Optimization Analysis for Alignment Criteria and Installation of Gravity Flow Underground Pipe

Eugene N. Balter

University of Central Florida

Part of the Engineering Commons

Find similar works at: https://stars.library.ucf.edu/rtd

University of Central Florida Libraries http://library.ucf.edu

This Masters Thesis (Open Access) is brought to you for free and open access by STARS. It has been accepted for inclusion in Retrospective Theses and Dissertations by an authorized administrator of STARS. For more information, please contact STARS@ucf.edu.

STARS Citation


https://stars.library.ucf.edu/rtd/4814
OPTIMIZATION ANALYSIS FOR ALIGNMENT CRITERIA AND INSTALLATION OF GRAVITY FLOW UNDERGROUND PIPE

BY

EUGENE NORMAN BALTER
B.S.E., University of South Florida, 1977

THESIS

Submitted in partial fulfillment of the requirements for the degree of Master of Science in the Graduate Studies Program of the College of Engineering University of Central Florida Orlando, Florida

Fall Term 1985
ABSTRACT

In 1982 the Business Roundtable prepared several reports which investigated various aspects of construction which posed significant research opportunities. Their findings placed piping construction in the group of activities categorized as having "highest potential" for improvements based on inefficiency, or construction difficulty and proportionate costs. It was estimated that over $1 billion could be saved annually if the difficulty in the piping industry was improved to only average of other areas. Further investigation into the piping area showed that the alignment process took 20% of the cycle time for installation and ranked either first or second as compared to the other task involved in pipe installation with regards to complexity, skills required and dependency on technical information.

Based on the above, this research project was performed to develop a new technique to aid in the alignment process of underground gravity flow pipe. Included in the research was a detailed investigation into existing techniques for performing this task, establishment of a sample analysis to establish workable tolerances for pipe
installation, the development of a laser-controlled excavation system and a cost analysis of the new technique presented. All technology used to develop this improved process consisted of currently available equipment used in other fields.
ACKNOWLEDGMENTS

Special thanks to my wife, Sue, without whose support and encouragement this project and degree never would have been completed, and to my children, Rebecca, Daniel and Anne, who motivated me to continue.

Thanks also to my parents who instilled in me the principles to always strive to improve myself.

Lastly, thanks to the management of Greiner Engineering Sciences, Inc., for their encouragement and financial support in my graduate studies.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>LIST OF TABLES</th>
<th>vi</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIST OF FIGURES</td>
<td>vii</td>
</tr>
</tbody>
</table>

## I. INTRODUCTION

1. Significance of Underground Pipe
   - Scope of Investigation: 3

## II. DESCRIPTION AND CRITIQUE OF CURRENTLY UTILIZED TECHNOLOGY

- Batter Boards: 15
- Level or Transit: 18
- Laser Level: 20

## III. ESTABLISHMENT OF TOLERANCES

- Necessity: 29
- Current Requirements: 31
- Establishing Sample Tolerances: 37

## IV. LASER CONTROLLED EXCAVATION TECHNIQUE

- Defining Objective: 43
- Pipe Installation Procedure: 45
- Explanation of Laser Controlled Excavation Technique: 51
- Evaluation of Laser Controlled Excavation Technique: 62

## V. ECONOMIC ANALYSIS

- Safety Considerations: 66
- Costs Due to an Accident: 73
- Costs Due to a Death: 84
- Total Safety Costs: 88
- Labor Savings: 89
- Total Annual Savings of System: 90

## VI. CONCLUSIONS

- Results of Research: 92
- Critique of Laser-Controlled System: 93
<table>
<thead>
<tr>
<th>Table</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Estimated Savings With Most Improvement in Areas of Highest Potential</td>
<td>4</td>
</tr>
<tr>
<td>2.</td>
<td>Self Cleaning Slopes</td>
<td>30</td>
</tr>
<tr>
<td>3.</td>
<td>Slope Constraints</td>
<td>40</td>
</tr>
<tr>
<td>4.</td>
<td>Certain Costs of Work Related Accidents</td>
<td>66</td>
</tr>
<tr>
<td>5.</td>
<td>Incident Rates Per 100 Full Time Workers</td>
<td>71</td>
</tr>
<tr>
<td>6.</td>
<td>The American Standard Scale of Time Charges</td>
<td>83</td>
</tr>
<tr>
<td>7.</td>
<td>Estimated Costs Due to an Accident</td>
<td>84</td>
</tr>
<tr>
<td>8.</td>
<td>Estimated Costs Due to a Death</td>
<td>88</td>
</tr>
<tr>
<td>9.</td>
<td>Laser-Controlled Excavation Equipment Costs</td>
<td>90</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

1. Typical Jacking Operation ........................................... 5
2. Typical Excavation Equipment ....................................... 7
3. Various Pipe Joints .................................................. 9
4. Average Ranking of the Technical Aspects of the Steps in the Erection Procedure of Piping ........................................ 11
5. Batter Board Set-Up ................................................... 17
6. Typical Laser System .................................................. 22
7. Temperature Gradient Formation ..................................... 27
8. Example of Proposed Sanitary Sewer System ...................... 37
10. RCP Rotating Ball Joint ............................................ 42
11. Use of Come-Along to Join Pipe ................................... 49
12. Proposed Laser-Controlled Excavation System ................... 53
13. Typical Electronic Distance Measuring System Configuration 54
14. Rotational Geometry System ........................................ 56
15. Example System Orientation ....................................... 59
CHAPTER I
INTRODUCTION

Significance of Underground Pipe

Everyday, almost every person in the world is affected by underground utility systems which serve them, or the unavailability of the benefits they provide. These systems range from distribution of potable water for drinking and cleaning, to sanitary sewer systems which transport waste products and sewage for proper disposal. Buried telephone, electric, gas, storm sewers and other systems have also become such a large part of our daily lives, that although we often take them for granted, significant effects would be felt by all of us if any of these systems were disrupted. This is demonstrated by news accounts focused on rare occurrences of power blackouts or water main breaks, stopping service to localized communities.

In addition to the dependence we have placed on these services, one should consider the enormous sums of money spent by governmental agencies and utility companies to provide these distribution systems which make these services available to everyone.
In consideration of the above it becomes clearly evident that both the uninterrupted service of these utilities and the minimizing of costs to provide them is crucial. In evaluating the cost effectiveness of monies spent on installation of piping systems it can be demonstrated that by developing improved construction techniques and/or procedures significant savings can be found.

In 1982 the Business Roundtable prepared several reports which investigated various aspects of construction which posed significant research opportunities. In addition, these reports outlined needs and priorities for construction technology advancements.

Their findings placed piping construction in the group of activities categorized as having "highest potential" for improvements based on inefficiency, or construction difficulty and proportionate costs. In addition, for the three (3) areas listed in with "highest potential for technological improvements", (which include along with piping, the areas of mechanical equipment and electrical construction) it was estimated that a savings of almost $2.2 billion annually could be realized if the indicated difficulties in these three areas were improved
to only average for other areas. The piping area contributing to over $1 billion of this estimated savings as shown in Table 1.

Compounding these costs is the current emphasis being proposed throughout this country to rebuild America's infrastructure. If this commitment is to become an economical reality, technical innovations which would reduce the cost estimates to perform this work would be in greater demand.

Scope of Investigation

Obviously the piping considered in the Business Roundtable report encompassed a broad spectrum of activity. These various types of piping include utility systems in residential and commercial structures, mechanical piping in manufacturing and processing plants as well as above and below ground utility distribution systems. This paper shall only be concerned with the category of underground piping installed by excavation and backfilling as opposed to jack and bore installed pipe.

The method of jacking and boring pipe into the ground involves drilling a shaft horizontally through the
### TABLE 1

**ESTIMATED SAVINGS WITH MODEST IMPROVEMENT IN AREAS OF HIGHEST POTENTIAL***

<table>
<thead>
<tr>
<th>Individual Project Basis ($ millions)</th>
<th>Piping</th>
<th>Mechanical Equipment</th>
<th>Electrical</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buildings (25 million)</td>
<td>.006</td>
<td>.039</td>
<td>.046</td>
<td>$ .091 million</td>
</tr>
<tr>
<td>Light Industrial ($119 million)</td>
<td>.241</td>
<td>.174</td>
<td>.258</td>
<td>$ 0.673 million</td>
</tr>
<tr>
<td>Heavy Industrial ($188 million)</td>
<td>3.802</td>
<td>1.002</td>
<td>1.410</td>
<td>$ 6.214 million</td>
</tr>
<tr>
<td>Power($467 million)</td>
<td>5.060</td>
<td>3.046</td>
<td>2.744</td>
<td>$10.850 million</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Gross Industry Basis ($ billions)</th>
<th>Piping</th>
<th>Mechanical Equipment</th>
<th>Electrical</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buildings (569 billion)</td>
<td>.017</td>
<td>.108</td>
<td>.128</td>
<td>$ .253 billion</td>
</tr>
<tr>
<td>Light Industrial ($33 billion)</td>
<td>.067</td>
<td>.048</td>
<td>.071</td>
<td>$ .186 billion</td>
</tr>
<tr>
<td>Heavy Industrial ($33 billion)</td>
<td>.667</td>
<td>.176</td>
<td>.247</td>
<td>$ 1.090 billion</td>
</tr>
<tr>
<td>Power($27 billion)</td>
<td>.292</td>
<td>.176</td>
<td>.158</td>
<td>$ .626 billion</td>
</tr>
<tr>
<td>Total ($162 billion)</td>
<td>1.043</td>
<td>.508</td>
<td>.604</td>
<td>$ 2.155 billion</td>
</tr>
</tbody>
</table>

*Assumptions
1. Labor component is 25% of a project.
2. Improvement would allow Piping, Mechanical Equipment and Electrical to achieve average indicator ratings.
3. Numbers in parentheses are total project costs.

Reprinted with permission of R.A. Tucker, University of Texas at Austin for the Business Roundtables.
earth from an excavated starting location and pushing a pipe or casing into the drilled hole. See Figure 1.

Figure 1. Typical Jacking Operation
Reprinted with permission of the American Concrete Pipe Association.

This is a common practice under structures, railways and roadways where open excavation installation would be cost prohibitive due to the removal and replacement of the overlying system. It also eliminates the need to shut down the system during construction. Due to the significant differences in construction techniques used in open excavation installation and jack and bore pipe installation, an analysis for one technique may not apply to the
other, thereby justifying studying each method independently.

In narrowing the area of research the next phase is to examine the steps necessary to properly install underground pipe.

In differentiating from the design phase of pipe installation to the construction phase, the first step to be considered in the construction process is transportation of the pipe to the site. Economics and site accessibility are generally the main considerations in this process, and these usually dictate that the pipe be hauled to the site by flat-bed truck or railway car. Obvious care should be taken in the selection of the site to off-load the pipe so as to avoid creating conflicts with future work and to avoid damage to pipe due to surrounding activities.

The next step involves excavation of the trench to install the pipe in the ground. This can be accomplished with many different types of equipment as shown in Figure 2. In this step, attention has to be paid to insure proper excavation to allow the pipe to be installed to proper line and grade.

The pipe is then lowered into the trench, properly aligned and the sections of pipe are then joined
Figure 2. Typical Excavation Equipment

Reprinted with permission of the American Concrete Pipe Association.
together. Many different types of joints are currently used. Some examples of these different types of joints are shown below in Figure 3.

Finally the bedding, backfilling and compaction process begins to cover and support the pipe and return the ground surface to the required elevation.

