Micro- and Small-Diameter Tunneling (1989)

Pages
33

Size
5 x 9

ISBN
0309317738

U.S. National Committee on Tunneling Technology; Geotechnical Board; Commission on Engineering and Technical Systems; National Research Council

MICRO- AND SMALL-DIAMETER TUNNELING

U.S. National Committee on Tunneling Technology
Geotechnical Board
Commission on Engineering and Technical Systems

NATIONAL ACADEMY PRESS
Washington, D.C. 1989

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SPONSOR: This project was sponsored by: U.S. Bureau of Mines, U.S. Army Corps of Engineers, U.S. Department of Energy, and U.S. Bureau of Reclamation which have contributed to the core funding of the U.S. National Committee on Tunneling Technology.

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0060 (7/89)

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EXECUTIVE SUMMARY AND RECOMMENDATIONS

A very large proportion of the demand for the construction and replacement of urban utilities falls in the size range for which micro- and small-diameter tunneling are applicable. This is a multibillion-dollar annual market worldwide and represents a large segment of the annual U.S. expenditures for the construction of gas, water supply, and sewer facilities ($8.4 billion in 1984 according to the U.S. Chamber of Commerce).

The potential use of this technology is particularly strong in microtunneling (less than 0.9 m [3 ft.] in diameter), as this represents the size range of a major portion of installed facilities and because technological improvements in geophysical sensing, remote guidance, and dealing with difficult or varied ground conditions offer the greatest increase in cost efficiency.

The use of microtunneling and specialized boring equipment is increasing rapidly worldwide, but U.S. utility owners are not likely to embrace this technology substantially (except in special locations) until the price differential between cut-and-cover and microtunnel or specialized boring installations is reduced. Severe restrictions against pavement cutting and traffic disruption for utility work do not generally exist in the United States and hence the full economic costs of these disturbances are not usually included in cost comparisons. The incentive for microtunneling is naturally greater when surface restoration costs are high.

Nevertheless, micro- and small-diameter tunneling represent an important technological area for future development in the United States. Investment in further research and development should be made if technological leadership in this area is not to be relinquished to countries with greater current needs for microtunneling and a greater commitment to research and development programs.

The size of the market for microtunneling is expected to increase rapidly as its relative cost, when compared to cut-and-cover installation, falls. Lower costs would allow microtunneling to compete in the installation of shallower utilities for which there is a much greater construction volume.

In order for the U.S. industry to keep up in the development of technology for microtunneling, the following actions are recommended:

- Basic research should be directed at the following technologies applicable to trenchless excavation:
  (a) surface mapping of subsurface conditions and structures (especially at depths of 4.5 to 6 meters (15 to 20 feet) or greater,
  (b) remote guidance systems,
  (c) cutter heads for mixed-face conditions,
  (d) obstruction sensing, and
  (e) remote development of service connections.
- Attempts should be made to document the impact of pavement cutting and restoration on the life-cycle cost of road pavement.
- Industry institutes such as the Gas Research Institute and the Electric Power Research Institute should continue to sponsor the development of microtunneling technology into commercially available techniques.
- Information on developments in microtunneling technology should be targeted at utility owners (for example, electricity, gas, water, sewer, telephone, cable television), permit-granting agencies, consultants, and contractors so that conditions favorable to microtunneling are identified in the planning of new or replacement utility construction.
- Efforts should be made to gather data and learn from foreign accomplishments.

MICRO- AND SMALL-DIAMETER TUNNELING

INTRODUCTION

An important aspect of the discussions surrounding the nation's infrastructure is the installation, maintenance, and upgrading of our urban utility systems. Current expenditures on this effort are large and the demands placed on our utility infrastructure are growing. For example:

- significant portions of the utility infrastructure in older U.S. cities have exceeded their useful life;
- in addition to requirements for expanded capacity of existing systems, there has been a demand for new utility systems such as cable television networks and data links; and
- environmental and aesthetic concerns are placing new restrictions on the location and quality of utility systems.

According to the U.S. Chamber of Commerce, in 1984 approximately $8.4 billion was spent in the United States for the construction of gas, water supply, and sewer facilities, much of which was related to pipeline installations. In New York City over 85 kilometers (53 miles) of gas-distribution mains are newly installed or replaced each year. In Chicago approximately 51 kilometers (32 miles) of water and sewer pipelines are installed annually. The combined replacements and new installations of gas, water and sewer pipelines in Boston amount to 40 kilometers (25 miles) per year (O'Rourke et al., 1985). In 1987, gas utilities in the United States replaced 11,410 kilometers (7090 miles) of pipe and installed approximately 29,000 kilometers (18,000 miles) of new pipe (data from Gas Research Institute).

Utility systems are a relatively recent development in the history of mankind but life in developed areas today would be unthinkable without them. The ancient Egyptians constructed water supply tunnels in about 3500 B.C. and the Romans had a well developed water supply system and sewage disposal system. A long period of neglect followed in almost all parts of the world except for the provision of water supply. Until the 1800s, sewer systems in urban areas consisted principally of open ditches, but since that time utility systems have developed rapidly in urban areas around the world. Water and sewer systems were followed by electricity and telephone systems, district heating systems, mass transit systems, and cable systems.

