Auger and Slurry Microtunneling Tests Under Controlled Ground Conditions

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Microtunneling tests using auger and slurry machines were performed at a test facility that was constructed by first excavating a trench 104 m (340 ft) long, 5 m (16 ft) wide, and 3 to 4 m (10 to 13 ft) deep into which six types of soils were placed and compacted in sections approximately 18 m (60 ft) long. The soil profiles included a lean silty clay (loess), a dry sand, highly plastic buckshot clay, wet sand, clay gravel, and silt. The interfaces between soil profiles were sloped to simulate mixed-face conditions and to provide challenges to ground control and alignment and grade control during these transitions. Moisture and density tests were performed to ensure uniformity. Horizontal inclinometers and settlement plates together with surface survey points provided data to evaluate settlement and heave along the test section. Penetration resistance was measured in each section of the completed test bed. Strain gauges were installed in eight of the centrifugally cast, fiberglass-reinforced polyester resin pipes 600 mm (24 in.) in diameter (supplied by Hobas Pipes USA) to measure strains in the pipe as it was being jacked into place. Steering jack loads, jacking thrust loads, and cutterhead torque were also measured during the drives. The results of these tests will be used together with other information to develop guidelines for conducting feasibility studies and selecting proper methods compatible with anticipated ground conditions and project requirements. Preliminary guidance for microtunneling and pipe jacking projects, including the effects of overcut and lubrication on jacking loads and ground deformations, is offered on the basis of test results and related studies.

The microtunneling test program is one of three main elements of the research project "Trenchless Construction: Evaluation of Methods and Materials To Install and Rehabilitate Underground Utilities." The other elements of this project include an evaluation and demonstration of horizontal directional drilling technology and pipeline rehabilitation systems. These elements of the research program have been described elsewhere (*1–4*). The research is a U.S. Army Corps of Engineers and industry cost-shared project funded under the Construction Productivity Advancement Research (CPAR) program. The laboratory partner is the U.S. Army Engineer Waterways Experiment Station (WES) Geotechnical Laboratory. The industry partner is Louisiana Tech University's Trenchless Technology Center. Industry participants are contributing more than half the total cost of this research. The objective of the CPAR program is to improve productivity in the U.S. construction industry.

The process of microtunneling is well understood in the United States and especially in Japan and Europe, where it originated and was refined and developed. However, the factors that govern successful performance or that can lead to catastrophe on microtunneling projects are not as clearly understood. This situation is especially critical in the United States, where this technology is just beginning to emerge. It is true that more than 83 km (50 mi) of microtunneling have been driven in the United States and there have been many successful projects. However, most of this experience has been gained in one metropolitan area in the southern United States, within a relatively narrow range of ground conditions. Microtunneling practice has evolved in this area to be a highly successful alternative to open trench construction when experienced, knowledgeable contractors, engineers, and owners are involved. As this technology spreads to other regions of the United States, some with very different ground conditions and design constraints, it is unclear how much of this experience can be directly transferred. The microtunneling research was intended to help bridge these knowledge and experience gaps.

The construction of the microtunneling test bed and the chronology of events during the tests of both the auger and slurry machines have been described in detail elsewhere (*5*) and are only summarized here. In this paper, the results of these tests and some of the implications for microtunneling are described. The final product of this element of the research program will be a set of guidelines based on the results of these tests, project case studies, and other information that owners and engineers can use to evaluate and select trenchless methods appropriate to project requirements and site conditions. Specific objectives of the microtunneling tests included the following:

- Development of reliable methods for predicting jacking loads for various ground conditions,
- Development of methods for predicting and controlling ground deformations associated with microtunneling, and
- Verification of alignment and grade control capabilities.

DEFINITION OF MICROTUNNELING

There is no universally accepted definition of microtunneling, but it can be described as a remotely controlled, guided, pipe-jacking process. The guidance system usually consists of a laser mounted in the jacking pit as a reference with a target mounted inside the microtunneling machine's articulated steering head. The microtunneling process does not require personnel entry. Since the same type of system can be used to install almost any size pipe from 250 mm (10 in.) to 3 m (10 ft) in diameter, no arbitrary size constraint should be placed on the definition. The process can be successfully used under a variety of ground conditions ranging from soft soils to rock, including mixed-face conditions and boulders, both above and below the water table.

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DESIGN AND CONSTRUCTION OF TEST BED

The design objectives for the experiment and test bed were to

1. Provide realistic but challenging ground conditions to test the limits of microtunneling capabilities (ground conditions were intended to be increasingly challenging from the drive pit to the end of the test bed);
2. Provide ground conditions that varied in a controlled fashion and minimized boundary effects so performance could be correlated with known ground conditions;
3. Allow measurements to be made for evaluation of machine-ground interaction, including cutterhead torque, jacking thrust, effects of lubricants on pipe loads, stresses, and strains, and ground settlement and heave; and
4. Allow evaluation of two types of microtunneling systems (auger and slurry systems) under the same ground conditions.