Other tasks may be required depending on the use of the pipe and special needs or interests (i.e., inspections, tests, chlorination, etc.). In the Business Roundtable report (which again did not limit its scope to underground installation) they divided the pipe installation process into the following tasks:

1) Procurement
2) Transport Materials
3) Lift Pipe
4) Align Pipe
5) Connect Pipe
6) Inspection

Analysis of the pipe installation tasks by this Business Roundtable report showed that the alignment process requires 20% of the cycle time for pipe installation and is ranked first or second as compared to all other steps in the pipe installation cycle with regards to
Figure 3. Various Pipe Joints
complexity, skills required, and dependence on technical information. See Figure 4.

Based on the magnitude of priorities placed on the alignment process noted above, the area of investigation in this paper was further narrowed down to the specific topic of alignment procedures and techniques for underground pipe installation, as opposed to above-ground pipe systems and those installed in buildings and factories.

Many of the problems associated with improper alignment of gravity flow systems are not applicable when the pipe is for electrical cable or similar utilities, or when the flow of liquid (or gas) is under pressure.

The most critical area of alignment analysis is for the case of gravity flow of liquid in the pipe. The following helps to explain this.

Listed below are considerations regarding pipe alignment which are common issues to consider in an optimization analysis of various types of piping systems including gravity flow pipes:

1) Pipes installed in an alignment other than as specified can create conflicts with other structures, utilities, etc., either existing or planned.
Figure 4. Average Ranking of the Technical Aspects of the Steps in the Erection Procedure of Piping

Reprinted with permission of R. A. Tucker, University of Texas at Austin for the Business Roundtable.
2) Force mains and gravity-fed pipes installed at improper alignments which fluctuate significantly can affect flow rates or other hydraulic considerations.

3) Force mains and gravity-fed pipes with improper alignment changes at joints have a significantly higher probability of developing leaks.

4) As it is obvious that time required for a given task is money, improvements in alignment techniques which could reduce the time or minimize the effort required would be beneficial.

5) Similar to the concept that a savings of time saves money, when analyzing underground installations, safety must also be considered. Any effort which can reduce the time required to perform this task reduces the risk of accidents. This is due to the decreased probability of workers or equipment falling into the open excavation and the decreased possibility of a slope collapse potentially burying the workers.

On the contrary, the following considerations are unique to gravity systems only:
1) Improper alignments in pipes can cause situations where water is pocketed in low sections of pipe. This creates, in addition to undesirable flow characteristics, problems with sedimentation in pipes and possible problems of the formation of dangerous gases in sanitary sewer lines.

2) Pipes which have a constant fall, but are aligned incorrectly, with either too steep or too flat of a slope, can develop problems with scouring of the pipe or cause the depositing of sediment in the pipe respectively.

3) Pipes aligned improperly may not provide a proper fit or connection at existing or pre-cast structures.

4) Minor conflicts encountered cannot be as easily avoided by making slight adjustments to the pipe so as to pass just under or over the conflicting structure as can be done in force mains or other utilities.

5) Due to the requirement for a constant drop in the elevation except at lift (or pumping) stations, gravity flow pipes usually require a much deeper average excavation.
6) As a general rule all horizontal alignment changes must occur at a structure.

Based on the above, it is evident that gravity flow lines are significantly more alignment-dependent than other systems, and therefore these gravity flow systems shall be of prime concern herein.
CHAPTER II

DESCRIPTION AND CRITIQUE OF CURRENTLY UTILIZED TECHNOLOGY

Batter Boards

Of the three main techniques used to check the alignment of pipe installed in a trench, the use of batter boards is the oldest and the least utilized method today.

As part of the research process for this paper a survey was sent out to 74 contractors to provide input of current practices, problems, and techniques. A copy of this questionnaire is included in Appendix 1. A copy of the list of contractors the questionnaire was sent to is shown in Appendix 2. Of all the contractors responding to the survey only two (2) indicated they use batter boards, and even then only 10% or less of the time.

Batter boards consist of erecting a level cross board to straddle the open trench. The cross board is secured on both sides by vertical supports. A nail is placed in the cross board directly above the center line of the trench. These batter boards are placed at a constant, predetermined height above the invert elevation.
of the pipe and are spaced 10' to 50' apart, dependent on the uniformity of the surrounding ground. A string is pulled taut from nail to nail across the tops of the boards to provide a checkpoint for both horizontal control (by use of a plumb bob or level down to the center of the pipe) and vertical control (by measuring down from the string the predetermined distance to the pipe invert by use of a story pole or tape). See Figure 5.

Although few, batter boards do have some advantages over other methods. They include:

1) Minimum expense of all alignment procedures on a per-job basis.

2) Equipment is usable in all types of weather with the possible exception of high winds. Unlike other alignment procedures, excessive heat or rain is not a problem.

3) Minimal technical skill is required to use.

4) Equipment can be left in place overnight with minimal chance of vandalism or theft.

Disadvantages to using batter boards include:

1) Most time-consuming system to utilize.

2) Dependent on other equipment (i.e., level or
transit to establish centerline and cross board elevations).

3) Creates conflicts with excavating equipment working in trench.

4) In most cases, accuracy is less than other methods, but when supports are installed in soft or spongy ground the accuracy is always questionable.
5) Requires more clearance and occupies more space than alternative methods.

6) Is impractical for installation of large pipe due to long span across ditch.

7) More trouble in deep excavations.

In summary, batter boards are the least desired method of aligning pipe. They are generally only used by the "old-timers" who have either not taken the time, or made an effort, to use the more modern techniques available.

**Level or Transit**

The use of a level or transit both utilize the same principle for aligning pipe. In this case, a line of sight is established from a tripod-mounted survey instrument placed along the centerline of the pipe. In the case of a transit, the line of sight is sloped at the same rate of the slope of the pipe to provide a constant offset from pipe invert to the instrument cross hair. In the case of the level, the line of sight which is set horizontally, is used to measure down to the individual pipe section inverts. This measurement is adjusted for each length of pipe based on the nominal pipe length times the rate of rise or fall in the pipe.
This more modern technique of pipe alignment is the "middle of the road" method. Of the three techniques to be discussed, it ranks second in the following categories:

1) Cost.
2) Percentage of usage by contractors surveyed.
3) Speed.
4) Ease of confirming alignment.

Advantages for using a level or transit include:
1) Variety of other uses for equipment.
2) Provides opportunity to document as-built conditions of pipe due to individual readings.
3) Very quick for short lengths of pipe.

Disadvantage for this method include:
1) Largest potential for human error.
2) Requires a person to be away from location of pipe being set (at instrument) thereby either dictating additional manpower or being shorthanded in setting pipe.
3) As the instrument should be set on the centerline of the pipe, there are limited locations for set up. As excavation equipment is at one end of ditch, the level or transit
can be at the other end usually near the structure or in ditch on or around previously placed pipe which has been at least partially backfilled.

**Laser Level**

The current "state of the art" method of checking pipe alignment is the use of laser levels. In response to the questionnaire in Appendix 1, a percentage of usage summary by all contractors indicated lasers were utilized 85% for pipe alignment. Transit or level usage was second highest at 13% with batter boards usage coming to just under 2%. This laser level method consists of utilizing a helium neon laser with a beam of 2.0 to 3.0 mw. The laser is set to project a linear beam along the line established for the pipe and set at the same grade as the proposed pipe.

Several methods of laser set up can be used depending on certain conditions or line of sight constraints. The most commonly utilized arrangement is to set the laser directly in the initial section of pipe laid and then subsequent pipe sections can be checked for proper alignment by either measuring the constant distance between beam and pipe invert, or by utilizing a
target. These targets which are usually made of a translucent material are adjustable for various pipe sizes and are set in the invert of the section of pipe being checked to see if the beam from the laser hits the proper location on the target. The translucent material allows the beam to be seen from either side of the target.

Other methods of setting the laser for checking pipe alignment include the following:

1) Tripod-mounting the laser above the pipe. The pipe is then checked for alignment by measuring down from the beam to either the top of the pipe or invert.

2) Top of pipe arrangement involves setting the laser directly on the top of the initial section of pipe placed and checking subsequent sections in the same manner as originally stated.

3) Suspending the laser from supports inside a structure to project the beam through the pipe. This is sometimes used to provide through the pipe alignment verification when it is not practical to set either the laser and/or target in the pipe invert. Examples
of this can be seen when flow of water through the pipe cannot be prevented or invert line of sight is obstructed. See Figure 6 for these and other methods of laser-setting techniques.

Figure 6. Typical Laser Systems
Reprinted with permission of the American Concrete Pipe Association.
The technology of today's pipe lasers is extremely advanced and although this is the most sophisticated method, it may also be the easiest or least technical dependent for the operator to use. Numerous options that are available include:

1) Simple dial in grade indicators.
2) Self-leveling lasers.

In addition to the above, the other significant advantages to lasers are:

1) Reduces number of workers required (i.e., no instrument man or laborers setting batter boards). A summary of respondants to the contractors' questionnaire indicated (as averaged for all responses) a 6.8 man crew is required to set pipe with laser-leveling, a 7.5 man crew is used to utilize the transit or level method and a 8.4 man crew utilized to do the same task with batter boards to check alignment of pipe.

2) Requires minimum set-up time as compared to alternative methods of pipe alignment.

3) According to questionnaire responses, if used properly and with minor constraints
(see disadvantages below), lasers provide maximum accuracy.

4) Provides immediate response to pipe layers as to alignment of pipe. There is no need for communications with personnel on top of excavation bank.

5) The laser beam can provide a non-obstructing guide from which the equipment operator can rough check the excavation depth. This is done by mentally noting the location of the laser beam on the bucket when on grade, and attempting to maintain this constant beam-on-bucket relationship.

6) Most contractors questioned in the survey indicated that lasers provided the least possibility of having human error create alignment problems.

7) Minimum technical dependence is involved in the use of a laser. Once the initial invert is established, it is strictly a matter of setting a laser in the pipe, leveling the laser and dialing the required slope on the grade indicator. In fact, some lasers are now so advanced that only a rough leveling
is required and the laser will self-level. The unit will also self-level if accidentally knocked out of the initial set-up. These lasers even give visual indications that the level has been lost and is being reset by either pulsing the beam or shutting it off altogether. This eliminates the chance of installing a section of pipe during the releveling period. Comparing this to the required transit or level work and the associated basic surveying techniques required to set batter boards or to check pipe directly with the survey instrument, it is obvious that a reduction in technical skills is required with a laser.

As this is not the perfect system, there are obviously disadvantages associated with the laser levels. They include:

1) In bright environments, some lasers with less powerful beams are difficult or impossible to see.

2) This is the only method discussed which requires an external power source. This usually involves carrying a spare 12-volt
car battery to the location of the laser set-up.

3) Although laser beams are highly collimated or intensely focused they can spread out over long distances. This widening of the beam can make accuracy a potential problem.

4) The cost of equipment for this method of aligning pipe is far greater than the other alternatives.

5) Initial set-up to properly set the first section of pipe to grade and correct slope usually requires additional equipment. This equipment may include a survey instrument, hand level, etc.

