# Comparative Performance Evaluation of Tele-Operated Pipe Laying

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# Comparative Performance Evaluation of Tele-Operated Pipe Laying

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**Abstract:** Excavation, in particular, trenching, presents a hazardous working environment for workers. Many deadly accidents still occur even though the Occupational Safety and Health Administration has increased its training for safe trenching. The work presented in this paper originated with the belief that the best approach to remedy this problem is technology. Its premise is the need to remove the workers from this deadly trap and replace them with a mechanical device capable of doing the work necessary to lay pipes accurately. Presented is the result of a comparative field evaluation designed to prove that such a technology is not only technically feasible, but also cost-effective. For this purpose, a tele-operated pipe manipulator was built, capable of being easily attached to an excavator bucket and controllable from the safety of an operator cabin. The new technology was subsequently evaluated during field tests using both qualitative and quantitative performance criteria. Data from the study clearly demonstrate that this technological intervention not only works as intended, but also promises to reduce the cost of installing pipes, especially with increasing trench depths.

## Introduction

For a variety of reasons, construction safety has received more and more attention over the past few decades. Nevertheless, the construction industry in 1997 accounted for 1,137 deaths according to the Bureau of Labor Statistics (1999). This number equals 18% of the total fatalities from all industries and indicates that construction has the highest number of fatalities, as shown in Fig. 1. Another source shows that the construction industry employed approximately 5% of the industrial workforce, but generally accounted for nearly 20% of all accidental deaths (National Safety Council 1997).

One way to prevent construction accidents is to provide a safe work environment and to establish safe work procedures. Despite this effort, an analysis by the National Institute for Occupational Safety and Health (NIOSH) (1995) of workers' compensation claims for 1976–1981 shows that excavation cave-ins were the cause of about 1,000 work-related injuries each year. Of these injuries, 140 resulted in permanent disability, and 75 in death.

According to a report published by the Federal Highway Administration (FHWA) (1995), it is not surprising that trench excavation and pipe laying have been listed as one of the most impor-

tant opportunities for utilizing advanced technologies. The report was the result of an extensive study that included two workshops; site visits of automation experts, and a life-cycle cost-benefit analysis. Respondents of a survey rated ''the impact of improved safety in trenching and pipe laying operations'' (FHWA 1995) as the most important of six technologies proposed by a panel of experts who had investigated the needs and potentials of advanced technologies in highway construction and maintenance.

## Pipe Installation As Process

A trench is defined as a narrow (in relation to its length) excavation made below the surface of the ground (U.S. Department of Labor 1989). Current methods of trench excavation and pipe laying involve construction workers excavating trenches to the required width and depth using surveying methods and approximation to control depth and grade.

Due to its operational flexibility, the backhoe excavator is one of the most commonly used pieces of equipment for excavation and pipe. Since equipment operators are limited in what they can see and do with the controls available, they have to depend on additional helpers to provide visual as well as physical guidance.

The process of a traditional pipe laying operation consists of a sequence of tasks needed to meet the installation requirements presented in Fig. 2; they are briefly reviewed in the following section.

### Excavation

If no special advance preparations are required (e.g., sheet piling), the process commonly starts with a backhoe excavator digging a segment of the trench. The width of the trench depends on the pipe diameter, type of backfill material, and compaction method used; the depth of the trench depends on the pipe diameter and local regulations [e.g., the city of Raleigh, N.C. requires that the top of the pipe be at least 0.91 m (3 ft) below the grade].

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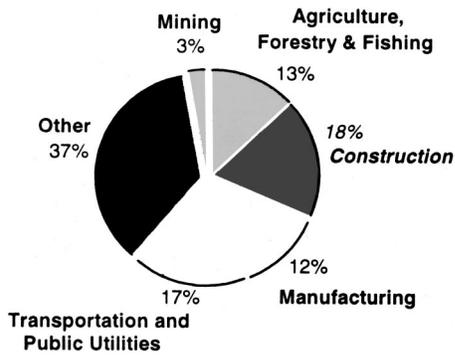
**Fig. 1.** Distribution of industrial fatalities in United States (1997)



**Fig. 3.** Slope and trench box as protective systems

### Establishment of Safe Environment

Before a person is allowed to enter the trench, an appropriate protective environment has to be established. Commonly used methods include (1) the use of a trench box; (2) sloping of the walls; (3) installation of a shoring system; or (4) a combination of these methods.

### Preparation of Bedding

A firm foundation at the bottom of the trench has to be established. For this purpose, the trench bottom is commonly slightly overexcavated and filled in with a special bedding material. The main purpose of bedding is to distribute the resistive load around the bottom circumference of the pipe in order to reduce the point load. Materials that provide the necessary firm contact between the bed and the pipe include crushed rock, gravel, or even sand. For smaller concrete pipes, "bell holes" have to be dug at the end of the pipe to avoid point loading on the obtruding ring of the bell. In a most common scenario, the lowering, placing, and spreading of the bedding material are done with the backhoe bucket.