The microtunneling demonstrations and evaluations were performed during September and October 1992 at a specially constructed test facility built at WES in Vicksburg, Mississippi. Figures 1 and 2 show an end view and a profile view, respectively, of the test facility, which was constructed by first excavating a trench 104 m (340 ft) long, 5 m (16 ft) wide, and 3 to 4 m (10 to 13 ft) deep into which six types of soils were placed and compacted in sections approximately 18 m (60 ft) long. The various backfill materials were placed and compacted in thin lifts, and moisture and density tests were performed on all materials in each lift to ensure uniformity. The soil profiles included a lean silty clay (loess), a dry sand, highly plastic buckshot clay, wet sand, clay gravel, and silt. Select backfill properties are summarized in Table 1. As shown in Figure 2, the interfaces between soil profiles were sloped to simulate mixed-face conditions as the machines exited one zone and entered another and provided challenges to ground control and alignment and grade control during these transitions. Horizontal inclinometers and one level of settlement plates were installed 0.6 m (2 ft) above the crown of the centerline of each tunnel. A second level of settlement plates was installed 1.2 m (4 ft) above the crown. Additional backfill was then placed to provide a berm 1.2 m (4 ft) high over original ground level so that at least 2.4 m (8 ft) overburden was provided over the tunnels, for proper operation of the slurry microtunneling machine. A third level of settlement rods was then installed with the anchors approximately 15 cm (6 in.) from each planned tunnel springline. Figure 1 is an end view of the test bed showing the relative locations of all instrumentation. The settlement plates and rods and the horizontal inclinometers, together with surface survey points, provided data to evaluate settlement and heave along the test section. Penetration resistance was measured in each section of the completed test bed, and these values are summarized in Table 1. Strain gauges were installed in eight of the 600-mm (24-in.) ID Hobas jacking pipes to measure strains along the tunnel length and around the pipe circumference. Jacking loads generated in the drive pit are resisted by soil shear stresses along the pipe string and soil pressure against the face of the microtunneling machine. Consequently, the thrust at the face of the machine is only a fraction of the force generated by the jacks in the drive pit. The strain gauges were installed in the first two pipes that were to be installed behind the steering head for each tunnel, in a third pipe to be installed at approximately the midpoint of each drive, and in a fourth pipe to be installed near the end of each drive. This arrangement was intended to provide continuous strain data on a given pipe as it was pushed from the drive pit and to provide measurements of strain at key points between the drive pit and steering head. These data would allow evaluation of the pipe stresses and loads along the length of the tunnel and evaluation of the resistive soil shear stresses in the different soil profiles. In addition, the strain gauges were installed at three locations 120 degrees apart inside each of the instrumented pipes. This arrangement provided information about eccentric loads applied to the jacking pipe or those that might develop because of steering corrections. The multiple gauge locations also provided a measure of redundancy in case of failure of one or more gauges. This scheme was followed for both tunnel drives.

The gauges were installed in a full bridge circuit at each location using two active gauges to measure axial strains. The two gauges positioned to measure hoop strains in the bridge were mounted on "dummy blocks" isolated from the pipe with a bonding material that would not transmit strains to these gauges. This arrangement allowed net axial strains to be measured and accounted for temperature and cable length effects. The arrangement worked remarkably well, and excellent quality strain data were

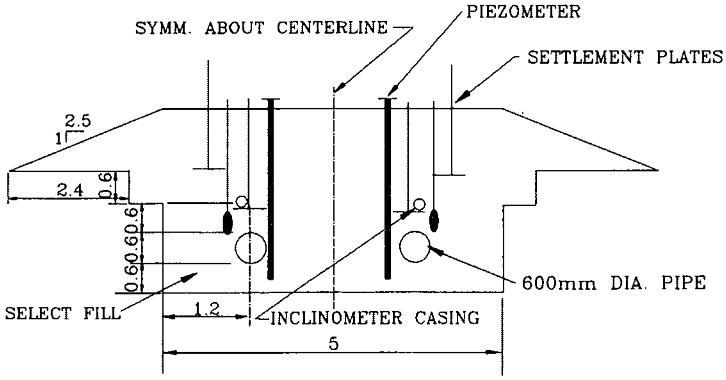


FIGURE 1 End view of test bed showing location of microtunnels and instrumentation.

obtained during both tunnel drives. Only 1 of the 24 gauge installations was destroyed during the microtunneling tests. Strain data were recorded continuously during each tunneling operation using a computer data acquisition system. Zero and check readings were made with a Vishay strain indicator.