6) Laser levels are more environmentally sensitive than other procedures. A laser, like a transit or level, should not be exposed to rain. Many manufacturers of these pieces of equipment state the product is waterproof, but after extended use or wear this may not hold true. In addition, a laser is more sensitive to heat than the other techniques. This is especially true when the beam is transmitted through pipes (as opposed to
sighting over the pipe) where circulation of air is a greater problem. This is demonstrated by the following formula which calculates beam deflection due to temperature change (see Figure 7):

\[
x = \frac{0.040}{T^2 \sin^2(\pi/2-S)} \left( \frac{dt}{dx} \right) y^2 + Sv + X_0
\]

where:

- \( x \) = height of beam at the target, in meters
- \( X_0 \) = initial height of beam at the laser, in meters
T = temperature, in degrees kelvin
s = slope of the pipe, in percent or radians
y = distance between target and laser, in meters
dT = vertical temperature gradient measured at the level of the laser beam, in kelvin (or Centigrade) per meter

dx

If, for example, it is necessary to set a pipe at a slope of 0.067%, with a temperature gradient of \(-1/2^\circ F/in\) \((-7.5^\circ C/m)\), at a distance of 250 feet, a deflection of 0.84 inches is expected. At 500 feet, this deflection increases to 3.32 inches.

Typically, blowers are utilized in cases like this to circulate the air and reduce or eliminate the temperature gradient effect.
CHAPTER III
ESTABLISHMENT OF TOLERANCES

Necessity

In gravity flow systems, it is important to maintain the proper slope of the installed pipe. Slopes which generate flows greater than 15 feet per second can cause damage to the pipe interior due to scouring. Conversely, slopes creating flows less than 2 feet per second when pipe is flowing full can cause drainage problems due to settlement of suspended solids settling out and building up in the pipe invert. The following table indicates minimum slopes required to achieve a 1 foot per second minimum velocity at a flow depth of 1/6 diameter.

The question arises, "What are acceptable slopes?". It is important for the design engineer to thoroughly understand all design constraints. This includes evaluating all requirements of the utility, including capacity and materials to be transported in the pipe. In addition a complete understanding of the pipe should be determined so as to evaluate its performance under various conditions. Lastly the engineer must evaluate the economic situation of the owner or financing agency. This will allow the engineer to design a system
TABLE 2
SELF CLEANING SLOPES

<table>
<thead>
<tr>
<th>Pipe Diameter (inches)</th>
<th>% Slope (ft/ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>0.33</td>
</tr>
<tr>
<td>10</td>
<td>0.25</td>
</tr>
<tr>
<td>12</td>
<td>0.19</td>
</tr>
<tr>
<td>15</td>
<td>0.14</td>
</tr>
<tr>
<td>18</td>
<td>0.11</td>
</tr>
<tr>
<td>21</td>
<td>0.092</td>
</tr>
<tr>
<td>24</td>
<td>0.077</td>
</tr>
<tr>
<td>27</td>
<td>0.066</td>
</tr>
<tr>
<td>30</td>
<td>0.057</td>
</tr>
<tr>
<td>36</td>
<td>0.045</td>
</tr>
</tbody>
</table>


that serves the purpose for which it was intended, and also specify one that is financially feasible.

Based on the above criteria, the engineer can selects the type of pipe to be utilized and establishes the "optimum" slope. The desired slope is referred to in this paper as optimum because as in any type of construction the installation of pipe is not an exact function. Due to equipment limitations, soil tolerances and human factors the pipe is adjusted and/or reworked until a slope is achieved which is relatively close to the specified alignment. Without establishment of acceptable tolerances it is impossible for the contractor to deter-
mine if a given section of pipe will be accepted by the owner or inspector. Also how is the person checking the pipe for conformance with the plans and specifications to decide what is acceptable?

In professional practice, disagreement often occurs over acceptance of pipe sections between inspectors and contractors. This could be eliminated along with the field guesswork associated with pipe installation by the establishment of functional tolerances.

Compounding this problem of alignment is the consideration of grades or elevation. Incorrect alignment produces incorrect grades, and even with the correct line established grades can be set incorrectly. These grade problems lead to unexpected conflicts with other underground utilities or structures, possible undesirable coverages and problems with precast structures like manholes or inlets.

**Current Requirements**

During research for this paper, previously established tolerance requirements were investigated. It became apparent that most standard specifications and
industry-guide specifications do not address tolerances for pipe line and grade.

The Florida Department of Transportation Standard Specifications for Road and Bridge Construction, 1982 Edition, covers pipe installation in paragraph 430-4. This paragraph states, "All pipe shall be carefully laid, true to line and grades given . . . ." Additionally it states, "Any pipe that is not in true alignment or which shows any settlement after laying shall be taken up and relaid . . . ." What percentage of pipe is exactly placed to the lines and grades established? How does one decide what is acceptable and what is not? One other ironic item found in this specification is that although the placement of pipe is so lightly covered in this specification, the material requirements for pipe have well-defined and functional tolerances. In reference to rubber gasket joints, paragraph 430-7.2 states, "For concrete pipe laid with rubber gasket joints, any deviation from true alignment or grade, which would result in a displacement from the normal position of the gasket of as much as 1/4 inch, or which would produce a gap exceeding 1/2 inch between sections of pipe for more than 1/3 of the circumference of the inside of the pipe, will not be acceptable . . . ." This provides a defini-
tive method for accepting or rejecting pipe joints with tolerances specified so as to insure infiltration of exfiltration shall not occur, but says nothing about effects on line and grade. Does this mean that pipe that was designed with a very slight slope and meets this requirement is acceptable even if in the process a hump is created in the line? Additional material specifications are included in Section 941 for concrete pipe and use ASTM C76 as the main controlling specification. Examples of the details in this specification include, "Variations in laying lengths of two opposite sides of pipe shall not be more than 1/8 inch per foot of diameter with a maximum of 1/2 inch in any length of pipe . . . ." This specification again provides a detailed material requirement with defined tolerances but no reference to line and grade.

Another example of undefined tolerance was found in the State of Kentucky Department of Transportation Standard Specifications for Road and Bridge Construction. In this document, paragraph 611.06 deals with pipe installation. It states, "Any pipe which is not in true alignment and grade or which shows undue settlement after laying, or is otherwise damaged, shall be removed and replaced . . . ."
Another specification that was reviewed for tolerances deals with specifications in the area of civil airport work. These projects are governed by the Federal Aviation Administrations (FAA) Advisory Circular No. 150/5370, Standards for Specifying Construction of Airports. In this Advisory Circular Item D-701, paragraph 3.5 states, "Pipe shall be inspected before any backfilling is placed; any pipe found to be out of alignment, unduly settled, or damaged shall be removed and relaid or replaced . . . ." Again no tolerance criteria for accepting or rejecting anything but perfectly aligned pipe. Considering these same specifications provide a five-degree rotational allowance for elliptical pipe to be placed from true level, uniformity is not evident as similar tolerances are not defined for alignment requirements.

A roadway specification that has been prepared on a national level as opposed to a state level is the American Association of State Highway and Transportation Officials (AASHTO), Guide Specification for Highway Construction. Paragraph 603.06 states, "Conduit shall be inspected before any backfill is placed. Any pipe found to be materially out of alignment, unduly settled, or damaged shall be taken up and relaid or replaced." What
is materially out of alignment? This qualitative requirement can be interpreted in many different ways. Again, the same problem surfaces while utilizing a specification with input from every state in the union and represented by the Federal Highway Administration.

The preceding has demonstrated the lack of attention paid to alignment criteria by certain agencies utilizing underground culverts. Additional guide specifications are also provided by pipe manufacturers on their products. The American Concrete Pipe Association publishes both the Concrete Pipe Handbook and the Concrete Pipe Installation Manual which is an abbreviated form of the Concrete Pipe Handbook addressing the construction aspect only. The wording provided by this Association which oversees all concrete pipe manufacturing in U.S., Canada and approximately 40 other foreign countries, regarding line and grade during installation states, "Line and grade should be checked as the pipe is installed and any discrepancies between the design and actual alignment and pipe invert elevations should be corrected prior to placing the backfill or fill over the pipe." Here the term "any discrepancies" can be interpreted to require an absolute condition. Consider an example of a field inspector with little to no
experience. A section of pipe checked with a transit or laser is one thousandth of a foot, or less than 1/8 inch off. What option does this inspector have besides rejecting the pipe? He cannot rely on past experience to evaluate the system and make a sound decision.

Although most commonly used storm and sanitary sewer pipe is concrete, the following is from the Sewer Manual for Corrugated Steel Pipe by the National Corrugated Steel Pipe Association. Under their paragraph titled Field Layout and Alignment it states, "Of critical importance in the process of constructing a sewer system is the correct placement of the pipe in its intended location. This can be done by applying basic surveying procedures." That is the complete portion of this manual dealing with establishment of line and grade.

In all research done for this paper no recommended tolerances for specifications of field installation of underground pipe were found. Hopefully the need for such is evident by now. In addition, any consideration for evaluating alternative methods of checking and aligning pipe must include the analysis that the proposed equipment or procedure can produce results within these established tolerances.
Establishing Sample Tolerances

As there exist many factors which can control the allowable tolerances, the following example shall demonstrate the process that can be used for any combination of factors. In this example we shall consider the use of a 24" reinforced concrete pipe (RCP), Class 2, for a sanitary sewer system, which must be installed in the location shown in Figure 8.

![Figure 8. Example of Proposed Sanitary Sewer System](image)

The first item to consider is flow velocities. As previously shown in Table 2, the minimum slope
allowable for 24" pipe is 0.077 percent. Conversely, in order to maintain a flow of less than 15 feet per second, the maximum slope can be calculated using the Chezy-Manning equation:

\[ V = \frac{1.486 \ (r_H)^{2/3}}{n} \sqrt{s} \]

where:

\[ V = \text{velocity} = 15 \text{ feet/second} \]
\[ n = \text{Manning roughness coefficient} = .016 \text{ for concrete pipe} \]
\[ r_H = \text{hydraulic radius} = 0.5 \text{ ft. for a 24" RCP assumed to be flowing full (capacity at which this maximum velocity would be achieved)} \]
\[ s = \text{slope of energy line} \]

Therefore the maximum slope is:

\[ s = \left( \frac{V}{1.49 \ (r_H)^{2/3} / n} \right)^2 = \left( \frac{15}{1.49 \ (0.5)^{2/3} / 0.016} \right)^2 = 0.065 \text{ ft./ft.} \]

When evaluating a minimum slope to provide the necessary clearance under the existing water line, the following is found (neglecting pipe wall thicknesses):

| Waterline Invert at Crossing: | - 5.50 |
| Less Clearance | - 3.00 |
| Less Diameter of Sanitary Pipe | - 8.50 |
| Sanitary Sewer Invert El. | -10.00 |

\[ \text{From Station 0 + 00 to 5 + 00:} \]
\[ \frac{-10.5 + 10.0 = 0.10\%}{0-500} \]
For 24" RCP the maximum individual deflection from a straight line at any given joint as determined from a local pipe supplier is 1/2" to 3/4". This would appear as shown in Figure 9. This converts to a maximum change in slope of 3/4"/24" = 0.031 or an angle, \( \theta \) of 3/4"/24" = Sin \( \theta \), therefore \( \theta = 1.8^\circ \) per pipe section.

![Figure 9. Maximum Allowable Deflection in Typical RCP Joint](image)

Lastly, it should be recognized that from a cost standpoint by minimizing the slope, the required excavation is also minimized thereby providing the least expense for earthwork.