### Pipe Placement

This task consists of lowering, aligning, and jointing of a new pipe element. With the help of slings or cables, one new piece of pipe is connected to the backhoe bucket and lowered into the trench. A line-and-grade laser provides the "invisible" survey points for the pipe layers to achieve proper alignment, before the pipe is jointed with the already installed pipe.
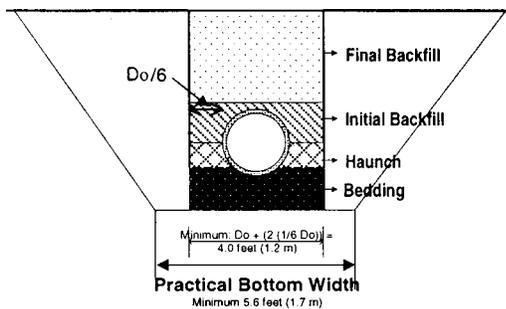


**Fig. 2.** Standard installation of 0.94 m (36 in.) pipe (American Concrete Pipe Association 1995)
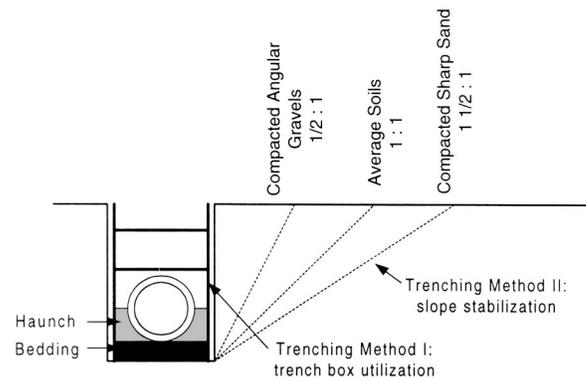
### Haunching of Pipe

The haunch, created by careful backfill and compaction, provides the main support for the pipe in the long run. The minimum width of a haunch area is 1/6 of the outer diameter of the pipe at each side, as shown in Fig. 2. Thus, the minimum trench width can be established using the following formula:

$$W_{min} = D_o + (2*1/6*D_o) \qquad (1)$$

where $D_o$ = outer diameter; and $W_{min}$ = minimum trench width.

However, in practice, a wider trench is commonly dug in order to provide sufficient "elbowroom" for the pipe layers and helpers.

### Backfilling

Backfilling is divided into initial and final backfill. The initial backfill covers the pipe and haunch to up to 0.3 m (12 in.) and is followed by the final backfill.

## Important Considerations

Pipe installations, large or small, made of concrete, steel, plastic, or clay, require a special engineering expertise, a unique set of tools, and a skilled work crew. The following section discusses some of the important matters of concern.

### Technologies to Protect Against Cave-ins

As mentioned earlier, several approaches for creating a safe work environment have been developed over time. Fig. 3 presents two typical examples—the trench box and sloping of the trench walls. The American Concrete Pipe Association (1995) suggests the use of slope ratios that are linked to key soil characteristics. As depicted in Fig. 3, loose soil (e.g., compacted sharp sand) requires a slighter slope angle than stiff soil (compacted angular gravels). It implies that the loose soil requires more excavation than stiff soil in order to achieve a stable trench wall.

Fig. 4 presents a flowchart, adopted from the Occupational Safety and Health Administration (OSHA), describing a method for selecting the appropriate protective system, depending upon soil conditions assessed by an experienced engineer. A protective system is recommended when working in any unstable soils, but is required for trenching deeper than 1.5 m (5 ft). For trenches deeper than 6.0 m (20 ft), the protective system has to be designed by a registered professional engineer. Simple slopes and
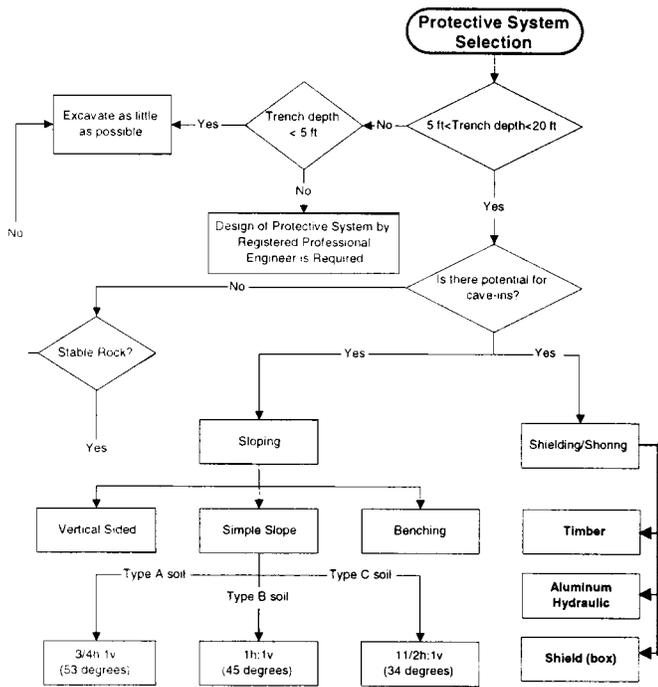
**Fig. 4.** Flowchart for protective system selection (OSHA)



**Fig. 5.** Design of Prototype 2

benching are applicable to cohesive soils only. The more involved shielding or shoring systems include timber/steel structures, sheet piles, and flexible or fixed trench boxes.