MICROTUNNELING TESTS AND RESULTS

Auger Microtunneling Test

The auger microtunneling tests were conducted using a Soltau RVS 250A machine, furnished by American Microtunneling, South Daytona Beach, Florida, with an outer diameter of approximately 670 mm (26.3 in.) resulting in an overcut of 13 mm (0.5 in.) on the diameter. The reader is referred to the manufacturer's specifications for a full description of this machine. The control panel was set up adjacent to the drive shaft and fitted with a computerized data acquisition system to monitor and record machine performance parameters, including position of the steering head, torque, thrust, and steering jack pressures. This data acquisition system was set up to record data at 3-min intervals, keyed to time, date, and distance. The jacking frame was fitted with jacks of capacity 2225 kN (250 metric tonnes). The jacking pipe used was 3.05 m (10 ft) long, 600 mm (24 in.) inside diameter by 655 mm (25.8 in.) outside diameter standard Hobas GRP, rated at 1025-kN (115-U.S. ton) design load with a factor of safety of 2.5. Four of the jacking pipes were strain-gauged as discussed previously. Strain data were recorded continuously during the jacking operation. A separate computer data acquisition system read all strains 60 times per minute, and the average of the peak strains over that minute for each channel was recorded. This setup was intended to correlate peak jacking thrusts with strains while avoiding extraneous data from unloading cycles with the jacking system.

A plywood spacer ring was placed between the pushing plate and the pipe to distribute loads more evenly and minimize point loads. Plywood spacer rings were also placed between each pipe as the job progressed.

During the auger microtunneling trials, approximately 95 m (312 ft) of tunneling was performed over 12 days, which includes 11 days of tunnel boring, for an average of 8.5 m (28 ft) per day. Mobilization and installation required 6 working days. Demobilization and site cleanup required 3 working days. These production rates were affected by the research nature of this project and may not be typical of commercial projects.

Slurry Microtunneling Test

The slurry microtunneling tests were conducted using an Iseki Unclemole Z TCZ furnished by Iseki, Inc., San Diego, California, with an outer diameter of 660 mm (26.0 in.), resulting in an overcut of only 5 mm (0.2 in.) on the diameter. The reader is referred to manufacturer's specifications for a complete description of this machine. The control panel was set up adjacent to the drive shaft. Machine performance data were displayed on gauges on the control panel and recorded manually as each pipe was pushed. Recorded data included penetration rate, torque, thrust, slurry flow rates, and position of the steering head. The jacking frame was fitted with three stage Molemeister jacks of 1430 kN (150 metric tonnes) capacity. The jacking pipe was 2.44 m (8 ft) long, 600 mm (24 in.) inside diameter by 655 mm (25.8 in.) outside diameter standard Hobas GRP, rated at 1025 kN (115 U.S. tons) design load. Four of the pipes had strain gauges installed as described previously. As with the auger machine test, strain data were recorded continuously during the jacking operation.

During the slurry machine test, approximately 66 m (216 ft) of tunneling was performed over 21 days, including 17 days of actual tunneling, for an average of 4 m (13 ft) per day. Mobilization and installation required 6 working days, whereas demobilization and site cleanup required 4 working days. Again, these production rates may not be typical of commercial projects because of the research aspects involved.

TEST RESULTS

Alignment and Grade Control

The computerized data acquisition system used with the auger machine recorded and plotted the position of the steering head in

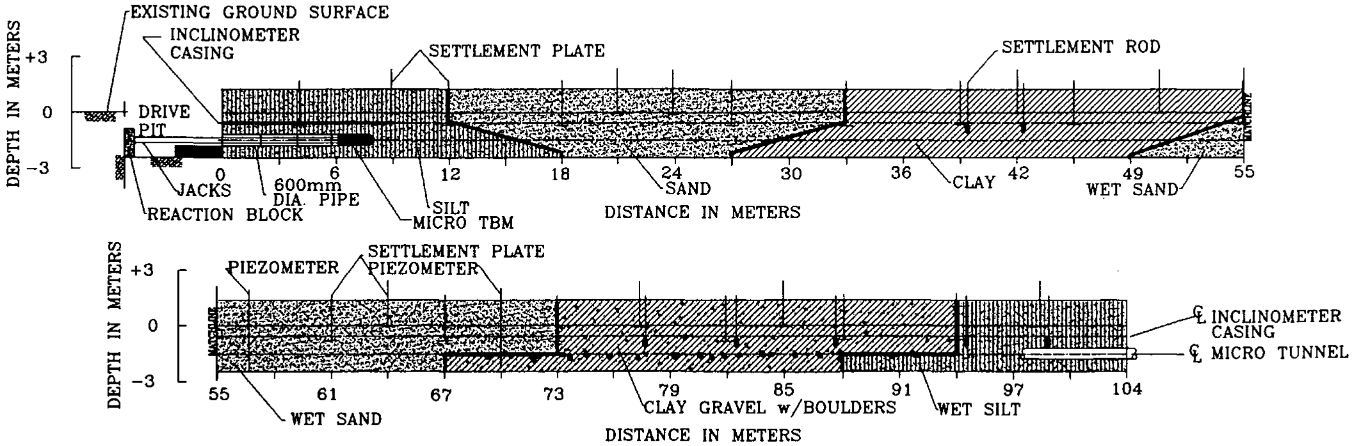


FIGURE 2 Profile along test bed showing location of microtunnels, instrumentation, and various zones of select backfill.