Based on the above, Table 3 shows the slope constraints from the factors considered for this example.
TABLE 3
SLOPE CONSTRAINTS

<table>
<thead>
<tr>
<th>Factor</th>
<th>Min. Slope (ft./ft.)</th>
<th>Max. Slope (ft./ft.)</th>
<th>Max. Deviation (in./in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Velocity</td>
<td>0.00077</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum Velocity</td>
<td></td>
<td>0.065</td>
<td></td>
</tr>
<tr>
<td>Clearance</td>
<td>0.001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pipe Joint</td>
<td></td>
<td></td>
<td>0.031</td>
</tr>
<tr>
<td>Cost</td>
<td></td>
<td>Minimize</td>
<td></td>
</tr>
</tbody>
</table>

It would appear that by requiring the slope for this project at 0.001 ft./ft. all the factors could be achieved, but this would provide no tolerance for upward movement due to the clearance required under the waterline. By changing the required slope to 0.002 ft./ft., a 0.001 ft./ft. upward tolerance is provided and over the entire 1000' of the section of pipe, this would translate to a maximum additional excavation requirement of 1.0'. Therefore the recommended slope and tolerance for this example would be:

Slope = 0.2%
Tolerance = 0.1%

Notice that if depth was not a consideration a possible slope could be the average of the minimum slope required for clearance and the maximum slope required for
velocity or 0.033 ft./ft. In this case the tolerance could be 0.032 ft./ft., but notice this total tolerance exceeds the allowable deflection in a single pipe joint so an additional restrain would be placed on the contractor as noted below:

Slope = 3.3%
Tolerance = 3.2%
Maximum Deviation/Pipe Joint = 3.1%

The preceding example shows a typical analysis which should be performed by the engineer during the utility system design. By doing so, tolerances are provided the contractor and field representative to insure the installed pipe meets all design requirements and still allows some flexibility during the pipe installation procedure.

It should be noted that there is now available, reinforced concrete pipe culvert with a rotating ball joint which will allow a 15 degree deflection as shown in Figure 10. As this product is very new on the market, the results of its use are still being investigated, and may be limited in its applications.
Figure 10. RCP Rotating Ball Joint

Reprinted from Price Brothers Company brochure.
CHAPTER IV

LASER-CONTROLLED EXCAVATION TECHNIQUE

Defining Objective

The preceding chapters have provided a review of existing techniques available to align underground pipe during the installation process, and some guidelines for workable tolerances has been established. The next step is to attempt to develop an optimum method or procedure to perform this task. In developing and analyzing this technique the same factors are to be considered that were used to critique the current methods described in Chapter II which were:

1) Cost
2) Accuracy
3) Speed
4) Ease of Equipment Assembly
5) Minimal Technical Skills Required
6) Minimum Number of Persons Required
7) Equipment Size and/or Weight
8) Equipment Capable of Performing Other Functions
9) Others (i.e., safety, environmentally sensitive, etc.)

It should be noted here that it is not expected to find a method or technique that excels in all areas noted above, but rather achieve the optimal overall performance available by utilizing known technology today. In addition, not all factors above are equally weighted. In analyzing the importance of these factors, the following ranking was developed based on the results of question number 8, from the results obtained in the contractor distributed questionnaire as shown in Appendix 1. These results were tabulated by assigning a first place (or most important) vote a value of 5, a second place vote a value of 4, etc. Then the values for each feature were totaled and percentages assigned to each. The results in order of highest contractor priority to least with corresponding percentages was:

1) Accuracy 28.5%
2) Speed 24.8%
3) Cost 20.0%
4) Minimal Technical Skill Required 7.3%
Tie 5) Ease of Equipment Assembly 6.7%
Tie 6) Minimum Number of Persons Required 6.7%
Pipe Installation Procedure

In an attempt to optimize or improve the techniques currently available, a more detailed examination will be made of the currently utilized procedure involving a pipe laser. This existing technology shall then be used as a standard to evaluate any new technique against. As the laser-installation technique as described in Chapter II was shown to be the current state of the art procedure available, it shall be used for comparison purposes.

In reviewing the pipe laser method, the first step involves the initial system set up. This initial set up utilized a level or transit to establish line and grade for the first section of pipe or structure. Taking measurements from known horizontal and vertical control points (bench marks) the initial elevation and alignment can be established for this starting point. Once the initial structure is in place and properly bedded to insure against accidental disruption the laser can be set
in one of the various methods previously described and as previously shown in Figure 6. Sighting the laser through the pipe seems to be the most commonly utilized set up. The laser is set into the structure with the power cords extended to the power source. The laser is adjusted by either hand-leveled or set to self-level depending on the available options. Once the level has been established the desired grade is dialed in for the slope of the pipe. The translucent target is set for the size pipe being installed. If the laser is set in the initial pipe section the target is placed in the opposite end to check the laser beam for alignment. If, at this point, enough ditch has been excavated in front of the laser it is recommended to set an alignment control point as far from the laser as practical. This will provide a reference to check the line against. If the laser has been set in an initial structure (manhole, inlet, etc.) the alignment control point shall again be required to sight the laser beam on. Upon completing any adjustments to the laser to set it to proper grade, the system is now ready to be utilized to check subsequent pipe sections.

The excavation equipment shall now excavate a section of ditch of sufficient length to accommodate the nominal length of pipe being laid. The operator shall
attempt to grade the bottom of the ditch to conform to the required pipe bottom so as to set the pipe on line and grade. As previously mentioned, it can be useful during the excavation to observe the location of the laser beam as it strikes the bucket while excavating along the ditch bottom. This will provide a reference point during further excavation. Another technique sometimes utilized is checking the height of the beam striking a shovel resting on the bottom of the excavated ditch at certain locations along the ditch. It should be noted that this method of rough checking the ditch bottom requires a worker to be physically present in the open excavation.

Once it has been determined that the ditch bottom is close to the required depth and slope the next section of pipe is lifted and placed into the ditch. This placement is generally done by securing a sling around the pipe and lifting with a hook on the excavation equipment bucket. In some cases when PVC or small size corrugated aluminum pipe is being set, it can be lowered into the ditch by hand. This new section of pipe is seated against the previously placed pipe and properly aligned. For large and/or heavy sections of pipe adjusting of the pipe to insure a proper seat against the
adjacent pipe can be accomplished by one of the following procedures:

1) Exerting a horizontal force on the pipe from the excavation equipment by pulling toward the adjacent pipe with the sling.

2) Pushing against the free end of the pipe with excavation equipment in the direction of the previous section. Note, care must be taken in utilizing this procedure so as to avoid damage to the free end of the pipe.

3) By embedding a crowbar in the ground directly in front of the free end of the new pipe section, the pipe can be pushed toward the adjacent section by pushing against the crowbar.

4) For pipes of sufficient size to allow access to the inside, a "come along" can be utilized as shown in Figure 11.

For all the methods described above, workers must be in the ditch to assist the pipe, operate the various apparatus and keep the pipe joints clear of any sand or obstruction so proper seating is achieved.

With this task complete the translucent target is placed in the invert of the pipe at the free end and
the alignment is checked. Minor alignment corrections can be made by pushing against the side of the end of the pipe with the excavation equipment or by using a crowbar. The checking of the grade is of greater concern at this time. It should be noted that only the free end of the pipe requires checking as the opposite end has been firmly seated in the previously placed pipe which, as long as it has not been disturbed, was previously confirmed to be on line and grade. The results of this grade check can result in the end of the pipe being too high, which would be indicated by the laser beam striking the target below the center, the pipe being too low, which would result in the beam striking the target higher than the center, or the pipe being set correctly, within acceptable tolerances.
Obtaining results of the pipe being either too high or too low requires removal of the section of pipe from the ditch and corrections made. Additional excavation can then be performed for pipe too high or replacement and compaction of embankment material for pipe sections too low. These additional tasks all involve workers in the ditch to correct the ditch bottom to the proper grade. Once the ditch has been adjusted a repeat of the procedure of placing the pipe in the ditch and properly seating the pipe is performed. The procedure above is repeated until satisfactory results can be obtained. Generally, if care is taken in reading the displacement of the laser beam from the center of the target only one additional adjustment is required as the ditch bottom is carefully corrected to coincide with the displacement. Still it is not unusual in practice to regrade a ditch bottom a third, or in rare occasions, a fourth time prior to achieving acceptable results. This is usually a factor of the skill and experience of the crew as well as the care that is taken in adjusting the grades.

The final step in completing the pipe installation process is to bed the pipe so as to insure it maintains the proper alignment. This is accomplished by
either concurrently or alternately placing and compacting embankment on the sides of the pipe in predetermined lifts to at least two-thirds the way up the sides of the pipe. If practical, it is desirable to initially place this fill in lifts to approximately one foot above the pipe. This provides additional pipe support and protection for the pipe. At this point work can commence on the next section of pipe.

**Explanation of Laser-Controlled Excavation Technique**

The new technique being proposed herewith involves the use of lasers for electronic distance measuring as well as for alignment establishment. In addition, automatic hydraulic controls and a small computer are involved.

When assembled, this system determines the location of the cutting edge of the excavation equipment bucket at a given instant in time and calculates the maximum depth of cut to be made accordingly. This depth is the required line to place the section of pipe on and insure that the pipe is on proper grade. In addition, the computer signals the automatic hydraulic controls and prevents the equipment operator from digging too deep. This is done by locking out the hydraulic system if an
attempt is made to exceed this depth. Figure 12 shows the basic systems set up.

Materials required for this system not normally utilized by pipe installation crews are:

1 - Tripod-mounted, helium-neon laser including optical modifications
1 - Electronic distance-measuring device (EDM)
3 - Rotational sensors, encoded with digital interface
1 - IBM PC (hardened type, i.e., AT or XT)
1 - Audible beeper
2 - Optical receivers
1 - Transmitter and receiver
1 - Omni-directional receiver
1 - Electrically driven receiver mast
1 - Electric mast control box
1 - Staged control valve

The system set-up and operation is as follows.

The tripod, surface-mounted laser is optically modified to emit a pulsed and horizontally widened beam toward the excavating equipment. The beam is pulsed or modulated so as to provide the proper signal for the EDM. See Figure 13 for a typical EDM set-up. The beam is intercepted by the cluster of the laser receiver, optical receivers and EDM reflector mounted on the excavator.
Figure 12. Proposed Laser Controlled Excavation System
This beam striking this cluster provides information regarding the system status for all three-dimension axes. By reflecting the pulsed beam off the EDM reflector back to the EDM receiver, mounted back at the tripod-mounted laser, the EDM receiver then provides an instantaneous distance, $X_1$, from the fixed laser to the pole-mounted cluster, to a radio transmitter which in turn sends this information to the IBM PC via the radio receiver. At the same time the laser receiver provides a signal to the electrically driven receiver mast which vertically adjusts to remain level with the laser beam. Also the electric mast control box provides a signal to the IBM PC.
as to the vertical orientation or dimension $y_1$, of the system. Lastly, the two optical receivers provide a signal dependent on the laser beams intensity to the audible beeper to provide a signal to the equipment operator as to the $z$ axis orientation of the excavator. It should be noted that this is not provided to the computer for analysis as the other data is and the reason for this shall be discussed later.

Based on the above, a three-dimension data collection system is available for the exact location of the mast-mounted sensors. By installing the rotational sensors on the three pivoting locations along the excavator's arms, the tip of the bucket can be monitored at any time. This is done by establishing a polar coordinate system for the rotating section with reference to the excavator body as shown in Figure 14.