Water and sewer systems were placed underground for frost protection, maintenance of utility slope (sewers), and because of the large pipe sizes required. Electricity and telephone systems were not as constrained and the traditional practice outside of major downtown areas was to use overhead systems. Aesthetic pressures today force such utilities in most new developments to be placed underground.

The increase in the number and type of utilities being placed underground, together with the need for the replacement and upgrading of existing utilities, has raised serious concerns about the traditional methods of locating and constructing underground utilities.

Most utility systems are buried at shallow depth. The principal exceptions are sewer systems in hilly areas which require tunneling to maintain their slopes for gravity flow. Typically, shallow buried systems have been installed by the excavation of a trench to the depth required, preparation of the bedding, installation of the utility conduit, and backfill and compaction of the soil above the conduit. In terms of direct costs, this installation method, termed trenching, is usually the cheapest method for shallow utilities and requires little specialized expertise for its execution. It has, however, a number of disadvantages which are listed below:

- Street traffic is congested during utility installation and repair.
- Paved streets are continually damaged by pavement removal and settlement following its repair, thus shortening pavement life considerably.
- There are social, economic, and aesthetic damages to neighborhoods during major utility trenching projects.
- In dense urban areas, the near-surface zone beneath streets and sidewalks is almost fully occupied, thus increasing costs for trenching operations.
- The excavation of a large trench to place a relatively small utility is inherently inefficient if alternate methods of direct placement can be developed.

These disadvantages, together with a greater realization of the nonproject economic costs associated with trenching, have led to an increased interest in tunneling techniques for utility placement even at relatively shallow depths. Historically, tunnels have required personnel entry to permit tunnel advancement. The size of such tunnels needed for personnel access has limited the use of tunneling to larger utilities or groupings of utilities.

In the last decade the technology for remotely operated tunneling equipment, pipe jacking, and drilling operations has improved dramatically. Because of the size of the utility construction and replacement market, and the market share that micro- and small-diameter tunneling could achieve, this technology is expected to become an important factor in an internationally competitive construction industry.

Except in selected techniques, the United States has not been a leader in tunneling technology developments over the past few decades. An increasing share of major tunnel projects in the United States is awarded to foreign contractors or U.S. firms operating with foreign technology. The micro- and small-diameter tunneling field is particularly vulnerable because it is more heavily dependent on technological development, has a larger potential application than conventional tunneling, and is a more readily importable or exportable commodity. Because of its importance to our utility infrastructure and our future international competitiveness in this construction sector, the U.S. National Committee on Tunneling Technology established a subcommittee on Micro- and Small-Diameter Tunneling to study this issue. This report is a first step in the committee's work and attempts to describe briefly the techniques involved, the potential applications, the potential growth of the industry, and the critical areas requiring research and development for this developing technology.

TERMINOLOGY AND TECHNIQUES

There are no universally accepted definitions of micro- or small-diameter tunneling. The perception and use of size as a means of categorizing tunneling varies on a regional basis according to local needs, economics, familiarity, and availability of special construction equipment. In general, the distinction between a small-diameter and a microtunnel is made on the basis of personnel entry. Conduits that are too small for ease of access and maneuverability of personnel-operated repair or construction equipment require remote control for excavation, mucking, and steering. In this report, an internal diameter of 0.9 meters (3 feet) has been chosen as the smallest size attributable to small-diameter tunneling.

Microtunneling refers to a class of underground conduit construction with internal diameters ranging from as small as 50 millimeters (2 inches) to slightly less than 0.9 meters (3 feet). Consistent with previous work by Binnie and Partners (1985), the term "microtunnel" has been adopted in lieu of "minitunnel" to avoid confusion with a patented system for excavation and segmented lining which derives its name from the latter term.

Both micro- and small-diameter tunneling are parts of a broad technology known as trenchless construction, or trenchless pipelaying, which is being developed to provide alternatives to trenched construction as a means of installing subsurface facilities. Trenchless construction is defined as the installation of pipelines and ducts by subsurface excavation, thrust displacement of in-situ soil, or the enlargement of existing underground facilities. Trenchless construction involves the creation of new space, which is accomplished by conventional and specialized tunneling methods, special drilling and moling equipment, or the breaking and expansion of old pipelines to install larger or similarly sized ones.

The principal trenchless construction methods are listed in Table 1, which is adapted from information published by O'Rourke et al. (1985) and Binnie and Partners (1985). The table also summarizes typical lining and conduit types, dimensions, and suitable ground conditions associated with the various methods. Two general categories are identified in the table—small-diameter tunneling and microtunneling. In this second category a distinction is made between face excavation, ground displacement methods, and on-line methods. The first set of procedures involves the excavation and removal of soil from the excavation face, and involves methods such as pipe jacking with a miniature boring machine, pipe jacking with an auger borer, and horizontal drilling. Ground displacement methods involve the insertion of conduits while simultaneously displacing soil adjacent to them. These methods include percussive moling and pipe ramming. On-line replacement uses a percussive moling device and mechanical expander to break and expand an

