).

The slurry-charging pump is designed to pump the supernatant from the separation tank to the cutting head of the machine through small-diameter supply and discharge lines. The cutting head is designed to mix the cuttings with the slurry so that the spoil can be removed by pumping through the discharge lines into the slurry separation tank. The pumping pit bypass unit permits flow and pressure control of the slurry system.

A pipe-laying laser is used for alignment and grade control. An indicator panel at the rear of the machine houses numerous pressure gauges as well as the laser target. This panel is continuously monitored by a television camera. The operator controls the process by reading the indicator panel.

The earth-pressure counterbalance mechanism prevents the ground from collapsing. Slit plates automatically resist the excavated earth pressure. Slurry pressure at the chamber prevents ground-water removal. The automatic slit-opening system is synchronized with the changeable earth pressure at the cutter head. The cutter head rotates with the crushing rotor on a drive axis. Cobbles in the slits are instantly crushed for slurry transportation through the slurry chamber.

The cutting head is specially designed so that it can be controlled, and the thrust pressure is kept higher than the active earth pressure to prevent subsidence or a collapse of the face. It is also kept below the prevailing passive earth pressure to avoid the possibility of heaving or bulging of the ground (*Micro-Tunneling* 1987).

At the same time, the volume of soil removed by the cutting head is automatically controlled and correlated to the advance speed of the machine (*Micro-Tunneling* 1987).

Another method of spoil removal is with augers situated inside a casing through the jacked pipe. The pipe is hydraulically jacked in place, following the microtunneling machine by means of large thrust rams in the bore pit. A bentonite slurry is injected at the cutting head, and the excavated material is removed in a slurry solution, by means of augers inside a casing, to a holding tank beneath the machine in the bore pit. Therefore, this spoil removing slurry need not be of the same pumpable consistency as that used in the slurry method of spoil removal. The equipment relies on a mechanical spoil-removal process. The slurry retention vault in the bore pit should be sized to store spoil generated from one joint of pipe. Therefore, on each cycle the vault must be mechanically removed from the pit by a crane or excavator and emptied into a suitable container for removal from the jobsite.

The power source for operating the cutting head and augers originates from hydraulic motors in the bore pit. The hydraulic reservoir and pumps are at the surface of the bore site. The cutting head is specially designed to function in a closed area. The counterbalance earth pressure is created by the slurry that is pumped into the cutter-head compartment and the rate of feed generated by the thrust rams.

A pipe-laying laser in the bore pit is used for controlling the alignment. The target at the rear of the machine is monitored by a closed-circuit TV camera. The basic process is the same as with the slurry method previously described, with the exception that the spoil must be handled on each cycle and an auger-and-casing segment must be placed inside the casing.

The major disadvantage of the microtunneling method is that the machine's capital cost is high. However, on projects where this method has been competitively bid against others, the unit-price costs have been in line.

Pipe Jacking

Pipe jacking is a method of trenchless excavation construction (TEC) that requires workers inside the pipe. The pipes are prefabricated and jacked into position from a jacking pit. The excavation can be either mechanical or manual.

The excavation method varies from the very basic process of workers digging the face with pick and shovels to highly sophisticated tunnel-boring machines. However, regardless of the excavation method, it is normally accomplished inside an articulated shield. This shield can be guided with individually controlled hydraulic steering jacks. This shield is designed to provide a safe working environment for the workers and allow the bore to stay open for the pipe to be jacked in place.

The process requires a simple, cyclic procedure of using the thrust power of hydraulic jacks (rams) to force the pipe forward. In unstable conditions, the face is excavated simultaneously with the jacking operation to minimize overexcavation and risk of face collapse. In stable ground conditions, excavation may precede the jacking process, if necessary. The spoil is removed through the inside of the pipe to the jacking pit. After a section of pipe has been installed, the rams are retracted and another joint is placed into position so that the thrust operation can be started again.