By definition of polar geometry for a given point $P_x$, if polar coordinates are $(r_x, \theta_x)$ and this converts to a rectangular coordinate system of $(r_x \cos \theta_x, r_x \sin \theta_x)$. Therefore, the coordinates of $P_4$ in relation to $P_1$ at any time is given as $(r_1 \cos \theta_1 + r_2 \cos \theta_2 + r_3 \cos \theta_3, r_1 \sin \theta_1 + r_2 \sin \theta_2 + r_3 \sin \theta_3)$. As $r_1$, $r_2$ and $r_3$ are constants, and as $\theta_1$, $\theta_2$ and $\theta_3$ are continually provided to the computer by the rotational sensors, the
Figure 14. Rotational Geometry System

### POINT COORDINATES

<table>
<thead>
<tr>
<th>POINT</th>
<th>COORDINATES</th>
</tr>
</thead>
<tbody>
<tr>
<td>P₂</td>
<td>(r₁ cosθ₁, r₁ sinθ₁)</td>
</tr>
<tr>
<td>P₃</td>
<td>(r₁ cosθ₁ + r₂ cosθ₂A, r₁ sinθ₁ + r₂ sinθ₂A)</td>
</tr>
<tr>
<td>P₄</td>
<td>(r₁ cosθ₁ + r₂ cosθ₂A + r₃ cosθ₃A, r₁ sinθ₁ + r₂ sinθ₂A + r₃ sinθ₃A)</td>
</tr>
</tbody>
</table>

θ₂A = π + θ₁ + θ₂

θ₃A = θ₁ + θ₂ + θ₃
tip, or cutting edge of the bucket can constantly be calculated. Armed with the data collected above, the computer can then calculate from a reference point at the tripod laser along the proposed ditch bottom line the instantaneous X and Y orientation of the bucket with the following formulas:

\[ x_b = \text{location of the bucket along the } X \text{ (horizontal) axis} \]

\[ x_b = -X_1 + (r_1 \cos \theta_1 + r_2 \cos \theta_2 + r_3 \cos \theta_3) + C_1 \]

where \( C_1 \) is a constant horizontal distance from the electrical mast to point \( P_1 \).

\[ y_b = \text{location or height of the bucket along the } Y \text{ (vertical) axis}. \]

\[ y_b = Y_1 + (r_1 \sin \theta_1 + r_2 \sin \theta_2 + r_3 \sin \theta_3) \]

where \( Y_1 = 0 \) at the laser beam height which is established at the start of construction by initializing the laser receiver accordingly. It is also known that for any given \( X_d \), which is a horizontal distance along the line of the proposed ditch bottom, there exists a corresponding \( Y_d \), or depth at that point which can be calculated as \( Y_d = -S \cdot (X_d) + Y_s \), where \( S \) = slope in ft./ft. Therefore, for any given \( X_d = X_b \), \( Y_b \) must be greater than or equal to \( Y_d \), and if not the computer shall generate a signal to the staged control valve to activate the hydraulics to raise the bucket.
Based on the above, the following is a description of the way the system operates. The excavation equipment operator attempts to dig a trench as deep as possible. As he drops the bucket and pulls it toward him in order to dig, the computer will instantly advise the staged control valve when the bucket ($Y_b$) is equal to or less than the ditch bottom at that point ($Y_d$) and the staged control valve will raise the bucket or prevent it from going deeper. This hydraulic control connection can easily be made as most backhoes have a "cross" pattern control stick. Forward and back on the lever moves the bucket out and in respectively, whereas a side to side motion brings the bucket up and down. The staged control valve can be connected with hydraulic tubing on the excavation equipment corresponding to the "up" controls. This is the same type override device that is commonly used in an asphalt paver. This system has a previously installed stringline set relative to new paving grades which a rotational sensor rides along and signals the paving screed to move up or down and adjust the thickness of the asphalt mat on an instantaneous basis.

An example of the laser-controlled excavation system described above is as follows, and as shown in Figure 15.
Assume the following values for the system constants:

- $r_1$ = first arm length on excavation = 6 feet
- $r_2$ = second arm length on excavation = 7 feet
- $r_3$ = bucket opening = 2 feet
- $S$ = slope = 0.003 ft./ft. or 0.3%
- $X_0$ = location of EDM laser in the X direction = 0.0'
- $Y_0$ = height of instrument (H.I.) of laser = 0.0'
- $Y_S$ = proposed ditch bottom at instrument below $X_0$ = -6.0'
- $C_1$ = distance from electric mast to point $P_1$ in X axis = 3.0'

If, as shown in Figure 15 the variables in the system at this instant are:

- $X_1 = 1000$'
- $Y_1 = -4.0$'
- $\theta_1 = 30^\circ$
- $\theta_2 = 90^\circ$
- $\theta_3 = 110^\circ$

then $Y_b$ is calculated as:

$$Y_b = Y_1 + (r_1 \sin \theta_1 + r_2 \sin (\pi + \theta_1 + \theta_2) + r_3 \sin (\theta_1 + \theta_2 + \theta_3))$$
$$Y_b = -4 + (6(0.50) + 7(-0.87) + 2(-0.77)) = -8.63'$$

$X_b$ is calculated as:

$$X_b = X_1 - (r_1 \cos \theta_1 + r_2 \cos (\pi + \theta_1 + \theta_2) + r_3 \cos (\theta_1 + \theta_2 + \theta_3) - C_1$$
$$X_b = 1000' - (6(0.87) + 7(0.50) + 2(-0.64)) - 3.0 = 989.56'$$
The elevation along the proposed ditch bottom relative to the bucket location is calculated as:

\[ Y_d = -S(X_d) + Y_s \quad \text{where} \quad X_d = X_b \]

\[ Y_d = -0.003(989.56') - 6.0 = -8.97' \]

From the above it can be seen that at this instant in the example the cutting edge of the bucket, or \(X_b\) is at elevation \(-8.63'\) and the proposed ditch bottom elevation at this point along the X axis is \(Y_b = -8.97'\).

This means that since \(X_b \geq X_d\) then the operator can excavate an additional 0.34'. At that point any further digging would cause \(X_b < X_d\) and the computer shall signal the staged control valve to raise the bucket by overriding the hydraulic controls appropriately.

As previously mentioned, the laser beam from the EDM which strikes the cluster on the electrically driven mast hits the optical receivers which provide an audible signal to the equipment operator. This is the only portion of this system which does not provide data to the IBM PC. The reason for this is these receivers and the signal that is generated, provide data to the operator as to his position on the Z-axis or perpendicular to the director of pipe laying. As demonstrated in the review of pipe-laying techniques, the depth of the ditch is critical. Since the ditch is cut a minimum of 6" wider on
each side of the pipe than the pipe diameter, there is plenty of room for adjustment without requiring additional excavation once the pipe is placed in the ditch. As this axis is not critical, and by utilizing the audible signals provided to the operator to keep him relatively close on line, the use of computerized hydraulic controls are not required. As the laser beam has been widened, and if the excavation equipment moves off-line, the intensity striking one of the optical receivers will be greater than the other and an appropriate signal provided by the audible beeper will advise the operator which way to move. During excavation, the ditch cutting in the Z direction is not critical. When placing the pipe, the usual pipe laser, which is still required, shall be used to confirm the position of the pipe along this Z-axis. In the economic analysis in Chapter 5, no credit is considered for substituting the equipment specified for the new set up for the pipe laser currently used. The cost for the laser-controlled excavation system is all considered as additional costs over and above current costs.

Evaluation of Laser-Controlled Excavation Technique

As stated earlier in this chapter, this new technique shall be evaluated on the same criteria as the
existing available methods. This evaluation shall be
done in order of priorities as previously noted.

**Accuracy** - Compared with other methods of ditch
evacuation, this technique eliminates the guess work and
human element in the excavation process. The laser works
at the speed of light, the radio transmitter/receiver and
rotational sensors provide constant data to the computer,
and it is estimated that the IBM PC can work through the
calculations involved faster than the staged control
valve speed of approximately 10 adjustments per second.
This is significantly faster than an operator's hand
speed even if the operator could constantly "guess" the
proper depth along the ditch bottom. EDMs have proven
accuracy of $0.016 \text{ ft.} \pm 1 \text{ part per million (ppm)}$ at
distances from 50 ft. to 36 miles. This would mean at a
distance of 5000 feet, the standard deviation would be
$0.016 \text{ ft.} \pm 0.005 \text{ ft.}$ Remembering that the vertical
distance is only a fraction of the horizontal distance
due to the slope, the possible error in depth due to the
EDM is microscopic.

**Speed** - It has already been shown that by elimi-
nating the initial, and possible additional pipe place-
ment prior to achieving proper alignment, the time saving
of this portion of the work can be cut in half.
Cost - Chapter 5 contains an economic analysis of this system, wherein it is shown to be highly cost effective.

The above three features represented over 73 percent of contractor priorities from the survey responses.

Minimal Technical Skill Required - This item may be one of the few features which are jeopardized by the system. Due to the technical knowledge required to operate and understand maintenance requirements for the EDM and IBM, PC, additional skills will be required.

Ease of Equipment Assembly - Again a feature which may be reduced in desirability due to the extra equipment required.

Minimum Number of Persons Required - It should be expected that this system could be operated with the same crew size as used on a pipe laser crew. No additional work tasks have been either created or eliminated. The main impact on the work was, as previously mentioned, increased speed.

Equipment Capable of Performing Other Functions - It appears obvious that with the addition of the IBM PC and the EDM, all the standard functions provided by these
pieces of equipment could be made available to the contractor.

Equipment Size and/or Weight - Lastly, this function, which has a priority value of only 2.1%, would be adversely affected by the additional equipment required to operate the system.

As can be calculated from above, the functions which accounted for 77.2% of the priorities as shown on page 44 were improved. Only functions which had priorities of 16.1% were negatively affected. This indicates a positive improvement in features, which is important to the users.
A major consideration in an economic analysis of this proposed alignment technique is the potential cost savings due to improved safety. Work-related accidents cost billions of dollars each year and continues to escalate. Table 4 shows this increasing cost and a breakdown for some major items.

**TABLE 4**

**CERTAIN COSTS OF WORK-RELATED ACCIDENTS**

*(in billions of dollars)*

<table>
<thead>
<tr>
<th>Cost</th>
<th>1978</th>
<th>1982</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wage Loss</td>
<td>4.2</td>
<td>5.2</td>
</tr>
<tr>
<td>Medical Expense</td>
<td>2.5</td>
<td>3.6</td>
</tr>
<tr>
<td>Insurance Administration</td>
<td>3.9</td>
<td>5.9</td>
</tr>
<tr>
<td>Fire Loss</td>
<td>1.8</td>
<td>2.0</td>
</tr>
<tr>
<td>Indirect Work Loss</td>
<td>10.6</td>
<td>14.7</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>23.0</td>
<td>31.4</td>
</tr>
</tbody>
</table>

These accident costs in 1982 were equivalent to a cost of $320.00 for every worker in the U.S. to offset the accident expense.

In addition, in 1982 there were 11,200 work-related deaths and 1,900,000 work-related injuries.

Every job-related accident has the potential to incur all or a portion of the costs listed below as shown in Industrial Safety, Third Edition, by Roland P. Blake:

1) Cost of lost time of injured employee.

2) Cost of time lost by other employees who stop work;
   a. Out of curiosity.
   b. Out of sympathy.
   c. To assist injured employee.
   d. For other reasons.

3) Cost of time lost by foreman, supervisors, or other executives as follows:
   a. Assisting injured employee.
   b. Investigating the cause of the accident.
   c. Arranging for the injured employee's production to be continued by some other worker.
   d. Selecting, training, or breaking-in a
new worker to replace the injured employee.

e. Preparing state accident reports, or attending hearings before state officials.

4) Cost of time spent on the case by first-aid attendant and hospital department staff, when not paid for by the insurance carrier.