TABLE 1 Summary of Trenchless Construction Methods

Method	Lining Type and Size	Length of Drive	Suitable Ground Conditions
SMALL DIAMETER TUNNELS			
Tunneling	Bolted segments ≥ 1.5 m for smooth bore segments; ≥ 1.2 m for other in situ methods	Max. unlimited but typically around 200 m	Virtually all ground feasible by use of appropriate methods. Special techniques used to control movement of soft ground.
Pipe jacking	Jacked pipe 0.9 m up	Typically 100 m between shafts, Max. more than 1,000 m	Excavation can be carried out in virtually all ground as for tunneling. Difficult ground may restrict length of pipe that can be jacked.
MICROTUNNELING AND SPECIALIZED BORING METHODS			
Face Excavation Methods:			
Pipe jacking with TBM/shield	Jacked pipe 0.25 to 0.9 m	Max. to date 180 m	All except rock and large boulders. Microtunnel shields are designed to limit ground movement.
Pipe jacking with auger borer	Jacked pipe 0.15 to 1.4 m	Up to 100 m, often less	All except hard rock and boulders. Risk of ground movement in soft ground
Directional drilling	Steel pipe 0.05 to 1.4 m	Max. 1,600 m	Many ground conditions except rock, boulders, and some very loose and soft deposits.
Ground Displacement Methods:			
Percussive moling	Pulled plastic pipe 0.05 to 0.2 m	Max. 70 m; Typically 10 m to 15 m	Not suitable for very soft ground or rock. Can break up small boulders. Heave limits min. depth to above 10 times pipe diameter.
Pipe ramming	Driven steel pipe 0.05 to 1.4 m	Max. 60 m	All except rock and boulders. May be able to chisel soft rock. Little face control gives risk of ground movement.
On-Line Replacement:			
Pipe Bursting	Plastic pipe 100 to 400 mm ID	Typically less than 100 m, although larger runs are possible	Most soils.

*Table assembled from information reported by Binnie and Partners (1985), O'Rourke, et al. (1985), and Thomson (1988).

existing pipeline at the same time that replacement piping is installed (often referred to as pipe bursting).

The distinction between procedures utilizing excavation and muck removal and those which employ ground displacement measures can be important. The former group often results in volumes of excavated soil that exceed the volume of the pipes or conduits installed. As a result, the surrounding soil tends to displace, or converge, toward the openings. Moling and ramming devices often result in volumetric increases so that the surrounding soil expands, or displaces away from, the openings. The two general classes of procedures have been referred to as convergent and expansive installation techniques (O'Rourke, 1985) to emphasize the type of ground movements that can be anticipated. Convergent installation techniques result in ground movements that are analogous on a smaller scale to those generated by conventional soft-ground tunneling.

Small-Diameter Tunneling

Small-diameter tunneling includes tunnels larger than or equal to 0.9 meters (3 feet) finished diameter that are constructed by means of hand or machine excavation and pipejacking methods. In this report, the maximum size of a small diameter tunnel is taken as a 3.0 meters (10 feet) finished internal diameter. For sizes exceeding 3.0 meters (10 feet), a double-pass car system can be used so that the operational freedom for mucking (soil removal) and scale of the tunneling operation change significantly as the diameter increases above this cutoff. As a practical matter, the lower limit for normal personnel-operated mechanized excavation, mucking, and lining is about 1.8 meters (6 feet) finished internal diameter. The size range between 0.9 meters (3 feet) and 1.8 meters (6 feet) encourages mechanization but does not require full remote control.

Small-diameter tunnels can be constructed by hand or machine excavation at the tunnel face. Most commonly, the work is carried out with a shield or full face boring machine and mucking is performed by conveyor, rail-mounted cars, or slurry piping. When pipe jacking is used, pipe segments are jacked into the pre-excavated hole from a launching or staging area. Alternatively, the lining may consist of precast concrete segments or cast-in-place concrete, with the latter generally installed after ribs and lagging initial support when construction is performed in soil.

Pipe-jacked tunnels are often installed beneath busy transportation routes for distances typically between 50 and 100 meters (165 to 330 feet). Single lengths of jacking may exceed 1,000 meters (3,300 feet) (Clarkson and Thompson, 1983) and individual jacking stages can be linked to result in tunnel construction several kilometers long. Figures 1 through 3 illustrate various aspects of the pipe-jacking process that was followed during the construction of the Nashville Avenue Sewer System in Chicago, Illinois. The tunnel was constructed by jacking between vertical shafts to make up the total contract length of over 2 kilometers (1.2 miles). Vertical shafts were excavated primarily at manhole locations and pipe lengths up to 323 meters (1,060 feet) were jacked (Figure 1). The excavated diameter was slightly less than 3 meters (10 feet), and the depth below surface to the tunnel centerline was approximately 10 meters (33 feet). Pipes were 2.3 meters (7.5 feet) long, 2.4 meters (7.9 feet) internal diameter, and 2.9 meters (9.5 feet) external diameter. Three jacks, each of 200-ton capacity and 1.2 meter (4 feet) stroke (Figures 2 and 3) were used.