### Pipe Jointing

The most common method for connecting concrete pipes is the use of compression joints, where male and female ends are jointed together. Joint sealants and joint fillers such as internal rubber gaskets, mastic, mortar, or external rubber bands ensure leak-free linkages. It is a general practice to face the bell end of the pipe in the direction of the open trench in order to prevent the bedding material from being trapped between the two pipe ends while jointing (American Concrete Pipe Association 1995).

### Backfilling and Compacting

As mentioned earlier, backfilling is normally divided into two stages—initial and final backfill. Proper compaction prevents settlement of the backfill, surface, and the pipe itself. Steel wheel rollers for coarse aggregates and sheep-foot rollers for granular soils are fitting combinations. For years, several companies have offered compactors that can be remotely operated via radio control.

## Protection through Risk Avoidance

Even though OSHA has stepped up its efforts to train construction personnel in the ''science'' of safe trenching, trench cave-in accidents still occur, causing fatalities or serious injuries to workers. Accidents mainly occur because of ignored safety regulations/ standards or improper installation of protective systems. This paper offers an alternative approach—namely, the elimination of the risk to humans. The Construction Automation and Robotics Laboratory at North Carolina State University has developed a
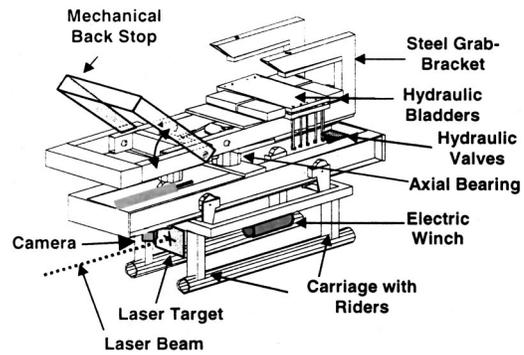
tele-operated pipe manipulator prototype, labeled PipeMan, consisting of a mechanical pipe laying device and a control system. With the intention to make such a system a viable economic alternative to the traditional methods, it was designed as an attachment to the backhoe excavator, rather than as a stand-alone device. The following section will discuss the key features of this technology, leading into a discussion of the results of a field test.

## Tele-Operated Pipe Manipulator (PipeMan)

The manipulation of large concrete pipes inside a narrow trench requires several important capabilities. First, the hardware has to be very robust and heavy-duty, since such pipes are generally heavy. Second, the O-ring compression joints require a linear insertion of the new pipe section into the bell of the previously laid pipe. Third, proper laying of pipes to meet line and grade requirements makes it necessary to utilize a beam laser. Fourth, a vision system has to be installed in order for the operator to be able to monitor his/her operation. Fifth, a release mechanism for the pipe has to be remotely controllable.

To meet the required capabilities mentioned previously, the manipulator was equipped with two degrees of freedom. One was a rotational joint, capable of rotating the pipe horizontally. The other was a carriage that allowed the pipes to be linearly jointed together. The hardware that supports such motions consists of a heavy-duty roller bearing and a linear track supporting a carriage with four rollers and a hydraulic cylinder, which provided the linear actuation. Each pipe segment is held by one or several cables powered by an electric winch mounted on the carriage (Fig. 5). A mechanical backstop powered by a hydraulic actuator and a chain secures the manipulator from sliding off the excavator bucket.

The first prototype, discussed by Huang and Bernold (1997), was used as the platform to add new features that improved ease of use, the control interface, and reliability based on the lessons learned from the first prototype. For example, it was found that it was very cumbersome to securely attach the manipulator to the bucket of the backhoe (Lee et al. 1999). As a consequence, the clearance provided by the forks to grab the manipulator with the bucket was increased to 27.9 cm (11 in.) from the original 15.2 cm (6 in.) To compensate for it, hydraulic bladders were installed, leading to a clamping effect that prevents slippage. The basic function of the bladder system is to introduce hydraulic fluid into the unit through the bladder intake, causing the bladders to inflate, which clamps the manipulator to the bucket. As shown in Fig. 5, an additional safety mechanism, the mechanical backstop, was also used to secure the device to the bucket. In total, PipeMan has
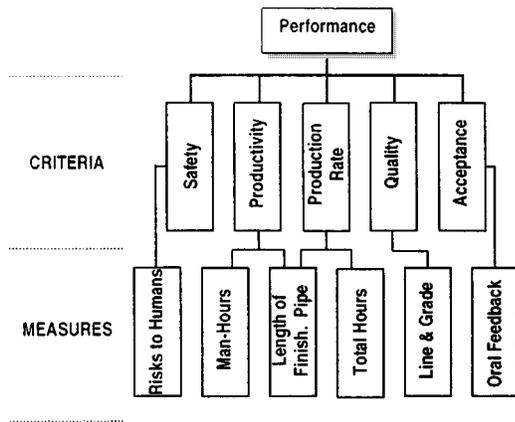
**Fig. 6.** Performance criteria and measures for assessment

five different actuation functions: (1) rotation of the pipe $\pm 100°$; (2) a mechanical backstop to lock the manipulator to the bucket; (3) a linear actuator to insert the bell of the pipe into the spigot of the already laid pipe; (4) hydraulic bladders to secure the bucket; and (5) a cable winch to secure the pipe to the manipulator.