5) Cost due to damage to the machine, tools, or other property, or to the spoilage of material.

6) Incidental cost due to interference with production, failure to fill orders on time, loss of bonuses, payment of forfeits, and other similar causes.

7) Cost to employer under employee welfare and benefit systems.

8) Cost to employer in continuing the wages of the injured worker in full, after he returns to work—even though the services of worker (who is not yet fully recovered) may, for a time, be worth only about half of their normal value.

9) Cost due to the loss of profit on the
injured worker's productivity and on idle machines.

10) Cost of subsequent injuries that occur in consequence of the excitement or weakened morale due to the original accident.

11) Overhead cost per injured worker—the expense of light, heat, rent and other such items which continue while the injured employee is a nonproducer.

In addition to this list other costs may include:

1) Insurance rate increases
2) Litigation
3) Loss of product or service image to company due to news of accident.
4) Compensation costs to worker for permanent disabilities.

The construction industry is a major contributor to these accidents and associated costs and has a higher-than-average rate of accidents. The U.S. Department of Labor, Bureau of Labor Statistics, reported the construction industry accounts for 19 percent of all fatalities and nearly 12 percent of all injuries and illnesses in the private nonfarm work sector.
Conversely, the construction industry accounted for only six percent of the work force during the survey period.

The Bureau also found that for all industries surveyed, that when reviewing the cases in which workdays were lost, the average time involved was 13 days, whereas in the heavy construction industry this lost time increased to 15 days, thereby indicating the severity of the injuries may also be greater.

Although specific statistics are not kept on the number or frequency of workers injured or killed while installing underground pipes, the data in Table 5 for 1982 and 1983 (latest available years) was obtained from the U.S. Department of Labor, Bureau of Labor Statistics.

In establishing a weighted average for these three industries as defined by the 1972 Standard Industrial Classification (SIC) Manual which may include accidents of the nature relevant to pipe installation the following is found:

Total Employment: \( 787,400 + 20,700 + 52,500 = 860,600 \) (1983)

Total Incidence: \( \frac{787,400 \times 15.4}{100} + \frac{20,700 \times 4.2}{100} + \frac{52,500 \times 20.9}{100} = 133,100 \)
### TABLE 5

<table>
<thead>
<tr>
<th>Industry</th>
<th>1983 Annual Average Employment (thousands)</th>
<th>1983 Annual Average Employment (thousands)</th>
<th>Total Cases</th>
<th>Lost Workday Cases</th>
<th>Non-Fatal Cases Without Lost Workdays</th>
<th>Lost Workdays</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy Construction</td>
<td>787.4</td>
<td>15.1</td>
<td>15.4</td>
<td>5.8</td>
<td>6.2</td>
<td>9.2</td>
</tr>
<tr>
<td>Pipe Lines</td>
<td>20.7</td>
<td>5.0</td>
<td>4.2</td>
<td>2.0</td>
<td>1.5</td>
<td>3.0</td>
</tr>
<tr>
<td>Sanitary Services</td>
<td>52.5</td>
<td>20.5</td>
<td>20.9</td>
<td>11.5</td>
<td>11.1</td>
<td>9.0</td>
</tr>
</tbody>
</table>

Lost Workday Cases (1983): \[
\frac{787,400 \times 6.2}{100} + \frac{20,700 \times 1.5}{100} + \frac{52,500 \times 11.1}{100} = 54,960
\]

Non-Fatal Cases: \[
\frac{787,400 \times 9.2}{100} + \frac{20,700 \times 2.7}{100} + \frac{52,500 \times 9.8}{100} = 78,145
\]

Lost Workdays: \[
\frac{787,400 \times 122.4}{100} + \frac{20,700 \times 24.7}{100} + \frac{52,500 \times 170.1}{100} = 1,058,190
\]

From this it can be implied that there are:

1,058,190 Lost Workdays/54,960 cases = 19.3 Lost Workdays/Case

Fatal Cases: 133,100 - 78,145 = 54,955 or 41% of the total incidents

With an incident rate of 133,100 incidents/860,600 employees or 15.5/100 full time workers and considering 6.8 men on the average pipe laying crew utilizing a laser, a given contractor can expect 1.05 accidents per crew per year. In addition, it would appear that there is a 59% chance that this accident would prove to be non-fatal and a 41% chance that a death would occur as a result of the accident.

It can be shown from a Poisson series for probability distribution, and the definition of expected
values, that the expected value (cost) of an accident is:

\[ E(V_k) = \sum P_k \cdot V_k \]

where:

- \( E(V_k) \) = Expected value of \( k \) mishap events
- \( P_k \) = Probability of \( k \) mishap events
- \( V_k \) = Value of \( k \) mishap events

In other words, the sum of all possible mishaps times the probability of the mishap occurring during an exposure time \( t \) is equal to the expected value during the exposure time.

If we consider the mishaps possible to occur during a pipe laying operation to be strictly a generic non-fatal accident or a death, of which the possibilities of each are statistically shown above, then the expected value (cost) per year can be calculated if the value or cost of each type of mishap is known.

**Costs Due to an Accident**

For a generic non-fatal accident the following costs are assumed to be of an average value:

1) Cost of lost time of injured employee.

   It was previously noted that the average lost work days per accident is 19.3. If this worker makes $10.00 per hour and his employer's payroll burden is
35% for vacation, holidays, sick leave, insurance, etc., then this cost would be:
19.3 days x 8 hours/day x ($10.00/hour x 1.35) = $2,084

2) Cost of time lost by other employees who stop work.

   If you assume this accident disrupts the entire 6.8 man crew less the injured employee and the Foreman (his cost shown in number 3 below) for two hours each, this cost becomes: 4.8 men x 2 hours x ($10.00/hour x 1.35) = $130

3) Cost of Foreman, supervisor or other executive.

   Assume two people are required to expend one day each for this effort at an average pay rate of $15.00/hour and the same payroll burden. This cost is:
   2 men x 8 hours x ($15.00/hour x 1.35) = $324

4) Cost of time spent on case by first-aid attendant, hospital department staff, when not paid by the insurance carrier.

   According to information from various insurance carriers it can be determined that the cost for these services are always borne by the insurance company except in extremely unusual cases. One instance which may cause additional expenses to the contractor is if the injured employee is transported to a hospi-
tal or doctor by another worker. This would incur additional lost time for other employees, but for this example this cost shall be considered as part of number 2 above. Therefore, no costs shall be assumed for this item. Any actual costs will further justify the use of this alternative method as will be shown later.

5) Cost due to damage to the machine, tools, or other property, or to the spoilage of materials.

This cost can vary drastically depending on the circumstances of the accident. Extremes can range from no cost to the cost of replacing a backhoe. It should be assumed to be conservative to estimate this cost at $500 per incident.

6) Incidental cost due to interferences with production, failure to fill orders on time, loss of bonuses, payment of forfeits, and other similar causes.

With most projects having liquidated damage clauses for late completion which can be as high as $1,000 per day, a $200 cost for this item is assumed.

7) Cost to employer under employee welfare and benefits system.

This cost is directly related to the cost of Workmans Compensation and modifications to the rates
for this insurance. These modifications, or mod rates, are calculated from the contractor's past safety records. A mod rate of 0.8 would provide a contractor with a 20 percent discount in his insurance premiums whereas a mod rate of 1.3 would require a contractor with a poor safety record to pay a 30 percent increase in his premiums. No cost is to be considered here as this is all calculated in number 12 below.

8) Cost to employer in continuing the wages of the injured worker in full, after his return even though the service of worker may, for a time, be worth only about half of their normal value.

   It is assumed that if the average incident causes an employee to be out of work for 19.3 days, then once he returns it will take approximately half that time or 10 days to get back to full productivity. During this 10-day period estimate his production at half the normal rate. Therefore, the lost value is:

   \[ 10 \text{ days} \times 4 \text{ hours/day} \times ($10.00/\text{hour} \times 1.35) = $540 \]

9) Cost due to the loss of profit on the injured worker's productivity and on idle machines.

   It shall be assumed that the only crew member which could affect machine productivity and therefore
the machinery profits is the backhoe operator. Since the increased level of safety provided by the new alignment technique described herein is for the workers in the ditch, the lost machinery profits shall not be considered as it would not be affected in this analysis. The lost profit due to the productivity of the worker can be considered 10 percent of item 8 above. Ten percent is used as this is a reasonable expectation for company profits for this type of work.

$540 \times 0.10 = $54

10) Cost of subsequent injuries that occur in consequence of the excitement or weakened morale due to the original accident.

This cost is extremely difficult to quantify. Accidents do sometimes occur soon after the initial incident due to the nervousness of other workers, excitement, or workers not concentrating on their job due to their fellow worker's injuries. In addition, the initial incident can create a productivity loss due to overcautiousness after the accident or lowered morale. This potential reoccurring accident may occur in 1 out of 10 cases and the productivity loss may approximate 10 percent. Therefore, this cost
shall be assumed to be 10 percent of all other costs. The total of the other costs as shown in Table 7 is $20,431 or this cost would be $2,043.

11) Overhead cost per injured worker. The expense of light, heat, rent and other such items which continue while the injured employee is a nonproducer.

As many of the previously listed standard accident cost show, this cost mainly applies to the injury of a worker employed in a factory or office. Overhead costs for construction workers mainly apply to office support staff and expendable supplies to support the field crews. This includes payroll clerks, secretaries, copy machines, office supplies, etc. This cost is estimated at 5 percent of wages during this worker's non-productive time (numbers 1 and 8 above):

\[(\$2,084 + \$540) \times 0.05 = \$131\]

12) Insurance rate increase.

Contractors typically carry three types of insurance. The first is Premises and Business Liability. This insurance protects the contractor from expenses due to accidents or injury to non-employees. Examples of this are salesmen injured at the contractor's office or jobsite as well as
"sidewalk superintendents" or children who may be hurt at the jobsite. The second type of insurance is Professional Liability. This protects the contractor for errors in the performance of his work. Examples of this, for the type of contractor discussed in this paper, would be collapsed pavement due to improper backfill or leaking pipe. Another example would be improper alignment found in completed work requiring large expenses to rework. The last type of accident coverage (excluding vehicular insurance) is Workers Compensation Insurance which is the type covering the worker-related accidents, injury or death to be considered here. Workers Compensation Insurance can cover anything from on-site first aid expense due to a minor cut or as significant a claim as remodeling an employee's home for handicapped accessibility due to a permanent disabling injury requiring the injured person to be confined to a wheelchair. Workers Compensation premiums are generally calculated based on a percentage of the contractor's total annual payroll. For our analysis the following shall be assumed:

Total number of employees: 30
Average weekly payroll per employee: $500.00
Safety Modification rate of 1.0 or average safety record

Based on the above this contractor's annual payroll is:

30 persons x $500/person/week x 50 weeks/year = $780,000/year

Estimated rate for Workman Compensation Insurance from a local insurance agent for this type of work is 9.43 percent:

$780,000 x 9.43% = $73,554

General reductions in premiums are provided for rates greater than $5,000 per year. In this case, the premium is $68,554 over this $5,000 limit and the quoted discount by the insurance agent was 9.5 percent or

$68,554 x 9.5% = $6,513 discount

$73,554 - $6,513 = $67,041 premium per year

Adjustments to insurance rates based on safety are made by modifying the calculated rate by a factor called a mod rate. In this case, as previously stated, we estimated an initial mod rate of 1.0, or assuming an average safety record. Mod rates can increase due to an accident as high as 1.4 due to

expenses incurred and the severity of the incident. The insurance agent consulted indicated that an increase in the mod rate of 1.1 would be very conservative for the type of accident being considered in this analysis in which a worker is required to be out of work for approximately 19 days. Therefore, an increased premium of 10 percent, or $6,704, could be expected by the contractor.