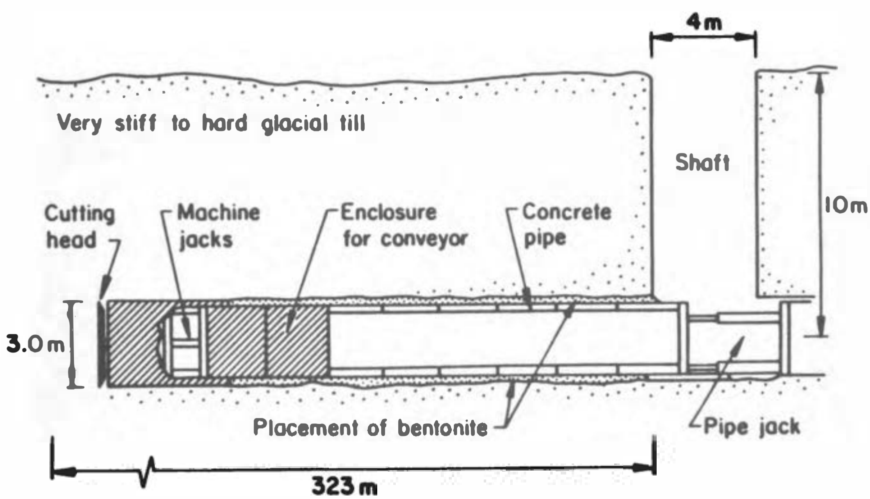


Figure 1 Cross-Section of Pipe-Jacked Tunneling for Nashville Sewer System, Chicago, Illinois (courtesy T.D. O'Rourke).

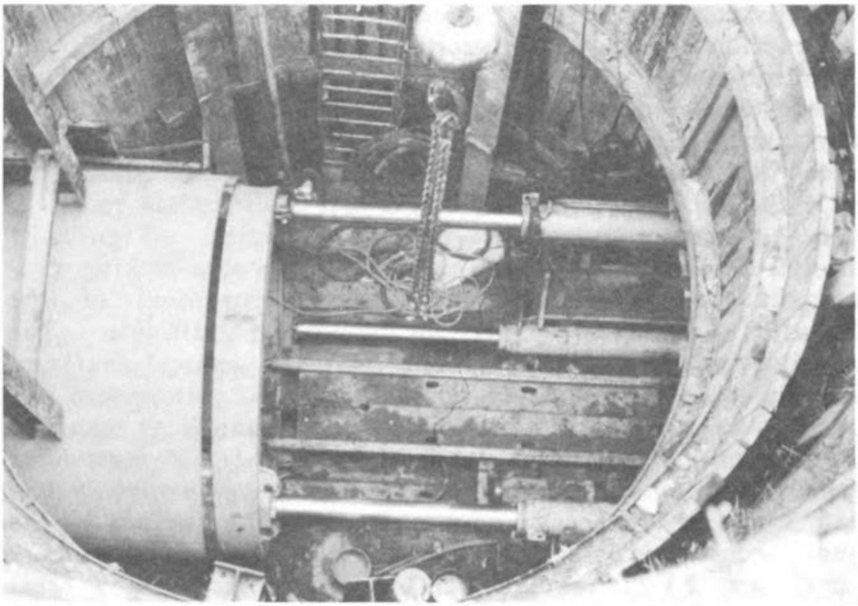


Figure 2 View of Pipe-Jacking Operation at Shaft (courtesy of T.D. O'Rourke).

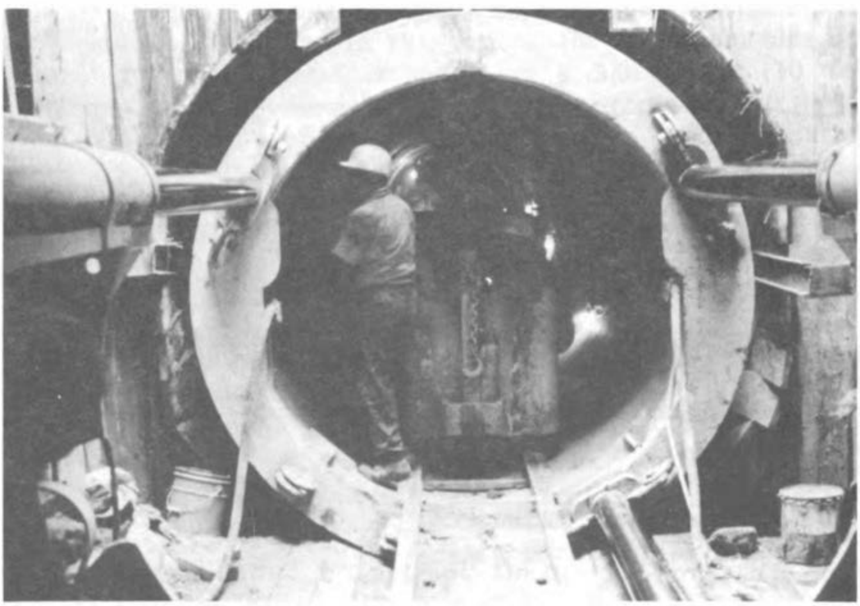


Figure 3 View of Pipe Jacking from Launching Area (courtesy of T.D. O'Rourke).