Because of the jacking forces required to push large-diameter pipe through

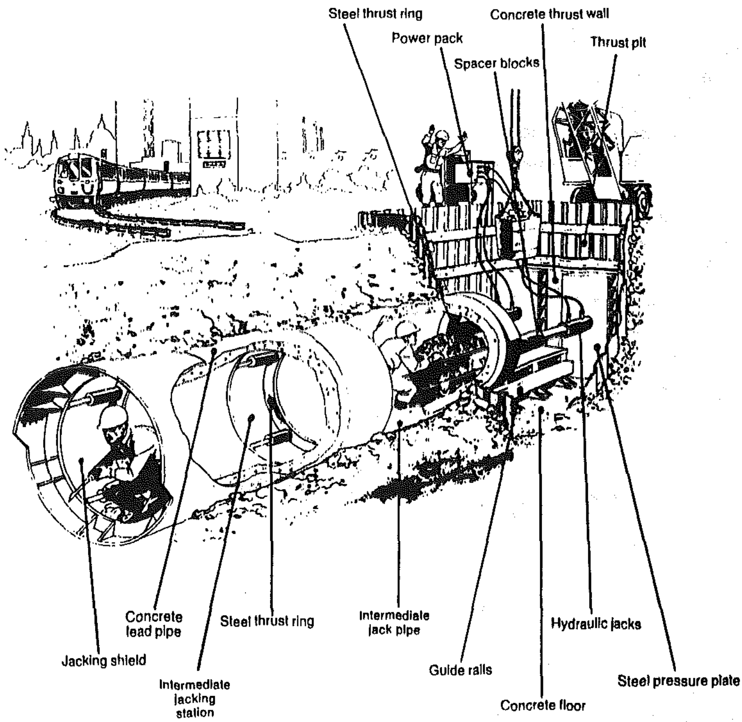

FIG. 7. Components of Typical Pipe-Jacking Operation with Shield

the ground, the jacking-pit design and construction are critical. The pit embankment supports must be properly designed and constructed. The pit floor and thrust-reaction structure must be designed to handle the repeated process of supporting extremely heavy sections of pipe as the operation is executed.

Fig. 7 illustrates the components of a typical pipe-jacking operation. Guide rails are prepositioned so that the jacking pipe will be properly aligned when it is placed on the guide rail. It is critical that the guiding frame be firmly supported to prevent movement during the operation. Much of the success in a pipe-jacking operation is based on ensuring proper alignment.

The anticipated jacking force should be calculated based on the job conditions. This force will include the penetration resistance, frictional resistance force between pipe and earth, and frictional resistance force due to the dead weight of the pipe (*Manual of Kubota* 1985).

The application of bentonite slurry to the outside skin of the pipe may reduce frictional forces. Another common method for minimizing jacking force is to operate on a continuous, 24-hour basis and to use intermediate jacking stations (IJS).

Excavation is done inside the shield. It may be done manually or mechanically. The spoil is commonly removed by small carts, which are manually operated or powered by a winch cable or battery. Spoil may be removed by a conveyer belt system or by small-diameter augers.

Primarily, this method has been used to install reinforced concrete pipe.

However it is appropriate for steel pipe, Hobas (fiberglass) pipe, ductile iron pipe, and corrugated metal pipe, depending on the project conditions.

The pipe-jacking method has been limited, by definition, to projects that require workers inside to perform the excavation. The method has been used on pipe sizes as small as 750 mm (30 in.) interior diameter; however, it is seldom practical for interior diameters less than 900 mm (36 in.). Even at an interior diameter of 900 mm (36 in.), it is very difficult for workers to function efficiently (*Jacking Concrete Pipe* 1968).

In stable ground conditions, negligible subsidence will occur. In unstable ground, or where stability is questionable, geotechnical stabilization techniques should be employed. These techniques can vary from lowering the ground-water table with well points or deep wells to the use of cementitious or chemical grouts.

Utility Tunneling

Utility tunnels are differentiated from the major tunneling industry by virtue of the tunnel's typical sizes and uses. These tunnels are used primarily as conduits for utilities rather than as passages for pedestrian or vehicular traffic. Further, while methods of excavation for the pipe jacking or utility tunneling may be identical, the differentiation is in the lining. With the pipe-jacking technique, the pipe is the lining; whereas, in utility tunneling either tunnel liner plates, or rib and lagging, become the lining.

In this process, excavation takes place inside a specially designed tunneling shield. Excavation can be either manual or mechanical. The lining is actually constructed in place in the tail section of the shield. This provides protection to the workers assembling the lining system.

Tunnel-liner plates are prefabricated modular units used to construct a temporary circular lining for the purpose of encasing a utility. Liner plates are typically made of steel or precast concrete. Steel liner plates are predominantly used because of weight and economy, but precast concrete liner plates are becoming increasingly cost-effective.

Typical operating procedures require that excavation be conducted at the face with spoil removed by carts, conveyers, augers, etc., or a combination of these systems. The tunneling shield is hydraulically jacked forward as excavation is being conducted. The jacks of the shield thrust against the previously installed liner plates. After the shield has been pushed forward far enough so that one or more courses can be placed, the jacking operation ceases; and the jacks can be retracted so that workers can install the plates in the tail section of the shield. The cyclic operation begins again.

These systems usually are considered practical at a minimum size of 1.2 m (4 ft) in diameter, theoretically with no upper limit. The tunnel access shaft can be of minimum size. However, it must be of sufficient size to accommodate spoil removal equipment and air-handling equipment. A high degree of accuracy can be obtained with a minimum amount of skilled labor.

Conclusion

The selection of a method for a particular project will be greatly affected by many factors such as the size of the bore hole, accuracy required, depth of water table, local soil conditions, and availability of funds. For example, modern microtunneling equipment, though good for most of the jobs, may not prove to be cost-effective for smaller projects. Since the technology is advancing very rapidly, there is a severe lack of understanding of the various TEC techniques. There is a definite need to train designers and contractors at all levels in how TEC methods and equipment may be effectively used. It also has been observed that significant variations exist within the country. Hence there is a need to standardize trenchless excavation construction.

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