relation to the position of the laser at 3-min intervals during the drive. These measurements indicated that maximum horizontal and vertical deviations were less than 32 mm (1.25 in.). In fact, deviations were typically less than 12 mm ($^1/_2$ in.). The position of the steering head was surveyed at the end of the test and was within 12 mm ($^1/_2$ in.) of its intended location, both vertically and horizontally.

The slurry machine deviations from the laser beam to the actual position of the steering head were monitored continuously by closed circuit television. The positions were recorded manually at least twice as each pipe was jacked. The deviations from planned line and grade were less than 25 mm (1 in.) in all cases and typically less than 12 mm ($^1/_2$ in.). The position of the steering head, when excavated, was within 12 mm ($^1/_2$ in.) of its intended position, both vertically and horizontally.

Ground Movements

Ground movements were measured after each pipe was pushed during both the auger and slurry tunneling machine tests, using the settlement plates at three levels, the horizontal inclinometers 0.6 m (2 ft) above the crown of each tunnel, and surface survey points.

For the slurry machine test, measured ground movements were less than 6 mm ($^1/_4$ in.) throughout the 66-m (216-ft) drive, as measured at all levels, and were typically within the level of measurement precision. These insignificant ground movements were due in part to the very small overcut but primarily to the careful control of slurry face pressures to balance the earth pressure. For the auger machine test, ground heaves of 12 to 38 mm ($^1/_2$ to 1 $^1/_2$ in.) or more were measured at a few locations, and large settlements were observed in the flooded sand section as shown in Figure 3. The large settlements measured in the flooded sand (approximately 200 mm at Station 0+55 and approx. 145 mm at Station 0+70) during the auger machine tests were due primarily to outside events. The large settlement at Station 0+55 was due to a 1$^1/_2$-hr storm shutdown and high groundwater levels, which resulted in sand being carried into the face of the machine with uncontrolled inflowing water. This event could have been prevented by sealing off the auger casing in the jacking shaft, which is normal practice, to prevent water and sand from flowing through the auger casing, or by use of compressed air at the face to dry the soil and stabilize the wedge of sand between the face of the shield and the cutter disk. After this event, compressed air was used and satisfactory ground control was maintained. At Station 0+70 the compressor failed momentarily, and another large settlement occurred, approximately 0.6 m (2 ft) from a piezometer that had been installed the previous day by jetting the tip down to tunnel level. This installation practice created a loose saturated pocket of sand adjacent to the planned pipe location and was a major contributing factor in the subsequent ground movement.

The large apparent heave shown near Station 0+55 in Figure 3 is believed to be an upward buckling of the inclinometer casing and is not an actual ground heave. No surface heave was observed at this location. The smaller ground heaves observed may have been partly caused by pushing the machine too hard and too fast (i.e., the face pressure exceeded the passive earth pressure). However, shearing dilation of the dense sand and swelling in the buckshot clay may have contributed to the measured heaves.

In general, slurry microtunneling machines are capable of more precise ground control because of the ability to balance earth pressures with slurry face pressures. However, with proper auger machine setup and operation based on the manufacturer's recommendations, a skilled operator can usually maintain satisfactory ground control. The auger machine has recognized limitations with regard to ground control, especially if high groundwater levels and wet flowing sands or silts are encountered. When difficult ground conditions are expected, advice should be sought from machine manufacturers or other competent, experienced persons.

TABLE 1 Select Backfill Properties

Test Bed Section	USCS Soil Classification	Max. Density (kN/m^3)	Optimum Moisture Content (w%)	Liquid Limit (LL)	Plastic Limit (PL)	Plasticity Index (PI)	Standard Penetration Test Blow Counts (N)	Other Test Data and Comments
1	Silty Clay (CL)	17	19.1	39	25	14		
2	Sand, medium to fine, poorly graded (SP)	18 16	-	-	-	-	54 to 58	
3	Plastic Clay (CH)	15	23.2	66	22	44	7 to 15	UC = 141 to 154 kN/m^2 Su_{vane} = 60 to 73 kN/m^2 Swell Press. = 48 to 96 kN/m^2 Swell Volume = 7.9%
4	Sand, poorly graded (SP)	(<------------same as Section 2------------>)						
5	Gravelly Clayey Sand (SC)	20	9.2	20	12	8	28 to 56	Presence of gravel makes interpretation of SPT values problematic
6	Clayey Silt (ML)	(<------essentially same soil as Section 1------>)					9 to 17	