Microtunneling

Microtunneling, which typically involves pipe jacking with remotely controlled miniature tunnel boring machines, has been developed principally in Japan and Germany, where equipment exists for the installation of pipelines 200 millimeters (7.9 inches) or more in diameter. With some devices, excavation is performed by a full-face rotary cutter head that exerts a counterbalancing pressure on the soil. The excavated material is removed by a bentonite slurry system, which is pressurized to prevent groundwater inflow and soil intrusion across the excavation boundaries. The tunnel boring machines are controlled by electric and hydraulic systems, which are monitored by instrumentation, computer processing, and closed-circuit television. Figure 4 shows a view of the cutting face of an exposed miniature boring machine at a reception pit during trial tests in Hamburg, Germany.

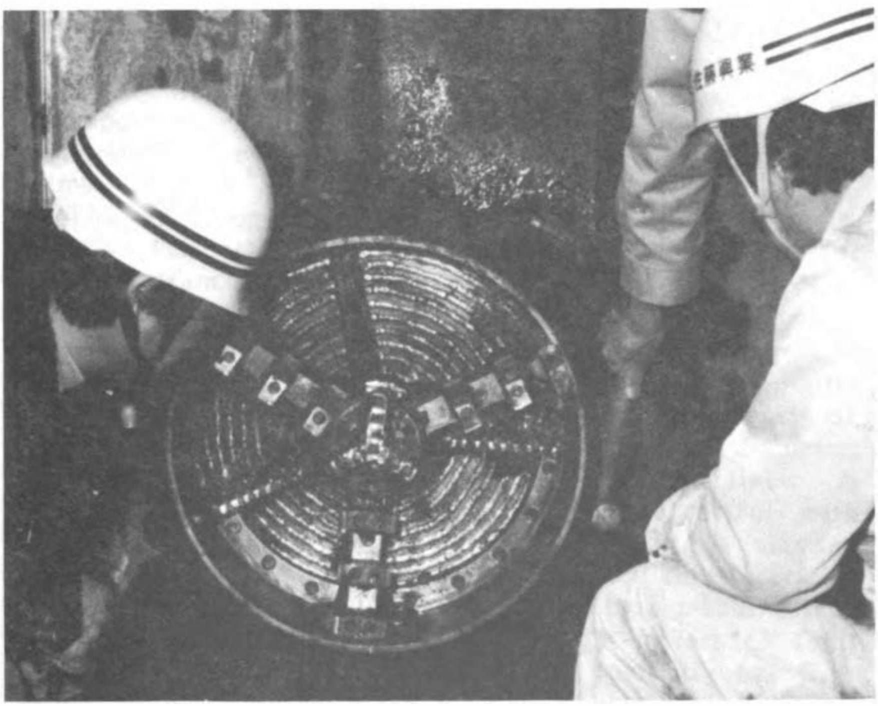


Figure 4 Miniature Slurry Shield Tunneling Machine Emerging at Reception Pit (courtesy of WRC Engineering).

By convention, a drilling technique often is identified as being distinct from true tunneling if it involves a rotating drill string. Directional boring devices, which employ rotating drill strings, are included in this report under the general category of face-excavation methods. This inclusion is principally for convenience in that it allows methods that may result in similar ground displacement patterns to be grouped within the same category.

An example of equipment that has been developed in the United States is a system that allows for directionally controlled miniature boring, as illustrated in Figure 5. Excavation is performed by water jets, which use a clay-water fluid pressurized to as high as 300 atmospheres (Mercer et al., 1987). Guidance is provided by means of a transmitter located in the head of the boring tool and an electronic locator operated at the surface. A crew member with the locator determines the position of the tool, and communicates steering directions by two-way radio to the operator of the drilling unit. Power, thrust, and steering are provided by the drilling unit from a remote location.

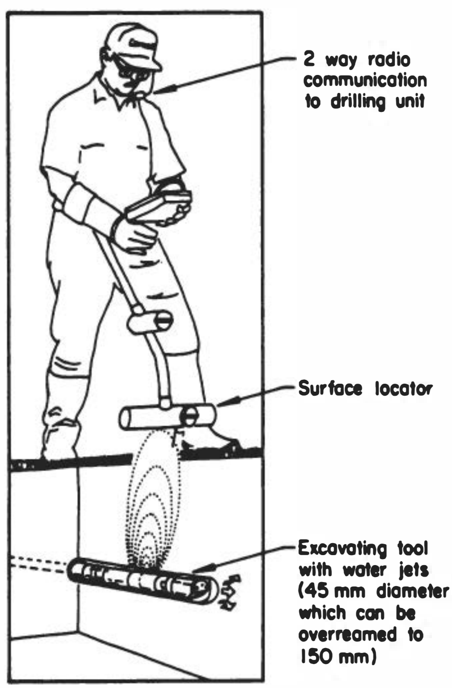


Figure 5 Operation of Remotely Controlled Water Jet Boring Tool (courtesy of Flow Mole).

APPLICATIONS

Small-Diameter Tunneling

The application of small-diameter tunneling varies with location across the continental United States and it was not possible in this report to conduct an extensive survey of agencies responsible for utility systems. As an example, however, the Milwaukee Metropolitan Intercepting Sewer System has approximately 480 kilometers (300 miles) of sewer in service of which approximately 390 kilometers (240 miles) have been constructed as tunnels. The present Milwaukee program will add over 80 kilometers (50 miles) of sewer of which over 65 kilometers (40 miles) will be constructed as tunnels. The breakdown by size for this 565-kilometer (350-mile) system consists of 92 percent at 3.9-meter (12-feet) diameter or less, with 60 percent being 1.8-meter (6-feet) diameter or less. Approximately 70 percent of the 450 kilometers (280 miles) of tunnels used in this system were 3 meters (10 feet) or less in size and would probably qualify as small diameter tunnels. While the Milwaukee project may not be representative of all metropolitan areas in this respect, it can be considered representative of some of the northern metropolitan areas that use gravity sewer systems.