## Framework for Collecting Field Data

According to Oglesby et al. (1989), the word "performance" encompasses four main criteria—(1) safety; (2) timeliness; (3) quality; and (4) productivity. While safety can be defined as accident-free including near misses, timeliness means both "being on schedule" and "everything is on hand when needed." Quality stipulates that a facility and all of its elements meet the specified requirements and perform in a manner that satisfies the owner's needs. Finally, productivity measures performance in terms of total or unit cost. For the purpose of this study, Oglesby's four performance criteria were slightly extended. Fig. 6 presents hierarchically all criteria that were found most relevant for the assessment of the performance of the new pipe-laying technology in the field, namely (1) safety, (2) quality, (3) production rate, (4) productivity, and (5) operators' responses.

## Comparative Field Test

A comparative field test was conducted on a jobsite at the East Park Industrial Subdivision in Raleigh. The comparative experiment included two different ways of laying the pipes, via (1) the traditional method; and (2) manipulator utilization. Site conditions including soil, trench width and depth, pipes, crew members, and weather were the same.

### Test Procedure

The crew members laid concrete pipes in the traditional manner one day, and the manipulator was used to do the same tasks the other day. The soil condition of the jobsite was sandy clay, and a concrete pipe of 0.9 m (36 in.) diameter and 2.4 m (8 ft) long was used as a material. The trench was 1.8 m (6 ft) deep, and a benching method was used as a protective system. A CAT 330 L excavator was used to excavate the trench.

First, the traditional process of laying pipes was observed. The crew of five consisted of one foreman functioning as the excava-
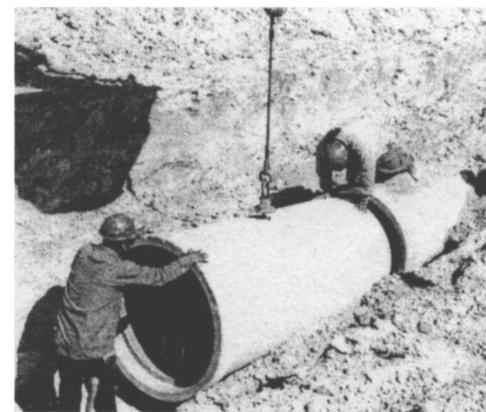


**Fig. 7.** Process of traditional pipe laying: (a) lowering pipe with hoist cable; (b) lining up guided by laser; (c) jointing with help of backhoe bucket

tor operator, two pipe layers, and two helpers. Fig. 7 presents the sequence of the traditional pipe laying process, consisting of moving a pipe into the trench using a hoist cable connected to the excavator bucket [Fig. 7(a)], aligning the pipe element to the proper line and grade [Fig. 7(b)], and jointing of the new pipe section with the bell of the previously installed element, always ensuring the proper line and grade [Fig. 7(c)].

Fig. 8 gives an idea about the situation when the same crew laid the same size pipes, in the same site, and using the same trench depth. This process sequence contains the following basic
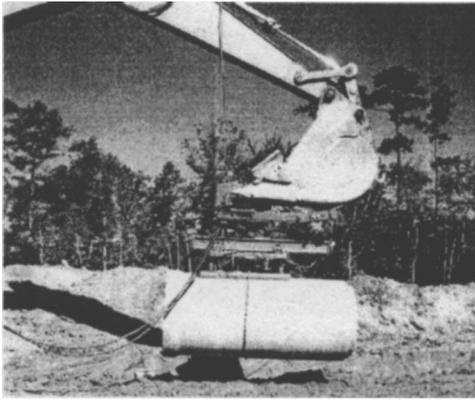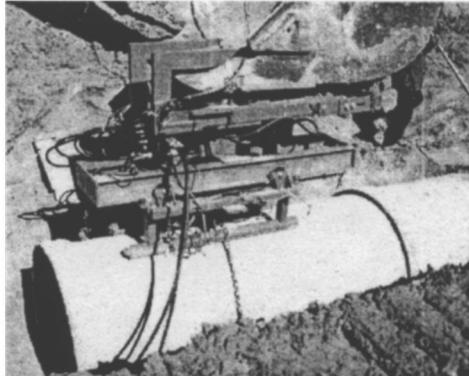
**Fig. 8.** Process of tele-robotic pipe laying: (a) transporting pipe; (b) lining up controlled by operator; (c) jointing by pushing carriage forward



**Fig. 9.** Completion of experimental field test

components: excavator/manipulator hoists one pipe element into the trench [Fig. 8(a)], operator aligns the segment guided by a beam laser and supported by two video cameras [Fig. 8(b)], and jointing, by pressing the male end linearly into the bell of the previous pipe [Fig. 8(c)]. Fig. 9 portrays the situation at the completion of the field test. Eight concrete pipe elements of 2.64 m (8 ft) were successfully laid using PipeMan. The following section will present the results of the observations that were made during the tests.

