Current and Future Prospects for Microtunnelling

R.L. Sterling
Trenchless Technology Centre,
Louisiana Tech University,
P.O. Box 10348,
Ruston, LA 71272-0046, USA
Email: sterling@coes.latech.edu

ABSTRACT

Microtunnelling involves the use of sophisticated small diameter tunnel boring equipment that is remotely operated to install non-person-entry, small-diameter tunnels. The development of this equipment in the past 25 years allows pipe installation in difficult ground conditions and below the water table without the cost and disturbance of open cut excavation. Assessing the expected ground conditions, choosing the right equipment and materials, and planning for the unexpected are keys to success in such projects. Historically, the development of microtunnelling equipment and market has been strongly influenced by need for suitable projects and the development of microtunnelling techniques continues in both the equipment area and the prediction of machine-ground interaction. Future developments are likely to include more hybrid excavation systems incorporating aspects of horizontal directional drilling, microtunnelling, pipe bursting and pipe ramming according to the project circumstances.

Keywords: Microtunnelling, pipe jacking, utility tunneling, tunnel boring machine, small diameter tunneling, overview, development

1. INTRODUCTION

Microtunnelling is a trenchless technology for construction of pipelines to close tolerances for line and grade. Microtunnelling installations are typically for gravity sewers, although other specialized projects have been constructed using this method. The method was developed in the 1970s in Japan, refined in Germany and the United Kingdom, and was introduced into the United States in 1984. Since then over 157 miles of microtunnelling installations have been completed in the USA up to 1997, a large proportion of the microtunnelling work carried out in the USA was part of the City of Houston's efforts to upgrade their sewer system and eliminate sewer overflows. As this work has been completed, the overall growth of microtunnelling in the USA has slowed but its use in other locations across the country continues to increase.

There is still some discussion about a definition of microtunnelling, but it can be described as a remotely-controlled, guided, pipe-jacking process that provides continuous support to the excavation face. The guidance system usually consists of a laser mounted in the jacking pit as a reference with a target mounted inside the microtunnelling machine's articulated steering head. The microtunnelling process does not require personnel entry into the tunnel. The ability to control the stability of the excavation face by applying mechanical or fluid pressure to the face to balance groundwater and earth pressures is a key element of microtunnelling (Bennett et al. 1995).

The principal difference from conventional tunneling techniques is that the pipe acts as the ground support and is forced through the ground from the launching shaft in a pipe jacking operation. In tunneling, the lining is erected within the tail of the tunneling machine or within the tunnel itself and is not slid longitudinally through the ground.

2. MICROTUNNELLING SYSTEMS

Much of the discussion of microtunnelling systems given here is adapted and shortened from *Guidelines for Trenchless Technology* (Bennett et al. 1995) prepared by Bennett, Guice, Khan and Staheli.

The primary types of microtunnelling systems are auger and slurry, defined by the method of spoil removal. Earth pressure balance machines may also be used in larger diameters. These operating systems differ in their degree of control of ground conditions at the face. The slurry system is generally capable of more precise control. The slurry system can handle higher groundwater pressures and more unstable ground conditions than the auger machine, but at the disadvantage of added mechanical complexity and cost. In addition, production rates may be slightly lower for slurry machines. Auger machines have limitations on the length and diameter of installed pipelines, due to the power requirements for turning the auger and head. Earth pressure balance machines adjust the advance rate of the machine and the spoil removal rate to maintain the soil pressure necessary to provide support to the soil face being excavated.

All the microtunnelling systems consist of five independent subsystems:

- Mechanized excavation system
- Propulsion or jacking system
- Spoil removal system
- Guidance and control system
- Pipe lubrication system

The *mechanized excavation system* is the cutterhead mounted on the face of the microtunnel boring machine and is powered by electric or hydraulic motors located in the machine. The cutterhead must be able to deal with all the types of ground conditions and obstruction that are anticipated along the drive length since the face of most microtunnelling machines is not accessible as in conventional tunneling. A few microtunnelling machines that can be retrieved through the installed pipe have been built but they are not normally available in practice. Some newer machines allow the cutterhead to be retracted from the face slightly to aid in freeing a stuck cutterhead or to replace cutters in rock microtunnelling. Machines intended for use in soils may incorporate rock crushers in the heads to handle small boulders, and other obstructions, up to 30 percent of the diameter of the machine. The crushing mechanism is designed to reduce a boulder to particle sizes of 3/4 to 1 in., so that it can either be removed by an auger or by the slurry spoil removal system. Machines designed for rock excavation use pick, button or disk cutters to fragment the rock.