13) Litigation.

If the circumstances of the accident indicate negligence on the employer's part or if the severity of the accident warrants additional compensation to the injured worker, a lawsuit may occur. The results of this litigation shall not be considered here as any additional compensation made will either be from the employer's insurance carrier and not considered an expense to the company, or shall be a cost considered in number 15 below. Consultation with a local attorney\(^1\) revealed legal expenses to defend a case of this nature could cost from $50,000 to $100,000 to defend, but so as to be conservative we shall assume this cost to be $35,000. Assuming 10

\(^1\)Interview with Andrew Showen, Foley & Lardner Van den Berg, Gay, Burke & Wilson, Orlando, Florida, July, 1985.
percent of all injuries go to court, this annual cost comes to $3,500.

14) Loss of product or service image to company due to news of accident.

This again is a cost not common to construction work. As most work is procured through a bidding process, company image will not prohibit the contractor from obtaining work. This may affect the contractor's ability to get selected by an owner for projects on a negotiated fee basis. Therefore, this cost shall be assumed to be 1 percent of all other items or: $22,474 x 1% or $225

15) Compensation costs to worker for permanent disabilities.

Generally this cost would be absorbed by the company's insurance carrier. In the case of negligence or due to deductible amounts in the insurance coverage a portion of this cost may be absorbed by the contractor. Listed below is the American Standard Scale of time charges for disabling injuries. Assuming that only 10 percent of all cases involve permanent injuries and of those, the contractor's liability is only 25 percent, this shall
be used based on an average of all disabilities as shown in Table 6 below.

**TABLE 6**

**THE AMERICAN STANDARD SCALE OF TIME CHARGES**

<table>
<thead>
<tr>
<th>Disability</th>
<th>Equivalent Loss of Work Days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permanent Total Disability</td>
<td>6,000</td>
</tr>
<tr>
<td>Arm, at or above elbow</td>
<td>4,500</td>
</tr>
<tr>
<td>Arm, below elbow</td>
<td>3,600</td>
</tr>
<tr>
<td>Hand</td>
<td>3,000</td>
</tr>
<tr>
<td>Thumb</td>
<td>600</td>
</tr>
<tr>
<td>Any one finger</td>
<td>300</td>
</tr>
<tr>
<td>Two fingers, same hand</td>
<td>750</td>
</tr>
<tr>
<td>Three fingers, same hand</td>
<td>1,200</td>
</tr>
<tr>
<td>Four fingers, same hand</td>
<td>1,800</td>
</tr>
<tr>
<td>Thumb and one finger, same hand</td>
<td>1,200</td>
</tr>
<tr>
<td>Thumb and two fingers, same hand</td>
<td>1,500</td>
</tr>
<tr>
<td>Thumb and three fingers, same hand</td>
<td>2,000</td>
</tr>
<tr>
<td>Thumb and four fingers, same hand</td>
<td>2,400</td>
</tr>
<tr>
<td>Leg, at or above knee</td>
<td>4,500</td>
</tr>
<tr>
<td>Leg, below knee</td>
<td>3,000</td>
</tr>
<tr>
<td>Foot</td>
<td>2,400</td>
</tr>
<tr>
<td>Great toe or any two or more toes, same foot</td>
<td>300</td>
</tr>
<tr>
<td>Two great toes</td>
<td>600</td>
</tr>
<tr>
<td>One eye, loss of sight</td>
<td>1,800</td>
</tr>
<tr>
<td>Both eyes, loss of sight</td>
<td>6,000</td>
</tr>
<tr>
<td>One ear, loss of hearing</td>
<td>600</td>
</tr>
<tr>
<td>Both ears, loss of hearing</td>
<td>3,000</td>
</tr>
<tr>
<td>Average</td>
<td>2,320</td>
</tr>
</tbody>
</table>


With an average of 2,320 days lost and based on the estimated frequency given above, this cost comes to:

\[
2,320 \text{ days} \times 8 \text{ hours/day} \times (\$10.00/\text{hour} \times 1.35) \times 10\% \text{ chance of permanent disability} \times 25\% \text{ expense to contractor} = \$6,264.
\]
The total cost for all 15 items above comes to $22,699 as shown in Table 7 below. This shall be called $V_I$ or value of an injury. The value due to a death shall be noted as $V_D$.

**TABLE 7**

**ESTIMATED COST DUE TO AN ACCIDENT**

<table>
<thead>
<tr>
<th>ITEM NUMBER</th>
<th>ASSOCIATED COST</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$2,084</td>
</tr>
<tr>
<td>2</td>
<td>$130</td>
</tr>
<tr>
<td>3</td>
<td>$324</td>
</tr>
<tr>
<td>4</td>
<td>$0</td>
</tr>
<tr>
<td>5</td>
<td>$500</td>
</tr>
<tr>
<td>6</td>
<td>$200</td>
</tr>
<tr>
<td>7</td>
<td>$0</td>
</tr>
<tr>
<td>8</td>
<td>$540</td>
</tr>
<tr>
<td>9</td>
<td>$54</td>
</tr>
<tr>
<td>11</td>
<td>$131</td>
</tr>
<tr>
<td>12</td>
<td>$6,704</td>
</tr>
<tr>
<td>13</td>
<td>$3,500</td>
</tr>
<tr>
<td>15</td>
<td>$6,264</td>
</tr>
<tr>
<td>Subtotal</td>
<td>$20,431</td>
</tr>
<tr>
<td>10 (10%)</td>
<td>$2,043</td>
</tr>
<tr>
<td>Subtotal</td>
<td>$22,474</td>
</tr>
<tr>
<td>14 (1%)</td>
<td>$225</td>
</tr>
<tr>
<td>TOTAL</td>
<td>$22,699</td>
</tr>
</tbody>
</table>

**Costs Due to a Death**

The next cost to be calculated is the expected expense to a contractor due to a death. In reviewing the items previously estimated for an injury the following would apply to an accident involving a death.

1. Cost of time lost by other employees who stop work.

   Estimated previously to be $130.
2. Cost of foreman, supervisor or other executive.
   Assume same effort required for documentation of a death or $324.

3. Cost due to damage to the machine, tools or other property, or to the spoilage of materials.
   Estimated previously to be $500.

4. Incidental cost due to interference with production, failure to fill orders on time, loss of bonuses, payment of forfeits, and other similar causes.
   Estimated previously to be $200.

5. Cost due to the loss of profits on the injured worker's productivity and on idle machinery.
   Estimated previously to be $54.

6. Cost of subsequent injuries that occur in consequence of the excitement or weakened morale due to the original accident.
   Previously estimated to be $2,043. Note, this is based on the subsequent accident being an injury not another death.

In addition to the above, the following items as discussed in the case of an injury would also apply but at a different anticipated expense.
7. Insurance rate increase.

Due to a death involved in an accident, a larger mod rate would probably be used to adjust the contractor premium than in the case of an injury. Let us assume the adjusted mode rate would be 1.2 for a death or a 20 percent increase, which again may be slightly conservative. This would generate an increase in the Workmans Compensation premium of $13,408.

8. Litigation.

In the case of a death, it shall be assumed that a higher percentage of cases would go to court than in the case of an injury. It shall be assumed that 50 percent end up in litigation. In addition, the expected court costs shall be assumed to increase to $50,000. Therefore, the expected cost for litigation per death shall be $25,000.

9. Loss of product or service image to company due to news of accident.

Assume the cost of damage to company image to be double that of an injury in the case of a death, or $426.

10. The final cost to consider here is compensation to the employee's family due to the death. From the
American Standard Scale of time charges a death is considered same as a permanent total disability as the person can no longer be a wage earner for his family. Therefore, 6,000 work days are used. It should be noted that this 6,000-day figure was not arbitrarily selected, but rather based on statistics furnished by life insurance companies which found the average man killed in an industrial accident to have had a life expectancy of approximately 20 years of work remaining. This can be shown by:

\[
\frac{6,000 \text{ days}}{5 \text{ days/week} \times 52 \text{ weeks/year}} = 23 \text{ years and this is denoted in the safety manuals as approximately 20 years. Also, if you estimate that the average worker puts in an average of 6 hours of paid overtime per week or 5.75 days per week you will arrive at almost exactly 20 years. As opposed to the case of an injury it shall be assumed that the contractor has only a ten percent liability for this expense, whereas the remaining 90 percent would be paid by the insurance carrier. This cost therefore is calculated as:}
\]

\[
6,000 \text{ days} \times 8 \text{ hours/day} \times (\$10.00/\text{hour} \times 1.35 \times 10\%) = \$64,800
\]
The total of the above ten items comes to $106,785 as shown in Table 8.

### TABLE 8

<table>
<thead>
<tr>
<th>ITEM NUMBER</th>
<th>ASSOCIATED COSTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$103</td>
</tr>
<tr>
<td>2</td>
<td>$324</td>
</tr>
<tr>
<td>3</td>
<td>$500</td>
</tr>
<tr>
<td>4</td>
<td>$200</td>
</tr>
<tr>
<td>5</td>
<td>$54</td>
</tr>
<tr>
<td>6</td>
<td>$2,043</td>
</tr>
<tr>
<td>7</td>
<td>$13,408</td>
</tr>
<tr>
<td>8</td>
<td>$25,000</td>
</tr>
<tr>
<td>9</td>
<td>$426</td>
</tr>
<tr>
<td>10</td>
<td>$64,800</td>
</tr>
<tr>
<td>TOTAL</td>
<td>$106,885</td>
</tr>
</tbody>
</table>

**Total Safety Costs**

The total expected value of expenses to a contractor in a given year due to accidents involving injury or death as described above is:

\[
E(V_T) = (P_I \cdot V_I + P_D \cdot V_D)
\]

\[
E(V_T) = (0.59 \times 22,699) + (0.41 \times 106,885) = 57,215
\]

If you estimate that half the time spent in the ditch by any crew member is for aligning the pipe, and if this time can be reduced in half by insuring that the pipe is on line and grade the first attempt, then the total annual savings is 25% of $57,215 or $14,304.
Labor Savings

The next factor to consider in this economic analysis is the labor savings due to the alternative technique. Assuming a typical pipe crew of 6.8 men work 48 weeks per year. This will allow two weeks for vacation and an additional two weeks for holidays, sick time, etc. Also assume an average 40 hours of work per week. The total manhours worked are then:

\[ 48 \text{ weeks} \times 40 \text{ hours/week} \times 6.8 \text{ men} = 13,056 \text{ manhours} \]

As shown in Figure 4, the alignment process accounts for 20% of the total pipe installation time or 2,611 manhours. If the average pipe is currently placed twice prior to obtaining an alignment within allowable tolerances and this alternative technique can achieve the results in one placement, this time can be cut in half, or a saving of 1,306 manhours per year. At the previously used payrate of $10.00 per hour plus 35% burden this comes to an annual savings of:

\[ 1,306 \text{ manhours} \times \$10.00 \text{ per hour} \times 1.35 = \$17,630.00 \]

Table 9 below indicates the estimated one time equipment cost required for the alternative technique.
TABLE 9
LASER-CONTROLLED EXCAVATION EQUIPMENT COSTS