### Data Collection and Preliminary Analysis

Table 1 charts the ''stop-watched'' cycle times of laying pipes in the traditional method. Because the first pipe served as a ''starter

pipe,'' Cycle 1 was not included in calculating the mean cycle time of 6.0 min and the mean durations for the individual tasks of excavating, pipe laying, and initial backfill of 4.8, 2.2, and 2.0 min, respectively. As indicated, slightly more than half of the cycle time (53%) was spent excavating and preparing the bottom of the trench, while the actual laying of the pipe took the experienced five-member crew a mere 2.2 min. It is also apparent that backfill and compaction would have added significantly to the total time.

**Table 1.** Cycle Times for Traditional Pipe Laying (Minutes)

| Cycle | Excavating | Pipe laying | Initial backfill | Total |
|---|---|---|---|---|
| 1[a] | 6.0 | 3.2 | 2.7 | 11.9 |
| 2 | 6.0 | 2.5 | 1.0 | 9.5 |
| 3 | 4.5 | 3.0 | 2.0 | 9.5 |
| 4 | 5.3 | 2.8 | 2.4 | 10.5 |
| 5 | 5.0 | 1.3 | 3.2 | 9.5 |
| 6 | 4.0 | 2.3 | 2.2 | 8.5 |
| 7 | 5.0 | 1.5 | 1.8 | 8.3 |
| 8 | 3.5 | 2.2 | 1.8 | 7.5 |
| 9 | 5.3 | 2.2 | 1.7 | 9.2 |
| [Mean] | 4.8 | 2.2 | 2.0 | 9.0 |
| [Standard deviation] | 0.8 | 0.6 | 0.6 | 0.9 |
| [Confidence interval][b] | ±0.55 | ±0.41 | ±0.44 | ±0.64 |
| [Distribution] | 53% | 25% | 22% | 100% |

Note: Excavating=excavating trench, smoothing surface, and checking grade. Pipe laying=connecting the pipe to the excavator using a hoist cable, laying and jointing the pipe with final alignment, releasing a hoist cable from pipe, and disconnecting a hoist cable from excavator. Initial backfilling=covering up to 0.3 m (1 ft) above the top of the pipe with excavated soils.

[a]Cycle 1 is not included in calculating the mean.

[b]Confidence interval from a mean at a 95% confidence level.

**Table 2.** Cycle Times for Tele-robotic Operation (Minutes)

| Cycle | Connecting manipulator | Chaining and lowering | Lining and jointing[a] | Disconnecting[b] | Total |
|---|---|---|---|---|---|
| 1 | — | — | — | — | — |
| 2 | — | — | — | — | — |
| 3 | — | — | — | — | — |
| 4 | 3.0 | 4.3 | 3.5 | 3.5 | 14.3 |
| 5 | 3.0 | 3.0 | 3.0 | 3.0 | 12.0 |
| 6 | 2.0 | 3.0 | 3.0 | 3.0 | 11.0 |
| 7 | 1.5 | 2.5 | 2.3 | 2.5 | 8.8 |
| 8 | 1.5 | 2.5 | 2.3 | 2.5 | 8.8 |
| [Mean] | 1.7 | 2.7 | 2.5 | 2.7 | 9.6 |
| [Standard deviation] | 0.3 | 0.3 | 0.4 | 0.3 | 1.3 |
| [Confidence interval][c] | ±0.34 | ±0.34 | ±0.45 | ±0.34 | — |
| [Distribution] | 17% | 28% | 27% | 28% | 100% |

Note: Cycle 1=training and practice; cycle 2=solving problems with broken winch; cycle 3=training and practice; cycles 4–8=pipes laid by crew alone.
[a]Lining up the pipe, jointing pipes with accurate grade and alignment, and releasing the chain.
[b]Swinging manipulator back to the ground, disconnecting the chain and cables, and tying the cables to the arm of the excavator.
[c]Confidence interval from a mean at a 95% confidence level.

Given the fact that the contractor decided to excavate the same safe trench for the remotely controlled operation (Fig. 9), the observations of the second day of field tests focused on the detailed evaluation of the pipe laying process itself. Of the eight pieces of concrete pipes laid using the system, only the durations for the last five were measured, since the first three pipes were needed to train and test system performance (e.g., substitution of the winch with chain.) As expected, the learning effect of the crew was extremely high, but leveled out after only three trials. Thus, the mean times shown in Table 2 were calculated based on the observations from Cycles 6–8. The cycle times for excavation and backfilling are not considered because they are the same as those in the traditional method. Table 3 contains the cycle time analysis in minutes (observed versus projected).

According to Tables 1 and 2, the mean cycle time of 9.6 min for pipe laying with PipeMan turned out to be much higher than the 2.2 min for the traditional method. As indicated in the two tables, the time spent on connecting and disconnecting the manipulator during each cycle contributes the major portion of the time disparity. The mean time for connecting the manipulator to the excavator bucket was 1.7 min, while the mean duration for chaining the pipe to the manipulator and swinging it into the trench was measured as 2.7 min.