The microtunnelling machine is attached to the lead pipe of the pipe string to be installed. The *propulsion* for the microtunnelling machine comes from the pipe jacking operation in which lengths of pipe are added to the pipe string in the jacking/launching pit and then thrust into the ground. Jacking forces can be very high on large microtunnelling projects sometimes exceeding 1,000 tons. The jacking force required has two principal components: the force required to cut the ground and advance the cutter head while maintaining support to the tunnel face, and the force required to overcome the friction and adhesion along the pipe string. When drive lengths are long and jacking forces are expected to exceed the safe jacking capacity of the pipe, intermediate jacking stations may be installed within the pipe string. This is only possible for pipes of large enough diameter to allow their removal after installation.

The *spoil removal system* moves the loosened or fragmented material from the microtunnelling machine to the ground surface. In the slurry system, the spoil is mixed into the slurry in a chamber that is located behind the cutting head of the tunnel boring machine. It is hydraulically removed through the slurry discharge pipes installed inside the product pipe. This material is then discharged into a separation system where the spoil is removed and the slurry prepared to be reused in the process. The auger spoil removal system uses an independent auger system in an enclosed casing inside the product pipe for spoil removal. The spoil is augered to the drive shaft, collected in a skip and then hoisted to a surface. Water may be added to the spoil in the machine to facilitate spoil removal. However, one of the advantages of the auger system is that the spoil does not have to reach pumping consistency for removal. In an earth pressure balance machine, the spoil is released from the face chamber via a short pair of augers or a chamber with sequentially operated openings. In either case, the soil is transferred to normal atmospheric pressure at the back of the machine from where it can be transferred by conveyor or other means to the jacking pit.

The *guidance and control systems* for microtunnelling are very important since the system is remotely controlled and the process must guide the machine to close tolerances in line and grade as well as control the excavation and pipe jacking and spoil removal processes to maintain ground support. Directional guidance for the machine typically is provided by a laser mounted in the shaft and a target mounted within the machine. Spreading of the laser beam with distance and refraction of the laser beam due to heat generation within the machine and pipe can limit the distances that can be driven using a single laser setup. Machine corrections to line and grade are made using hydraulic jacks connecting the two articulated sections of the microtunnelling machine. Gyroscopic control systems are being introduced for machine guidance and have the advantage of being able to be used on curved alignments. Most aspects of the microtunnelling process can be controlled from the operator's cabin on the ground surface. A key issue is to prevent over or under removal of spoil compared to the rate of advance of the microtunnelling machine. Over removal of spoil can cause ground settlement and under removal of spoil can cause ground heave. To provide proper face support under difficult ground conditions, it is necessary to counter balance both the earth pressure and hydrostatic pressure in the soil. The earth pressure should be regulated to stay higher than the active earth pressure but lower than the passive earth pressure

The *pipe lubrication system* is used to reduce the friction of the pipe string as it is jacked through the ground. The microtunnelling machine typically has a larger diameter than the pipe being installed to provide an "overcut." This overcut allows room for steering corrections, reduces lateral pressures on the pipe string and allows lubricant muds to be injected at application points inside the machine or along the inside of the pipe. The lubricant can be either a bentonite or polymer-based material. Lubrication can substantially reduce the total thrust required to jack the pipe as is evidenced by the comparative data collected by Bennett (1999).

3. PIPE SELECTION AND DESIGN

The types of pipe or conduit that can be installed typically include concrete, centrifugally-cast-glass-fiber-reinforced-plastic (Hobas), steel, vitrified clay, polymer concrete and plastic-concrete composites. Pipes are usually designed to have a smooth exterior profile and to use gasketed joints that allow some relative angular displacement of adjacent pipe segments. The smooth exterior profile reduces frictional drag and the joint design allows for easier steering corrections without pipe leakage. Steel pipes have high axial load capacities and either have welded joints or a patented "Permalok" press-fit joint. These joints are fairly rigid and hence steering is more difficult. The controlling conditions for pipe design for microtunnelling typically are the axial jacking loads experienced during operation rather than the lateral loads due to depth of burial. The boring process in existing ground (as opposed to backfill compaction in a trench) and the overcut used greatly reduce the lateral pressure expected to act on the pipe. Tunnel lining design approaches are usually considered more appropriate than open cut pipe design approaches for these lateral loads. Axial jacking loads may be very high on long drives in difficult ground conditions and large safety factors are necessary when comparing the average pipe stress resulting from the jacking load to the compressive strength of the pipe material. Because of alignment correction during the microtunnelling operations, the pipes often have slight misalignments with the next section. Despite the use of packing materials between pipe sections, this can cause high localized stresses at locations within the circumference of the pipe near the joints.