The technology for excavating small-diameter tunnels is relatively well established. For example, the present Milwaukee program has seen the use of a range of methods from hand mining with a four-piece set with top and side poling, to the latest rock boring and earth balance soft ground machines. From this perspective, the only changes under way in small-diameter tunneling appear to be the lowering of the commonly accepted lower size limit for tunnel diameter, and the use of a single pass concrete segmented liner. A local Milwaukee contractor who has been successful with jacking 1.2 meters (4 feet) diameter pipe using a manned mining machine, which is currently considered the lower size limit for small diameter tunneling, is building a machine that will be manned and used in jacking 0.9 meters (3 feet) diameter pipe. The Milwaukee program currently has four projects under construction where a precast concrete segmented liner is being used as the primary liner and also used as the finished conduit.

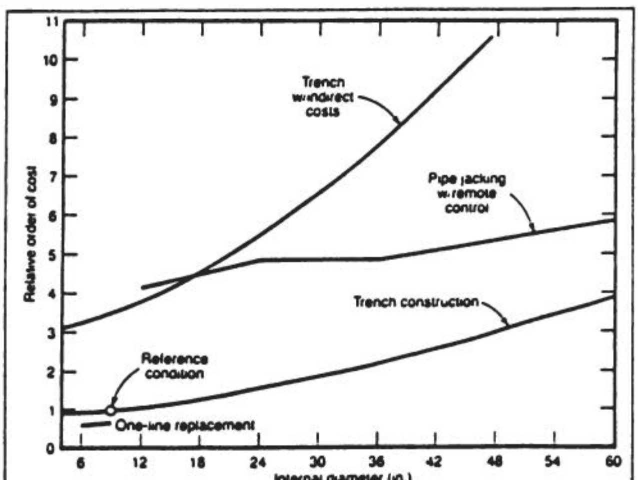
Microtunneling, Auger Boring and Directional Drilling

Microtunneling and related methods constitute a rapidly growing but still developing technology that has had, to date, a relatively limited application in the continental United States. Responses from seven metropolitan sewerage agencies in the continental United States (as part of an informal survey of utility tunneling conducted by the subcommittee) showed only a limited perceived need for microtunneling. The application of microtunneling by these agencies is limited to undercrossings where open-cut construction is not allowed. In the Milwaukee area, for example, utility contractors indicate that almost all of the micro size (under 36-inch diameter) tunneling is done for undercrossings by blind augering with a steel casing. Due to directional control problems, the maximum length of these augered tunnels is about 61 meters (200 feet). Where horizontal and vertical control is critical, small-diameter tunneling by established technology is often used because the skill and equipment required are readily available. These utility contractors do not see the use of microtunneling increasing in this area until the authority that controls excavation in the public right-of-way imparts strict limitations on open cut excavation. When questioned on this matter, the City of Milwaukee Department of Public Works indicated that there is no intent to further limit open-trench excavation at present. The present policy is to require tunneling at crossings of busy intersections, highways, or railroad tracks.

Discussions with contractors and owners in the Milwaukee area indicate that the cost of microtunneling will be the major factor limiting the use of this technology. These contractors and owners also express concerns that this technology may have a more difficult time competing with other technologies in areas such as Milwaukee because of the unpredictability of the glacial soils which are interspersed with boulders.

There are locations in the United States, however, where soil conditions are more favorable and the need to limit open-trench construction of small-diameter utilities apparently is important. For example, Houston, Texas is completing a sewer project consisting of 6.5 kilometers (4 miles) of gravity sewer with diameters from 0.2 meters (8 inches) to 0.75 meters (30 inches) In addition, the city is completing 3.7 meters (2.3 miles) of with diameters ranging from 0.1 meters (4 inches) to 0.45 meters (18 inches) force main. This 10-kilometer (6.3-mile) system is being installed using microtunneling techniques. Unit prices (1987) ranged from $738/meter ($225/foot) for 0.2 meters (8 inches) pipe sewer in tunnel to $869/meter ($265/foot) for 0.55 meters (21 inches) pipe sewer in tunnel. In comparison, the estimated cost in Milwaukee for deep open-trench construction—3.7 to 4.5 meters (12 to 15 feet)—of sewer pipe ranging in size from 0.2 to 0.25 meters (8 to 10 inches) is $165/meter ($50/foot), which includes pavement restoration. The Houston project is located in an exclusive neighborhood where the disruption associated with open-trench construction was not acceptable. The disruption would probably have included excavation through lawns and shrubbery and the closing of roads to traffic. Inconvenience, neighborhood disruption, and high restoration costs associated with open-trench construction justified the microtunneling approach (City of Houston, 1988).