Jacking Loads and Pipe Performance

As mentioned, strains were continuously monitored at three locations in four pipes for each microtunneling machine test. The strain-gauged pipes included the first and second pipes behind the steering head, a third pipe near the middle of the drive, and the fourth pipe near the end of the drive. Excellent quality data were obtained to determine soil resistance at the face of the machine and along the sides of the pipe in each type of soil. A typical strain data plot is shown in Figure 4, with strain in microns measured in Pipe 23 plotted against time in minutes required to push Pipe 23 during the slurry machine tests. For both the auger and slurry machine tests, the strain measurements indicated that the jacking loads on the pipe were eccentric at the point of application in the jacking pit and elsewhere along the pipe string, especially in the first pipe behind the steering head. At this location, measured strains varied widely as steering corrections were made. The effects of steering corrections were also evident in the second pipe behind the steering head, though to a lesser extent. Misalignment between the pipe string and the jacking plate and flexibility in the jacking system contributed to the eccentric strains measured in the jacking pit. These strain data are being used with additional data to improve methods for estimating jacking loads under various ground conditions for the different types of machines evaluated and for the machine setup and operating practices.

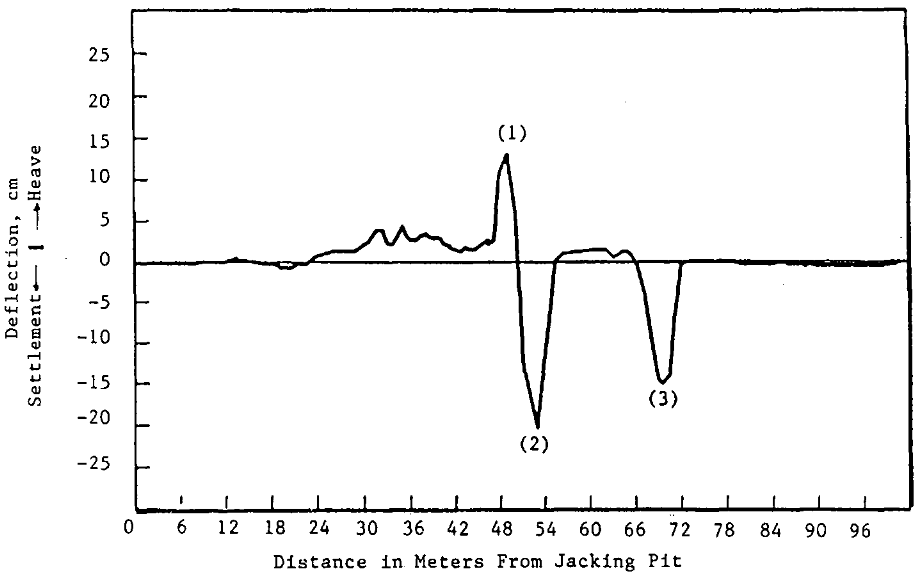
Jacking loads of more than 1070 kN (120 U.S. tons) were measured toward the end of the 95-m (312-ft) drive with the auger machine. The overcut was 6 mm ($^1/_4$ in.) on the radius, and no bentonite or other lubrication was used. These factors contributed to the relatively high jacking loads, though these loads were not considered abnormally high for the ground conditions by the machine manufacturer or operator.

The jacking loads exceeded 1160 kN (130 U.S. tons) toward the end of the 66-m (216-ft) drive with the slurry machine. The overcut was only 2.5 mm (0.1 in.) on the radius, and bentonite was used intermittently. These factors undoubtedly contributed to the high jacking loads, but time was also an important factor on both drives, especially with regard to the buckshot clay, which exhibited swelling tendencies. Heavy rainfalls during both tests may have also contributed to the high jacking loads by causing the density of the sands to increase further.

Predicted and actual jacking loads for both the auger and slurry machine tests are shown in Figure 5. The actual and predicted loads generally show good agreement. The largest discrepancies occurred in the transition or mixed-face zones between soil sections, which emphasizes the difficulty in reliably estimating shear stresses in mixed ground.

The jacking loads measured with the slurry machine were higher than with the auger machine throughout every soil section. This result was partly caused by the use of the much smaller overcut and may be partly due to the difference in operating principle of the slurry machine, especially in clay, where the soil must be mixed with slurry and squeezed through the cutterhead openings. The slurry machine test also required more time than the auger machine test. A complicating factor in this comparison is that no lubricant was used during the auger machine test, whereas bentonite lubricant was used intermittently during the slurry machine tests.

The high jacking loads and eccentric pipe stresses resulted in the pipe capacity being exceeded on four occasions during the



Notes: (1) Large apparent heave most likely upward buckling of inclinometer casing related to large adjacent settlement.
(2) Large settlement occurred after 1-1/2 hr. storm shutdown. Water carried sand into face & through auger casing. Used compressed air after this event for ground control in flooded sand.
(3) Large settlement occurred adjacent to piezometer jetted into place when air compressor momentarily quit. See text for further explanation of these events.