4. DESIGN AND SITE PARAMETERS

The design, site, geotechnical, and construction parameters all can affect the cost effectiveness and success of a microtunnelling project. Some of the key parameters to be considered are:

- Length and diameter of drive: typical drive lengths are in the 100 m to 170 m (300 ft to 500 ft) range but drives of over 1000 m (3,000 ft) are possible in the larger person-entry diameters where axial pipe load capacities are large. Length of drive is determined by expected jacking forces, use of intermediate jacking stations, potential wear on cutters, guidance system, and cost/ability to place intermediate shafts. Long drives with small diameter microtunnelling machines are riskier than shorter drives.
- Straight versus curved alignments: straight alignments are recommended because of easier guidance, lower concentrations of jacking stresses in the pipe string, and simpler future maintenance. Curved alignments are unusual in the USA but are more common in Europe. Curved alignments allow longer drives with fewer shafts when following curved alignments of public rights-of-way.
- Depth of drive and water table depth: the depth of drive and its relationship to the water table can determine whether microtunnelling is preferred against open cut and other trenchless methods. It also determines the hydrostatic pressure that must be balanced at the machine face. High hydrostatic pressures require additional jacking forces to advance the machine against the pressure. Also, if the pressure is very high, measures may be needed to avoid the pipe string from being forced back into the jacking pit when new pipe sections are being added. The main impact on cost of microtunnelling due to depth is the increased cost of the shafts required. Shafts are a major cost item in a microtunnelling job. Shaft dimensions typically range from 2.4 to 6 m (8 to 20 ft) in length or diameter for pipe lengths of 1.2 to 3 m (4 to 10 ft). The goal is usually to use the minimum shaft size that will allow reasonable production rates and thereby minimize the cost associated with this component.
- Soil conditions and their variability: soil or rock type and variability of soil conditions determine the type of cutter head and machine to be used and the expected advance rate. A radical and unexpected change of ground conditions can prevent a drive from being completed and require hand tunneling or a rescue shaft to permit the job to be completed.
- Likelihood of obstructions or boulders: boulders or man-made obstructions also can prevent a drive from being completed and it is often difficult to adequately determine the risk of obstructions being in the path of the bore.
- Machine type: newer microtunnelling machines have additional features that allow increased and/or more reliable performance under a range of ground conditions and the different types of machines available (principally slurry and auger boring) have different characteristics that make them more suitable under different site and job conditions. Use of a machine already owned by a particular contractor may be advantageous from a cost point of view but the machine should be suitable for the job conditions.

- Cutter head design: the cutter head is usually selected by the contractor but the selection of the cutter head is dependent on expected soil conditions and thus is dependent on the geotechnical report. A cutter head that does not match the soil conditions will cause slow advance rates at best and be unable to advance at worst.
- Amount of overcut: the amount of overcut also is usually selected by the contractor but the engineer may choose to limit the amount of overcut when very small settlements are required. Major settlement problems usually are related to loss of control at the excavation face rather than the closing of the annular overcut volume. Large overcuts coupled with lubrication and high groundwater pressures may lessen the resistance against the pipe being pushed back into the shaft from the water pressure on the machine face.
- Pipe selection: the owner may select one particular pipe type or may allow the contractor to choose the pipe according to specified pipe characteristics. If the pipe cracks or fails during installation, repair options are very limited in non-person entry pipes. If the failed pipe is near the beginning of the pipe string, additional sections may be jacked until the failed pipe can be removed from the arrival pit.
- Lubrication mud selection: lubrication can lower jacking forces and reduce the risk of pipe damage on most microtunnelling jobs (Bennett 1998). It can be critical on long microtunnelling drives. If lubrication is considered critical to the success of a drive, then its use may be included in the contract documents and bid items.
- Slurry handling, separation and disposal: decisions on these items are typically made by the contractor but it is important that accurate soils information be provided to the contractor to properly design the system. Large amounts of fine material can be difficult to remove from the slurry and may require hydrocyclone separation systems.
- Size of jacking pit vs length of pipe sections: the size of the jacking pit determines the length of individual pipe sections that can be used. Larger pipe section lengths increase productivity but increase the shaft size and hence the surface disruption caused by the microtunnelling operation. If the contractor's working area is restricted as to location and/or size, then this must be clearly designated in the contract documents.
- Ability to sink a rescue shaft if necessary: if rescue shafts are impossible at any point along the drive, this needs to be known in advance and accounted for in the geotechnical investigation, the selection of the size and type of machine and in the contract documents.
- A highly-skilled crew of four to eight is typically used, and production rates are approximately (10 to 20 m/day) 30 to 60 ft/day for routine jobs, although rates of 65 m/day (200 ft/day) or higher have been achieved. Mobilization time typically ranges from three to eight days.