## Qualitative Performance Evaluation

To assess performance, qualitative data that were collected during the field test were summarized. Technical performance of the new

**Table 3.** Cycle Time Analysis: Observed versus Projected (Minutes)

| Tasks | Observed (mean) | Projected (after modifications) |
|---|---|---|
| Connecting manipulator to excavator bucket | 1.7 | 0.7 |
| Chaining pipe to manipulator, hoisting pipe into trench | 3.0 | 1.0 |
| Lining, jointing, removing chain, back-cycling | 2.2 | 1.2 |
| Disconnecting manipulator | 2.7 | 0.7 |
| [Total] | 9.6 | 3.6 |

system was assessed in terms of (1) overall performance, (2) technical problems, (3) learning curve effect, and (4) acceptance and adoption by workers.

### Highlights

It is evident that the control interface of the innovative technology allowed the excavator operator to achieve the main goal of the experiment—namely, the laying of pipes without any workers in the trench. Using both his own laser and the laser-video targets, he immediately felt comfortable with the necessary adjustments and the accuracy of the installed pipes. The availability of an image showing a close-up of the pipe joint was praised, and was felt to be a special asset when laying pipes into deeper trenches.

### Problems

As pointed out earlier, the contractor willing to test PipeMan, ABE Utilities, Inc., in Raleigh, unexpectedly used 2.4 m long pipes instead of the 1.2 m long pipes, and a large size backhoe and bucket. These "upgrades" put the hardware under real-world scrutiny, which in turn brought four so far undetected limitations to light. First, the base plate of the selected electric winch, which promised sufficient lifting capacity to carry even the 2.4 m (8 ft) sections of concrete pipes, bent immediately under the eccentric load, rendering it useless. The improvised substitution consisted of a chain with a ratchet fastener borrowed from the contractor's toolbox, making the tying of the pipe to the carriage more time consuming, as will be demonstrated later. Second, the large (huge) excavator bucket did not lay within the expected size range, making the mechanical backstop ineffective. The improvised solution to this problem was a chain that connected the backstop to the hook on the back of the excavator bucket and a reverse action (e.g., tightening) of the mechanical backstop. This turned out to be an extremely safe and efficient adaptation. Third, not having a way to remotely release the chain strap, the trench had to be benched so that a helper was able to enter safely. This also allowed an easy check of the line and grade. Fourth, the operator had difficulty seeing the red laser dot on the flat screen monitor in his cabin, due to an insufficient contrast between the laser beam and the target.

**Table 4.** Cost Comparison

| Cost item/description | Unit | Traditional method, observed | Tele-robotic, observed | Tele-robotic, projected[a] |
|---|---|---|---|---|
| Crew size | Laborer | 5 | 3 | 3 |
| (a) Excavation and bedding | | | | |
| Excavation volume[b] | m³/pipe | 21 | 11.6 | 11.6 |
| Crew unit cost[c] | $/h | 121.7 | 74.80 | 74.80 |
| Productivity[d] | m³/h | 189 | 189 | 189 |
| Labor cost[e] | $/m | 5.63 | 1.91 | 1.91 |
| Excavator cost[f] | $/m | 8.33 | 4.53 | 4.53 |
| [Total excavation] | $/m | 13.96 | 6.44 | 6.44 |
| (b) Pipe laying | | | | |
| Cycle time | min/2.4 m | 2.2 | 9.6 | 3.6 |
| Adjusted cycle time[g] | min/2.4 m | 2.9 | 12.8 | 4.8 |
| Daily output | m/day | 397 | 90 | 242 |
| Labor hours per meter of pipe | LH/m | 5*8/397=0.10 | 3*8/90=0.27 | 3*8/242=0.10 |
| Labor cost[h] | $/m | 12.1 | 19.95 | 7.48 |
| Excavator[i] | $/m | 3.62 | 16.0 | 5.95 |
| [Total pipe laying] | $/m | 15.72 | 35.95 | 13.43 |
| (c) TR pipe manipulator (TRPM) | | | | |
| Rental cost | $/day | Not applicable | 500 | 500 |
| TRPM cost[j] | $/m | Not applicable | 8.45 | 4.99 |
| (d) Backfill and compaction | | | | |
| Backfill/meter of pipe[k] | m³/m | 7.9 | 4.0 | 4.0 |
| Labor cost[l] | $/m | 6.0 | 3.04 | 3.04 |
| Equipment cost[m] | $/m | 18.1 | 9.12 | 9.12 |
| [Total backfill and compaction] | $/m | 24.1 | 12.2 | 12.2 |
| (e) Insurance | | | | |
| WC insurance (10% of labor cost) | $/m | 2.5 | 2.5 | 1.3 |
| [Total unit cost] | $/m | 53.7 | 65.54 | 38.4 |

[a]Projected outcome after small technical modifications are made.

[b]Excavation volume for 0.9 m (3 ft) diameter, 2.4 m (8 ft) long concrete pipe.