FIGURE 3 Vertical deflections of inclinometer casing 0.6 m above tunnel crown measured during auger microtunneling machine tests.

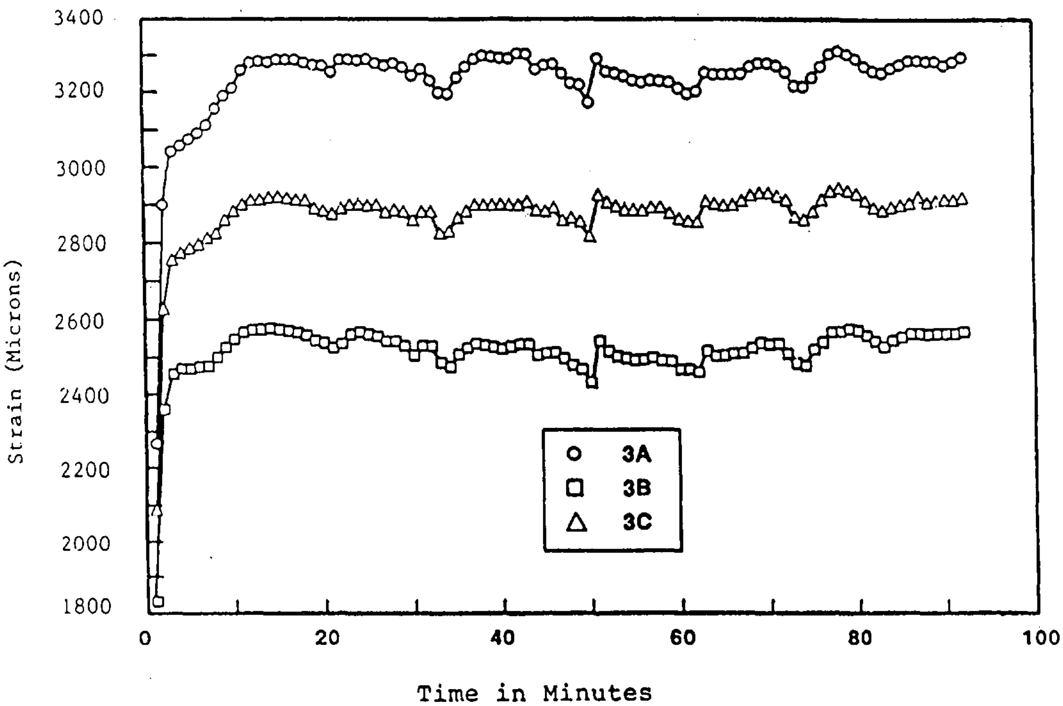


FIGURE 4 Strains in Pipe 23 versus time required to push Pipe 23 during slurry machine tests. Gauge locations A, B, and C correspond to 12, 8, and 4 o'clock, respectively.

auger machine tests and on eight occasions during the slurry machine tests.

Specimens were obtained from unfailed portions of the damaged pipe sections and tested in uniaxial compression to failure. Unconfined compressive strengths from three tests ranged from 9,220 to 10,100 psi. The average pipe stresses at failure during the field tests were 3,850 to 4,500 psi during the auger machine tests and 3,495 to 4,765 psi during the slurry machine tests.

The measured jacking loads, if distributed more uniformly, would not have caused pipe stresses high enough to result in pipe failure. However, because of the eccentric nature of the applied loads, as well as bending stresses and point loads that resulted

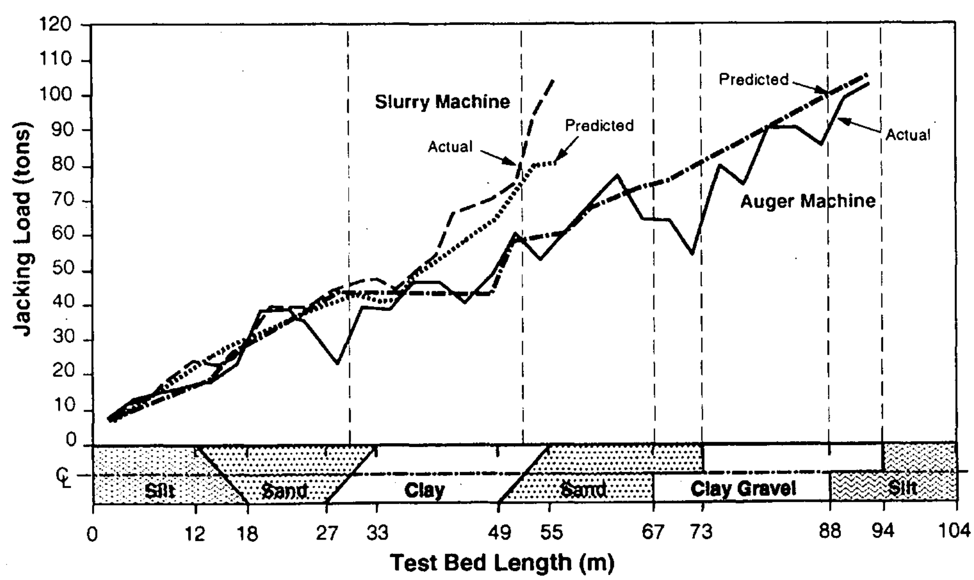


FIGURE 5 Actual and predicted jacking loads for auger and slurry microtunneling tests at WES.