Such direct cost imbalances severely curtail the current application of microtunneling techniques. Cost differentials may not be as great when more work is available to amortize the high cost of equipment development and/or purchase, and greater restrictions are imposed on surface disruption. Figure 6 shows a generalized trenchless versus open-cut cost



All prices are relative to cost of installation of 2,000 ft of 9 in. I.D., including manholes and ancillary work set 13 ft deep in a city street under difficult ground conditions. Relative order of costs is based on U.K. prices prevailing in May 1984. Indirect costs were assumed to be 2½ times the direct engineering costs.

Figure 6 Costs: Trenchless vs. Open Cut (courtesy of T.D. O'Rourke).

relationship, based on indirect costs (for example, traffic disruption, pavement damage) as well as direct construction costs.

POTENTIAL GROWTH OF THE INDUSTRY WORLDWIDE

A limited amount of data on the world market is available in published papers and reports. It has been estimated however, that the total market in the developed Western world for all types of utility installation is approximately 500,000 kilometers (300,000 miles) per year, with an approximate market value of $25 billion annually (Jason Consultants, 1987). There is also little doubt that the concept of "no dig" utility installation and replacement is growing rapidly. Just two years ago, some 10,000 kilometers (6,200 miles) of trenchless utilities were laid in the United Kingdom, and this year 16,000 kilometers (10,000 miles) are anticipated. Of these "tunnels", 99 percent are less than 1 meter (3.3 feet) in diameter.

It is evident that demand is much higher in the older urban areas in densely populated regions; for example, Europe, Asia, and the eastern United States. Utility companies in newer areas, such as California, express an expectation that technological developments (for example, fiber optics, higher voltages, super conductivity, higher pressures) will provide increased capacity in the next five to ten years without extensive installation of new tunnels.

The need for utilities in Japan and a few other highly developed urban areas in Asia is particularly acute. High real estate costs prohibit acquisition of right-of-way and make the cost of surface disruption unreasonably costly. In addition to monetary factors, the cost of disruption to the orderly flow of public transport and commerce has become unacceptable.

An additional trend in utility construction is toward deeper utilities, as the more commonly used zones of up to 3 to 4 meters (10 to 13 feet) below surface become criss-crossed with pipes and wires. The crowding of this zone plus the increasing costs of surface disruption favor a trend toward greater use and value of microtunneling in urban areas.

Factors limiting the growth of microtunneling at greater depths are the directional guidance of the tunnel boring equipment, techniques for dealing with boulders or rocks in the path of the tunnel, and the relatively short distance that can be bored without additional shafts from the surface.

POTENTIAL DEMAND IN THE UNITED STATES

The demand in the United States for microtunneling is similar to the demand in Europe. The major application is in older cities where utilities are aging, real estate prices are high, or the disruption of surface is both costly and unacceptable.

The younger U.S. cities, generally those west of the Mississippi, have exhibited a more orderly development than in the eastern United States. In newer cities many utilities were built oversize in a planned and maintainable grid. In addition, although there are some exceptions, real estate prices are lower and wider streets lend themselves to cut-and-cover operations with less disorder.

Many western U.S. utility companies are looking to alternate technologies to increase the capacity of existing lines and pipes, such as:

- electrical-higher voltages, superior conductors;
- telephone-fiber optics; and
- hydraulic line-higher pressures, storage and surface capacity.

A concept utilized in a few cases is to construct larger tunnels and install multiple utilities (utilidors). Unfortunately, in most cases, the needs and timing among individual service suppliers do not coincide to permit the necessary investment in the common tunnel (APWA, 1971).

In more northerly cities, the effects of the glaciated surface geology limit the use of present day technologies in microtunneling. In some urban areas virtually all of the soil has been pushed away, leaving bedrock only a few feet below surface or exposed in some places. In other zones, cobbles and boulders create difficulties for current microtunneling techniques. Improved capability for rock and boulder excavation is required before the market can expand.

Unfortunately, no market statistics for the United States in the microtunneling field were found in the brief literature search conducted. From the information gathered, however, there is little doubt that the field is currently expanding and that, with the anticipated improvements in the construction technology, the market will continue to expand significantly.

U.S. INDUSTRY COMPETITIVENESS

The microtunneling industry in the United States does not necessarily suffer from the same underlying weakness in its competitive position as is evident for large-diameter tunnels in difficult soft ground or weak rock. The Europeans and Japanese have passed the United States in technological developments for large-sized soft-ground tunnels, due in large part to the continuing and relatively stable demand for these facilities in their home countries. The lack of demand for this type of construction in the United States has caused the U.S. industry to lag in the development of improved technologies, as the industry has not had the base of local work that would justify the investment in new technology or the development of improved construction expertise. This lack of U.S. competitiveness in the world market also stems from the fact that U.S. firms have not been able to acquire the low-cost financing required on many large overseas projects which have been available to their competition. Foreign competitors have been able to further develop technology and expertise on these large projects, permitting more efficient handling of difficult tunneling conditions.

While the Japanese and Europeans have made substantial technological developments in microtunneling, a review of the advances in this field and in horizontal and directional drilling in the United States indicates that in certain techniques U.S. technology has kept pace with worldwide developments or, in fact, leads the field.