[c]Labor cost ($/h): operator=$27.9/h; pipe layer=$26.6/h; helper=$20.3/h. Five-member crew cost=$27.9+2*$26.6+2*$20.3=$121.7/h. Three-member crew cost=$27.9+$26.6+$20.3=$74.80/h.

[d]Observed time for 2.4 m excavation and bedding=5 min; considering a 75% operating factor, excavation time=6.66 min/21 m³.

[e]Labor cost/meter=$[(b/d)*c]/2.4$ m.

[f]Excavator cost=$180/h; excavator cost/meter=$[(b/d)*$180/h]/2.4$ m.

[g]Adjusted cycle time with operating factor of 75%.

[h]Labor cost=$(k*c)$.

[i]Excavator cost=$($180/h/i/8$ h$)$.

[j]Total time to excavate and lay 2.4 m pipe=6.66 min+12.8(4.8) min=19.46 min for observed and 11.5 min for projected option. Daily output of laid pipes=60 min/19.46 min(11.5)*8 h *2.4 m=59.2 m (100.2 m). Cost of pipe manipulator=$500/59.2 m (100.2).

[k]2.4 m pipe section results in 19 m³ or 9.6 m³ of volume to backfill (2 m³ occupied by pipe, etc.).

[l]Labor cost=$0.76/m³ ($1/cu yd).

[m]Equipment cost=$2.28/m³ ($3/cu yd).

## Learning Curve

The workers became familiar with the new process after only a few repetitions. They laid the last two pieces of pipe in a consistently shorter time than the first three cycles.

## Acceptance and Adoption

The operator, pipe layers, and helpers accepted the new technology wholeheartedly, engaged in finding substitutions for the broken or unworkable hardware, and took expert control of the hardware. They felt that the most important roles of the manipulator were (1) lining up the pipe, and (2) jointing the pipes without them having to enter the trench.

The operator clearly preferred his own laser target inside the pipe because he could see the laser dot on the target from his seat instead of through a monitor. Sending the laser beam through the pipe itself allows the contractor to start backfilling right away. Both methods of locating the laser target can be observed on today's construction sites.

## Quantitative Performance Evaluation

Table 4 presents the direct costs of the field tests and the technically modified system calculated using cycle times and common unit costs for labor and equipment found in *Building construction cost data, 1997*, by RS Means. The three cost columns compare
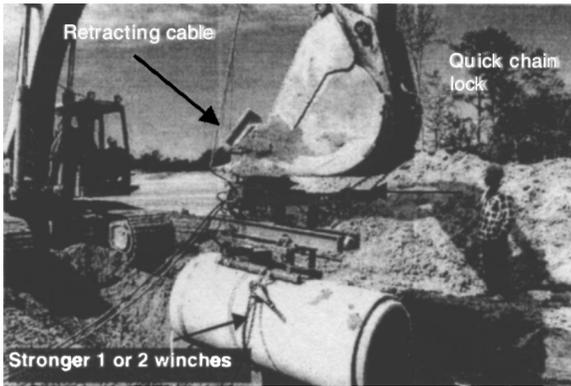
**Fig. 10.** Recommended simple hardware modifications



**Fig. 12.** Cost sensitivity

the traditional method with the tele-robotic method; included in the last column, labeled Tele-robotic, projected, is an effort to assess the cost effect of replacing the broken winch and the other encountered problems. Other improvements that were accounted for were a faster method for connecting and disconnecting a pipe element, easier cable and hose coupling, and a streamlined bucket-manipulator hookup, as indicated in Fig. 10.

The main cost items consist of (1) excavation and bedding, (2) pipe laying, (3) pipe manipulator rental, (4) backfill and compaction, and (5) insurance. The volume of excavation for the traditional method, 21 m$^3$, includes the benches as shown in Fig. 11, while the volume for the alternative method, 11.6 m$^3$, is based on vertical trench walls with a minimal width as required for proper haunching. The excavation time includes time for making the bedding, and is adjusted with a 75% operating factor. As expected, the resulting cost savings, $7.52/meter or 54%, were significant.

The cost of laying the pipes into the prepared trench section is directly related to the mean cycle times, again adjusted with an operating factor of 75%, and the crew size. It is apparent that the
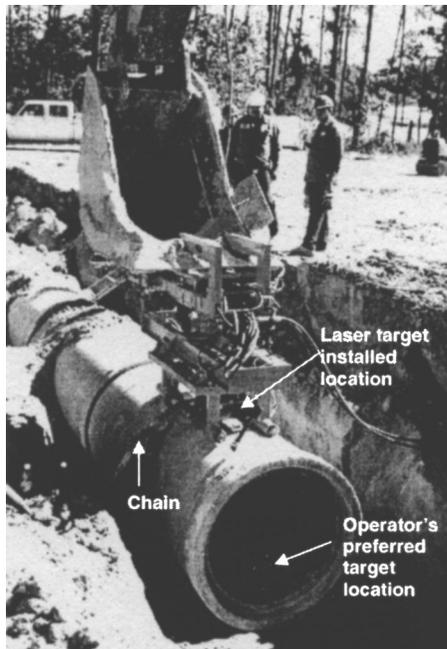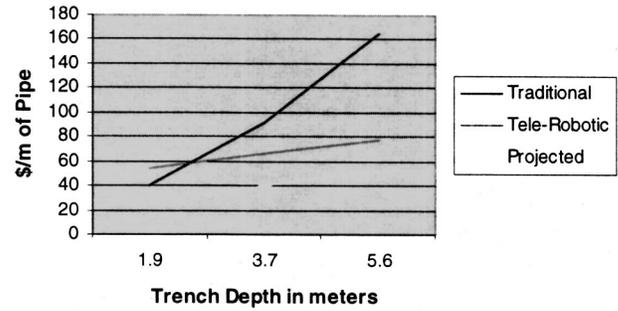
9.6 min measured mean cycle time for the tele-robotic method has a drastic impact on its labor and equipment cost, adding up to $35.95/meter, which is 128% higher than the cost for laying the pipes in a traditional manner. Although the cycle time of the projected option is 63% higher than that of the traditional option, the 15% lower cost of $13.43/meter is made possible by the smaller crew size of three.