from steering corrections and initial misalignment, the actual pipe stresses exceeded ultimate pipe capacity. The pipe was not defective, but a higher load capacity pipe should have been specified.

CONCLUSIONS AND RECOMMENDATIONS

The microtunneling tests provided a unique opportunity for an impartial documentation of performance of both auger and slurry systems in ground conditions that varied in a controlled manner, to provide increasing challenges from the beginning to the end of the test bed. Properties of the various soil profiles in the test bed were well documented, and the experiment was designed to allow correlations to be developed between the known ground conditions and machine performance. Even though some problems were encountered in the execution of the tests (*5*), a great deal was learned. Extensive measurements and observations were recorded and will form the basis for developing these correlations and predictive methods. Credible case history data will be sought to complement and verify these observations and correlations. Research and reliable case history data from Japan and Europe can provide valuable insights, and this information will be used to complement U.S. experience and these tests.

The results of the field evaluations underscore the need for better understanding of the interrelationships among machine characteristics, setup and operation, and the jacking loads and ground deformations that can be expected for given ground conditions. Some insights developed from the tests and complemented by review of other projects and conversations with microtunneling experts are given in this section.

It is unrealistic to assume that jacking loads are ever uniformly distributed around the pipe circumference and end-bearing area. Eccentric loads should be considered the norm, not the exception. All reasonable measures should be taken to keep maximum jacking loads within allowable levels and to minimize the eccentricity of the loads and resultant pipe stresses. These measures should include the following:

1. Ensure that pipes are straight and uniformly dimensioned, ends are square, and joints are designed to allow efficient load transfer from pipe to pipe.
2. Use a pipe joint spacer or packer that is highly compressible to aid in distributing axial stresses uniformly. The packer material should have uniform dimensions and should have a low Poisson ratio [i.e., the ratio of lateral (radial) to longitudinal (axial) strain] to minimize the development of tensile radial stresses at the joints. Research carried out at the University of Oxford (*6–8*) has shown the importance of selecting proper packer materials to reduce eccentric loads.
3. Ensure that the jacking frame, jacks, and steering head are correctly aligned along the planned line and grade and that the thrust block is square and true. The jacking frame must be robust to minimize flexibility under load, and the frame must be adequately supported so that it does not settle or shift during the jacking operations. The steering head and pipe must be supported in the jacking pit so that initial misalignment and settlement are minimal.
4. Make steering corrections gradually to minimize abrupt misalignment angles between adjacent pipes and resultant eccentric stresses. The University of Oxford research (*6–8*) and these tests have clearly established the adverse impact on pipe capacity of misalignment between adjacent pipes and resulting stress concentrations.
5. Provide adequate overcut space around the pipe to allow steering corrections to be made and to allow lubricant, when used, to more completely coat the pipe exterior. This measure also reduces the maximum expected jacking loads.

The amount of overcut between the cutterhead shield outside diameter and the pipe outside diameter can have an enormous influence on jacking loads, especially in relatively stable soils such as stiff clays. A smaller but still significant influence can be seen in dense sands. These soils, if given enough overcut space, dilate as the shield passes through the soil, reducing density and shear resistance along the trailing pipe string. This behavior is analogous to the behavior observed during direct shear tests on initially loose and initially dense sands. At constant normal loads, loose sands show a volume decrease during shear. Dense sands tend to dilate (i.e., show a volume increase) during shear under constant normal loads. If there is no annular space for this dilation to occur, normal loads increase and the shear resistance increases. The sand grains may be sheared through, which requires more jacking (shear) load than if the grains have sufficient space to dilate and roll over each other.

In addition, the beneficial effects of lubricants are enhanced with the use of a larger overcut because the lubricant more completely surrounds the pipe and promotes a stable opening, reducing frictional stresses along the pipe string. With a small overcut the lubricant cannot as easily coat the circumferential area of the pipe string and more mixing with the host soil occurs, as verified by excavations performed after the field tests. These excavations showed that there was no continuous annular ring of lubricant surrounding the pipe in any of the test bed soils. In some locations the soil to pipe interface was dry. In others (e.g., sands) the lubricant had migrated and mixed with the soil. These observations may also indicate the need for more than one lubricant injection point on the circumference of the tail shield portion of the steering head.