5. WHEN TO USE MICROTUNNELLING VERSUS OPEN CUT

Microtunnelling is a pipeline installation method with very different cost and surface disruption parameters from open cut trench installation. It also differs significantly in its applicability for pipeline projects from other trenchless installation methods such as horizontal directional drilling and simpler forms of pipe jacking installations involving open face excavation.

The direct costs of utility work include:

- Excavation and backfill
- Pipe and pipe laying
- Pavement reinstatement
- Temporary utility service diversions
- Traffic diversions and traffic control

The indirect/social costs of utility work include:

Traffic
- Traffic diversions and delays
- Increases in vehicle operating cost
- Loss of accessibility and parking spaces
- Delays to public transport

Environmental
- Increased noise
- Increased air pollution
- Increased construction mess
- Increased visual intrusion

Safety
- Decreased safety for motorists
- Decreased safety for pedestrians

Economics
- Loss of trade to local businesses
- Damage to other utilities
- Damage to street pavement
- Increased workload on other government agencies or utilities

In comparison to open cut excavation, microtunnelling costs are less dependent on depth than open cut and microtunnelling methods are less affected by weak saturated soil conditions that make both open cut work and other forms of pipe jacking methods either difficult or impractical. When pipe depths are large and especially in poor ground, microtunnelling will tend to have a direct cost advantage over open cut methods (Norgrove and O'Reilly 1990). This lessened dependence of cost on the pipe depth also can influence the overall design of a gravity pipe network allowing longer runs of gravity flow and fewer lift stations. This can significantly reduce the life cycle operating and maintenance cost for the system.

In comparison with other trenchless techniques, microtunnelling machines are more expensive to purchase and operate than most other trenchless excavation systems. This means that they will tend to be used when the other methods are not suitable or when the microtunnelling system has a significant advantage. The conditions that tend to favor microtunnelling use are:

- Installations deeper than 10-15 feet
- Need for precise control of line and grade
- Weak soils or running ground below the water table
- Environmental, traffic or business loss reasons to minimize surface disruption
- Sufficient project size to justify the mobilization of the microtunnelling equipment and crew

6. GEOTECHNICAL INVESTIGATION

In the case of microtunnelling, most projects are relatively small in overall cost compared to major tunnel projects. Since on typical projects, 1 to 5 percent of the total contract value is budgeted for the geotechnical investigation, the amount normally available to determine the expected conditions along the microtunnel alignment typically is inadequate. In addition, many microtunnelling jobs are changed from an open cut design as the difficulties of open cut excavation at the particular job site are better understood. In these conditions, the original site investigation may not have determined the right parameters or have been conducted to sufficient depth to be appropriate for a microtunnelling project.

Boreholes should be located at all shaft locations and at intermediate points not greater than 300 ft apart. Closer spacing of boreholes is appropriate in highly variable ground conditions, especially in mixed face conditions. Boreholes at shaft locations should be extended beyond the floor elevation by at least the maximum width of the shaft to allow evaluation of floor heave potential. Intermediate boreholes on the alignment should extend two tunnel diameters below the invert in case changes in design depth or grade are necessary.

Boreholes provide the most reliable indication of conditions to be encountered if they are located along the proposed centerline of the tunnel. However, some prefer to locate boreholes some distance off the centerline, to minimize the potential for loss of slurry through the borehole as the tunnel passes that location. If boreholes are located along the centerline, they must be properly abandoned, by grouting with a bentonite cement grout mixture, to eliminate this potential problem. Boreholes that are to be converted to piezometers or wells must be located off-line (Bennett et al. 1995).

The relative importance of individual characteristics will vary from project to project. Important site characteristics to be determined include:

- Soil type
- Groundwater (depth relative to the tunnel alignment)
- Obstructions

- Rock (cuttability and abrasiveness)
- Difficult ground conditions (boulders, running ground, squeezing soils, sticky clays that can clog the cutterheads, etc.)
- Contaminated groundwater or soil
- Existing utilities, building foundations, and environmentally sensitive features

The likelihood of buried objects, their nature and relative sizes, should be established by the site investigation. This task requires evaluation of information from a variety of sources including regional and site geology reports, geophysical surveys, borings, and test pits. Regional and site geology reports and land-use records help to establish the likelihood and nature of buried objects. Geophysical surveys, borings, and test pits add detail and serve to verify preliminary conclusions drawn from these sources.