To include the cost for PipeMan, a daily rental cost of $500 was estimated and divided by the daily output of 59.2 or 100.2 m of laid pipe for the two options. The cost for backfill and compaction per meter of pipe is again drastically reduced because of the smaller volume that has to be excavated. Finally, the insurance cost, which possibly could be reduced by the insurance company, is estimated as 10% of the total labor cost.

Overall, the total costs for the excavation and laying of 0.9 m (36 in.) concrete pipes into a 1.8 m (6 ft) deep trench during the field tests are $53.7/meter ($16.37/foot) for the traditional method and $65.54/meter ($20/foot) for the observed tele-robotic method. As was anticipated, the tele-robotic option turns out to be 22% more expensive—mainly as a result of the drastically higher cycle time for laying one pipe element. However, the technical repairs and simple improvements will undoubtedly reduce the observed time. As one can see from Table 4, even if all of the time reductions will not materialize as projected, increased productivity and lower volumes to be excavated will make the safe technology economically very competitive.

## Cost Sensitivity Based on Trench Depth

As mentioned earlier, the economic benefit of using a tele-robotic approach to laying pipe should increase with the depth of the trench. The final section of this paper will assess the cost sensitivity of the different technologies for different depths. Fig. 12 shows the cost sensitivity of the new technology based upon the assumptions mentioned earlier. The costs were computed for 1.9, 3.7, and 5.6 m (6, 12, and 18 ft) deep trenches for excavation, pipe laying, and compacted backfill using productivity rates and unit costs from comparative field tests. The soil condition was assumed to be Type C (loamy sand), according to OSHA's soil classification (U.S. Department of Labor 1989), for which a maximum allowable slope of $1\frac{1}{2}H{:}1V$ (34°) is required (Fig. 13).

As the cost curves in Fig. 12 depict, total costs per meter of laid pipe with PipeMan are much less sensitive when compared to the traditional method. The main reason for the rapid growth of the cost/meter is the increase of the volume of soil to be excavated, backfilled, and compacted when a slope is required. Changing to a trench box would reduce that effect of overexcavation but would not eliminate it, since the available space needs
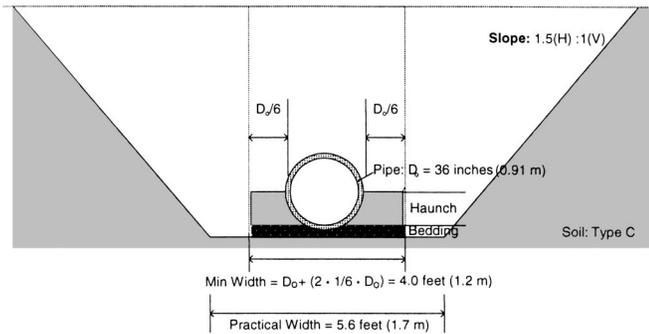


**Fig. 11.** Options for laser target installation

**Fig. 13.** Excavation volume comparison using simple slope

to be practical. The necessary steel bracing and the time spent moving the box along would add more unproductive time, an effect that was beyond the scope of this study.

## Conclusions

Traditional trenching and pipe laying requires workers to enter the confined space of a trench. Due to the complexity of accurately predicting the behavior of the soil and many other risks that go along with working with large and heavy components, such as concrete pipes, the number of accidents and fatalities is unusually high. This paper presents a technological intervention as an alternative to the present method of laying pipe. A remotely controlled pipe manipulator capable of transporting, lining, and jointing large pipes eliminates the need for pipe layers and helpers to work at the bottom of the trench. The description of the innovative technology is followed by a discussion of the design and results of a comparative field test that demonstrated its technical and, most important, economic, viability. As expected, the cost savings have two major sources—a smaller work crew and the elimination of the OSHA requirement to build a protective system. While the hardware problems that surfaced during the field tests suggest that modifications and further improvements are possible, the fact

that a field crew on their own installed a set of concrete pipes with reasonable productivity and production rate offers testimony that this technological intervention could become the cornerstone for eliminating a deadly trap.

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