Typically, overcut ranges from approximately 6 to 12 mm ($^1/_4$ to $^1/_2$ in.) on the radius for pipes of diameter 750 mm (30 in.) or less. The concern usually expressed with using a large overcut [say 25 mm (1 in.) on the radius] has been that surface settlements may be unacceptably large. However, analytical studies and comparisons with studies of settlements around larger-diameter soft ground tunnels (*9–13*) suggest that large settlements should not be an undue concern for any reasonable amount of overcut as long as ground conditions are well defined, sound operating principles are followed, and the machine is set up properly. This is especially true for deeper installations and smaller-diameter pipes. The general relationships among surface settlement, pipe diameter, and depth are shown in Figure 6, which is intended to show general trends only. Actual settlements would depend on ground conditions, stabilization measures, and other factors. Indeed, catastrophic settlements almost always can be traced to improper machine setup or operation or unexpected ground conditions coupled with the inability to quickly implement corrective actions, rather than to amount of overcut.

A problem experienced in the slurry machine tests that may have occurred as a result of using a very small overcut is that some of the coupling bells or sleeves that seal adjoining pipes were damaged or destroyed, compromising the watertightness of the installation. This problem may be minimized by ensuring that pipe sleeves are flush (i.e., no protrusions exist) and through the use of a more robust sleeve design. At the very least, if the contractor plans to use a small overcut [less than 6 mm ($^1/_4$ in.) on the radius], the pipe manufacturer or supplier should be made aware of this intent, because more care may be required in installing the sleeves to avoid protrusions and a more robust pipe or coupling may be required. This problem was not observed with the auger machine that used a 6-mm ($^1/_4$-in.) overcut on the radius.

Finally, steering corrections can be more easily accomplished when a reasonable amount of overcut or annular space is allowed for articulating the steering head, especially in hard ground or rock.

In the light of these observations, an overcut of less than 12 mm ($^1/_2$ in.) on the radius is not generally recommended. However, the selection of proper overcut should take into consideration pipe diameter, straightness and roundness, manufacturing tolerances on these characteristics, the design jacking load capacity, depth and length of the installation, ground conditions, and allowable ground movements as well as machine characteristics and steering requirements. For example, larger overcut is usually required for hard ground or rock for proper steering. Larger overcuts are also required for larger-diameter pipe.

The use of pipe lubricants is generally recommended. The lubricants should be injected continuously from the very beginning of the job. If use of lubricants is delayed until jacking loads have escalated to dangerous levels, it is usually too late to obtain any meaningful benefit. The inconvenience of this additional operation is offset in most cases by the reduction in jacking loads and reduction of risk of damage to the installed pipe string.

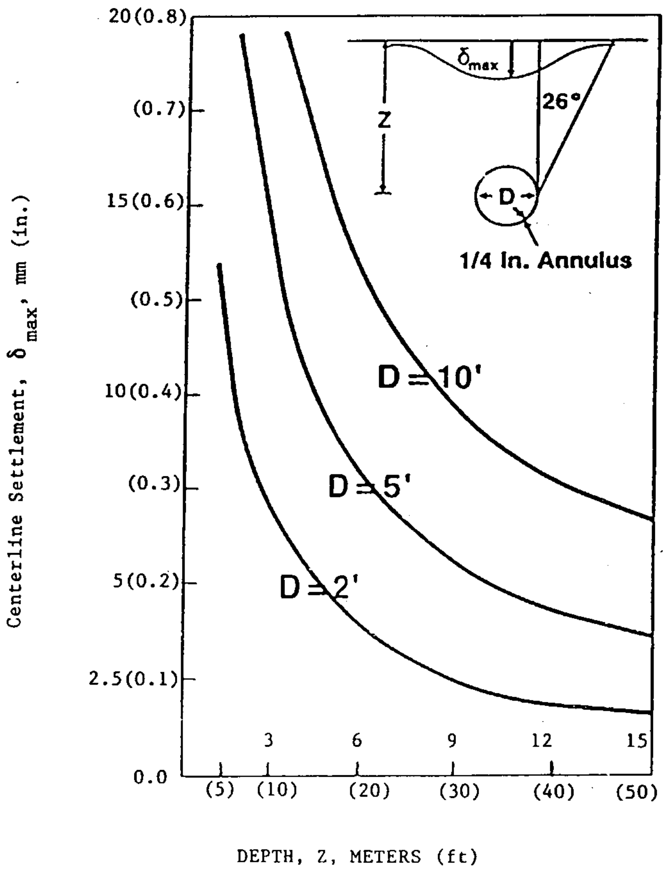


FIGURE 6 Estimated settlement versus depth for various diameter tunnels. Figure shows only general trends. Actual settlements would depend on ground conditions, stabilization measures, and other factors.

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