7. GEOTECHNICAL PROBLEMS ENCOUNTERED

While microtunnelling has been successful on the majority of projects, there have also been a number of projects on which major problems and cost overruns have occurred. Most problems in microtunnelling relate to a lack of planning for the ground conditions encountered – either because of an inadequate site investigation or inadequate preparation for the conditions in terms of project layout, machine or pipe selection, and contractual provisions. Some specific examples are given below:

- Extremely soft ground providing inadequate vertical support to the microtunnelling machine. The machine tends to sink and the combination of the pipe string and steering correction available cannot keep the machine on grade. This problem has been solved by ground improvement methods (including creating strengthened soil columns) along the microtunnel alignment.
- Cobbles or boulders of too high a compressive strength to be crushed in the machine or too large to enter the machine.
- Hard rock inclusions or boulders in a very soft ground matrix. The soil may not provide the resistance to allow the cutting teeth or disks to properly fragment the rock.
- Changing from soil to rock layers inclined at low angles to the centerline of the tunnel. It may be difficult or impossible to hold the microtunnelling machine to line and grade.
- More abrasive rock than anticipated. The cutting teeth on the machine may become worn and ineffective prior to the end of the drive. At best, this will mean very slow progress. At worst, the drive may not be completed.

8. RECENT DEVELOPMENTS

Microtunnelling technology has not remained static. Continued equipment and material-related developments are occurring in the following areas (Nicholas & Furey 2000, Soltau 2000):

- Digital control, fault warnings and improved graphical displays.
- Improved hydraulic and electrical equipment providing higher power and torque to the cutting face for dealing with difficult ground.
- High pressure water jets used to clean the cutters and break up plastic clays.
- Improved rock cutters with discs adapted to the size, power and longevity requirements of microtunnelling machines. Cutters can also be changed on long drives in machines over 1800 mm outside diameter.
- Increased use of specialized polymers to improve the properties of slurries for the distinct functions of lubrication of the jacking pipe, breaking down of sticky clays for removal in the slurry pipes, and improved separation of the excavated material from the slurry at the surface.
- Higher power slurry pumps and use of slurry jets in slurry machines.
- Continued improvements in laser effectiveness in long drives and gyroscopic guidance systems for curved microtunnels.
- Continued improvements in the strength and suitability of specialized pipes for microtunnelling
- Development of hybrid systems incorporating aspects of horizontal directional drilling, microtunnelling and raise boring. These are particularly cost-effective in smaller diameter installations.

In the design and performance prediction area, the Japan Society for Trenchless Technology has continued to collect data on jacking loads for microtunnelling in a variety of ground conditions. In North America, the American Society of Civil Engineers in cooperation with the North American Society for Trenchless Technology is releasing early in 2002 a new standard for microtunnelling. Some other relevant publications are listed in the references and bibliography.

9. FUTURE DEVELOPMENTS

Future improvements in microtunnelling technology are expected to include:

- Improved abilities to reliably complete longer drives in difficult ground conditions – thus reducing shaft costs.
- An increase in the number of curved microtunnel drives and the use of gyroscopic guidance systems.
- An improved ability to sense ground conditions and obstacles ahead of the microtunnelling machine using ground penetrating radar, seismic or other appropriate techniques.
- Increasing use of hybrid excavation techniques as exemplified by the pilot tube method. This is expected to apply to both microtunnel-scale and large-scale excavation systems.

Other trenchless excavation techniques such as horizontal directional drilling and pipe ramming may encroach on parts of the traditional applications for microtunnelling. Microtunnelling, however, will itself continue to encroach on projects once carried out only by conventional shield or TBM tunneling.

10. CONCLUSIONS

Microtunnelling is a very effective method for installing pipelines of diameters from 150 mm (0.5 ft) to over 3 m (10 ft) with little disturbance to the surface. The method tends to become competitive in direct cost as the pipeline becomes deeper and the ground conditions poorer and is competitive in total cost when the costs of traffic congestion or surface environmental damage are high. In some cases, it may be the only feasible solution.

While most microtunnelling jobs are completed successfully, such a remotely-controlled, non-person entry technique is vulnerable to unforeseen conditions. This places a premium on an appropriate geotechnical investigation and requires that project design, contracting and construction decisions adequately address the risks that may be present.

Current and future technology developments will continue to increase the cost-effectiveness and reliability of microtunnelled installations.

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