In soft ground using remote-controlled guidance of slurry-head type moles, the Europeans and Japanese appear to have a technological and competitive lead in the manufacture of equipment as well as in construction expertise involved in micro- and small-diameter tunnels. There appears to be little incentive at this time for U.S. industry to expend the effort to develop this technology further because there is insufficient demand for this type of construction in the United States at present. Should demand increase, the construction industry would need access to foreign technology, either through the necessary licensing of technology from overseas to manufacture the equipment in the United States or through the direct acquisition of the equipment.

LIMITATIONS AND HAZARDS

The limitations of microtunneling manifest themselves in the problems of the blind advance of the microtunnel and thus the placement of the utility is done under the same conditions. This restraint becomes more critical as the depth of cover to the utility increases. Controlling the microtunnel advance and the location and repair of a damaged installation become more difficult as the depth of cover increases. It is anticipated that the majority of microtunnels will be utilized in congested urban areas and will be installed below existing utilities in order to assure clearance. This makes their use dependent on economical and accurate remote-sensing methods of locating existing utilities and obstructions at depths up to about 6 meters (20 feet). It follows that it is critical to the success of the microtunnel that it can be monitored for accurate location and steering during the construction phase. The requirements for accurate, at-depth location of existing utilities and steering the microtunnel to reasonable tolerances have not yet been met satisfactorily and therefore this technology must be developed further if microtunneling is to realize its potential.

The blind installation of a utility in a microtunnel at-depth also renders installation and maintenance of the facility more difficult and requires, for assurance of its useful life, the designer to address the following factors in the design of the utility:

- construction loading,
- corrosion resistance,
- expected life,
- long-term maintenance, and
- quality assurance during the construction stage.

In order to overcome the limitations of blind installation, these systems ideally should incorporate the capability of continuously monitoring obstacles (for the ground being tunneled), the movement of any ground surrounding the microtunnel, and the proper installation of the utility associated with the microtunnel. Such monitoring is not provided in a microtunneling system, it will not be considered a reliable method by private industry and will not be extensively adopted in the congested urban areas where these systems would be economically viable.

A further limitation to the use of microtunnels has been legal and building code restrictions that have been written to apply to other types of facilities constructed by cut-and-cover or conventional tunneling methods. In order to overcome or eliminate these restrictions, a program to disseminate information on the latest advances in these tunneling systems is needed, which targets the utility owner, permit-granting agencies, and the designer. This information should include the parameters necessary to develop and manufacture the specialized materials, conduits, and transmission facilities needed to allow the utility owner to use the microtunneling systems with confidence. If the information is properly distributed to show the advantages of microtunneling, it is felt that the resulting social and economic pressures will effect changes to the legal and code restrictions.

CRITICAL AREAS REQUIRING CONTINUED RESEARCH AND DEVELOPMENT

As discussed earlier, the market for microtunneling is growing. The upward trend is most pronounced in older urban areas where land and surface disturbance result in the highest costs. The wider application of microtunneling techniques can be encouraged by technological advancements in several areas.

Guidance

Active guidance of the microtunneling machine (control of direction between the starting and finishing points of a drive based on the measured location of the excavating head) is currently common only at very shallow depths of small diameters, or in tunnels large enough for manned entry. The lack of active guidance limits the distance that straight pipe-jacking operations can undertake and virtually eliminates projects that would otherwise benefit from tunnel curvature. Passive guidance methods (directional control not linked to the actual position of the excavating head), such as for under river crossings, are successfully employed, but the process is not accurate enough for many purposes. "Misses" are frequent.

Mixed Face and Rock

Most of the mole-type machines, even so-called "crunching mole" types, can handle occasional cobbles only up to 30 percent of the diameter of the tunnel bore. Larger boulders jam or deflect the mole. In general, small moles utilize ripper-type teeth that can be destroyed when solid rock or large boulders are encountered. If the trend of microtunneling continues toward deeper tunnels, this limitation becomes more serious, since rock is more likely to be encountered. Cutters of the type that can resist impact and attack rock, and machine mucking systems that can digest larger rock chunks, are needed.

Remote Connections

Once the problem of accuracy in microtunneling is improved, remote connections are a feature needed to avoid the necessity for frequent shafts to provide service connections to the microtunneled utility. This requirement is particularly acute in the connection of sewer laterals into the main. Preferably this should be able to be done while the main is kept in service.

Obstruction Sensing

The ability to sense obstructions is a critical need. Cases where microtunneling activity has severed an existing service are common. Sensors on the tunneling devices may include sensors for microwave, magnetic, or sound signals or a change in drilling conditions. In addition to the sensors, automatic response control, and identification of the obstruction is required. Ideally, the warning signal would permit an actively guided unit to take avoidance action.

In addition to improved capabilities of the microtunneling equipment, improved methods of site investigation are needed in two principal areas:

- *Improved Geologic Definition for the Tunnel Route.* Because of the large distances traversed and the urban locations involved in most microtunneling projects, core sampling is seldom thorough. Usually, widely spaced core samples can provide only general geologic conditions. A technique needs to be developed that can follow the intended route and nondestructively (using geophysical sensing) characterize the route.
- *Utility Locator.* Simultaneously with identifying geological conditions, existing utility lines and pipes should be located. The type, size, and depth of the line should be identified along with its plan location. Development of successful techniques would help prevent the common occurrence of a severed utility line with the associated hazards and damage which result.

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