<table>
<thead>
<tr>
<th>EQUIPMENT</th>
<th>COST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tripod Mounted Laser</td>
<td>$9,000</td>
</tr>
<tr>
<td>Optical Modifications to Laser</td>
<td>50</td>
</tr>
<tr>
<td>EDM Receiver and Reflector</td>
<td>3,000</td>
</tr>
<tr>
<td>Encoded Rotational Sensors (3)</td>
<td>900</td>
</tr>
<tr>
<td>IBM PC AT or XT</td>
<td>2,000</td>
</tr>
<tr>
<td>Optical Receivers (2)</td>
<td>100</td>
</tr>
<tr>
<td>Audible Beeper</td>
<td>200</td>
</tr>
<tr>
<td>Radio Transmitter &amp; Receiver</td>
<td>2,000</td>
</tr>
<tr>
<td>Omni-Directional Receiver</td>
<td>2,450</td>
</tr>
<tr>
<td>Receiver Mast</td>
<td>1,975</td>
</tr>
<tr>
<td>Electric Mast Control Box</td>
<td>1,550</td>
</tr>
<tr>
<td>Staged Control Valve</td>
<td>1,095</td>
</tr>
<tr>
<td>Misc. Modifications and Wiring</td>
<td>250</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td><strong>$24,570</strong></td>
</tr>
<tr>
<td>50% Design Fee</td>
<td>12,285</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$36,855</strong></td>
</tr>
</tbody>
</table>

Total Annual Savings of System

If it is estimated that the equipment has a life expectancy of five years, which is conservative, and an annual maintenance cost of $2,000 with no salvage value, the annual savings can be expressed as follows:

Annual saving due to safety + Annual labor savings - Total equipment cost spread over 5 years - Annual maintenance cost = Total annual savings

With an annual interest rate (i) of 12% and a capital recovery factor of 0.277, this cost comes to:

$14,304 + $17,630 - $36,855 (0.277) - $2,000 = $19,725
The above cost analysis demonstrates the described system is cost effective due to the factors considered.

In Chapter IV it was shown that by utilizing the laser-controlled excavation system, both accuracy and speed of installing pipe can be improved. The above analysis demonstrates the economic feasibility of the system by utilizing conservative estimates. The combination of these factors, which were noted as being of significant importance to contractors, demonstrate the need and desire for such a system in the pipe installation/alignment industry.
CHAPTER VI

CONCLUSIONS

Results of Research

It was shown in Chapter I that significant savings can be recovered in the construction of piping systems. This paper was an attempt to recover a portion of the potential saving in one area of piping. Obviously, much more research is needed to improve other aspects such as industrial piping, pressure piping systems and even improvements in other tasks involved in the installation of underground gravity flow systems. One of the significant points in the Business Roundtable reports was the analysis that revolutionary new technology is not required to realize the anticipated savings. By just utilizing existing technology, or improving the technology to average that of other areas of construction, the construction costs of pipe installation can be reduced significantly.

The laser-controlled excavation procedure described herein was one small improvement in this vast realm of piping system which can be improved by utilizing currently available equipment, but arranging it in a manner which has never before been attempted.
Subsequent work in this research revealed the lack of coordination between the design professionals and construction industry to develop acceptable tolerances to both parties. It was demonstrated that by minimal analysis during design, tolerances can be established on a project-by-project basis which can result in a final product acceptable for the purpose intended. These tolerances can also be reasonable from a construction standpoint, and also provide the agency responsible for accepting the system, guidelines which do not require an absolute finished product.

**Critique of Laser-Controlled System**

As very few things in this world are perfect, the same holds true for the laser-controlled excavation system described in this paper. The following are some of the shortcomings of the system which may be corrected by further study. These corrections may be found in currently available technology which was utilized in the development of this paper, or may be found in future technological breakthroughs.

1) The new system shall probably require additional set-up time. Due to the need to set the EDM and pipe laser, additional time will
be required. Note all other equipment (i.e., computer, electrical mast with cluster, rotational sensors, etc.) can remain on the excavation equipment if secured from vandalism and protected by the weather. Additionally, each time the system is set up, the various constants for the particular location will have to be manually loaded into the computer. Certainly the program can be written "user-friendly" to minimize this task, but still the data must be entered.

2) As in most systems, the more complex, the greater the chance of mechanical breakdown and possibly an increase in down time. It cannot be determined as to how these breakdowns will impact a crew's productivity until such time as a prototype is built and tested, but the impact should be considered.

3) The major factor in calculating the economic analysis is based on reduced costs due to safety. Although it was attempted to keep all the numbers conservative so as to provide the minimum saving possible, it still
may be difficult to sell the idea to contractors. When it comes to safety, most contractors, and especially small firms, would be reluctant to expend approximately $37,000.00 to prevent accidents. Most contractors would rather "roll the dice" and hope a severe accident or death does not occur on one of their jobs. Possibly the company that has had historically a bad safety record may give the system a try to reverse their record. It may also be discovered that these firms with the bad safety records are no longer in business.

Conversely, the company with a good safety program, insists on worker awareness and conscientiously performs the required work, will have a good safety record and would not be able to justify the cost from a safety standpoint.

Even so, as lasers and related equipment costs continue to decrease as they have over the last decade, and as labor costs continue to escalate as they historically do, a point in time will soon arrive, where the savings due to labor will overtake the initial equipment outlay costs.
Even with consideration given for the above potential problems the laser-controlled excavation system can improve upon the current state of the art procedures. By improving accuracy of pipe being laid, and the decrease in time by eliminating excavation "guesswork," drastic economic gains are obtained. Possibly the most significant achievement is found in the area of safety. By reducing the worker's exposure, accident probability is decreased. Even though an economic analysis can be performed on the cost of an accident or death, do they accurately portray the actual loss? Possibly if only one life is saved every year by utilizing such a system, the expense and effort would be justified.
APPENDIX 1
CONTRACTORS QUESTIONNAIRE

PART I - RESPONDANT INFORMATION
(Questions 1 through 3 not required)

1. Name ________________________________________________

2. Address ______________________________________________

3. Phone No. (  ) ________________

4. Title ________________________________________________

5. Brief Experience Description:

6. Years Experience in Pipe Installation: ____________________

PART II - PIPE INFORMATION

1. Have you in the last 3 years installed the following type of Pipe?

<table>
<thead>
<tr>
<th>SIZE INSTALLED</th>
<th>YES</th>
<th>NO</th>
<th>MAX.</th>
<th>MIN.</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Reinforced Concrete</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B. Steel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C. Corrugated Metal</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D. Plastic or PVC</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E. Transite</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F. Clay</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G. Others (list):</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

PART III - ALIGNMENT PROCEDURES

1. Show percent usage of various methods to align pipe:

Laser ______%  
Transit or Level ______%  
Batter Boards ______%  
Others (list):
2. Unless you indicated 100% for one particular technique, please describe how alignment procedure is selected (i.e. equipment or personnel availability, pipe size, trench depth, etc.):

3. Indicate estimated time to set-up the following equipment to begin checking pipe alignment:

   A. Laser _____ minutes
   B. Transit or Level _____ minutes
   C. Installation of batter boards for 1000' of pipe: _____ minutes

4. For the following methods, estimate the time required to properly align one (1) section of pipe in rough excavated ditch? (assume 8 foot section 36" RCP).

   A. Laser _____ minutes
   B. Transit or Level _____ minutes
   C. Batter Board _____ minutes

PART IV - CREW DATA

1. Please list the number of personnel required on the average pipe installation crew based on the various alignment techniques.

<table>
<thead>
<tr>
<th>Worker Classification</th>
<th>NUMBER OF WORKERS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Batter Board</td>
</tr>
<tr>
<td>Foreman</td>
<td></td>
</tr>
<tr>
<td>Laborer</td>
<td></td>
</tr>
<tr>
<td>Equip. Operator</td>
<td></td>
</tr>
<tr>
<td>Surveyors</td>
<td></td>
</tr>
<tr>
<td>Carpenters</td>
<td></td>
</tr>
<tr>
<td>Mechanics</td>
<td></td>
</tr>
<tr>
<td>Pipe Layers</td>
<td></td>
</tr>
<tr>
<td>Others (list)</td>
<td></td>
</tr>
</tbody>
</table>
PART V - PRODUCTION

1. Do you feel the output in pipe installation is affected by the various alignment techniques, and if so, how?

2. Do you feel the cost per section of pipe installed is affected by the various alignment techniques, and if so, how?

3. Have you ever installed pipe in a curved alignment (horizontal or vertical) as opposed to making alignment changes in structures only? If yes, please describe why and how often you have done this.

4. List advantages for the various methods of pipe alignment procedures (i.e. accuracy, speed, cost, project size, weather or ground conditions, technical skills required, complexity, etc.).

Batter Boards:
5. List disadvantages for the various methods of pipe alignment procedures (same criteria as above as well any others you may know of):

Batter Boards:

Transit or Level:

Laser:
6. What other phases of pipe installation cause problems for you in establishing proper alignment (i.e. improper compaction of bedding, excavation techniques or procedures, pipe material tolerances or design, etc.):

7. For research in developing new alignment techniques and equipment, what features not currently available would you like to see?

8. For the features listed below, rank the top five (5) as far as importance to you in properly aligning pipe (1 = most important):

   ____ Cost
   ____ Accuracy
   ____ Speed
   ____ Ease of Equipment Assembly
   ____ Minimal Technical Skills Required
   ____ Minimum Number of Persons Required
   ____ Equipment Size and/or Weight
   ____ Equipment Capable of Performing Other Functions
   Others (list)

   ____
   ____
   ____
   ____
   ____
APPENDIX 2
LIST OF CONTRACTORS SURVEYED

<table>
<thead>
<tr>
<th>Company Name</th>
<th>Address</th>
<th>City, FL</th>
<th>Zip Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>A &amp; B Utilities</td>
<td>P. O. Box 3367</td>
<td>Hialeah</td>
<td>33013</td>
</tr>
<tr>
<td>T.W. Blount Jr. &amp; Son Contr.</td>
<td>10249 Beach Blvd.</td>
<td>Jacksonville</td>
<td>32216</td>
</tr>
<tr>
<td>Central Fla. Underground, Inc.</td>
<td>745 Clay Street</td>
<td>Winter Park</td>
<td>32789</td>
</tr>
<tr>
<td>Coastal Pipeline, Inc.</td>
<td>104 N.W. Spanish River Blvd.</td>
<td>Boca Raton</td>
<td>33431</td>
</tr>
<tr>
<td>Dade Utility Contractors, Inc.</td>
<td>1385 S.W. 139th Ct.</td>
<td>Miami</td>
<td>33186</td>
</tr>
<tr>
<td>Dawkins &amp; McGucken Inc.</td>
<td>420 S. Rome Avenue</td>
<td>Tampa</td>
<td>33606</td>
</tr>
<tr>
<td>H.L.H. Corporation</td>
<td>1102 Kissimmee</td>
<td>Kissimmee</td>
<td>32144</td>
</tr>
<tr>
<td>Hubbard Construction Co.</td>
<td>P. O. Box 7217</td>
<td>Orlando</td>
<td>32854</td>
</tr>
<tr>
<td>Jobalia Construction Co.</td>
<td>3875 Nova Rd.</td>
<td>Pt. Orange</td>
<td>32019</td>
</tr>
<tr>
<td>A.J. Johns, Inc.</td>
<td>3225 Anniston Rd.</td>
<td>Jacksonville</td>
<td>32216</td>
</tr>
<tr>
<td>C. J. McGeehan</td>
<td>700 48th Street South</td>
<td>St. Petersburg</td>
<td>33711</td>
</tr>
<tr>
<td>Orange Environmental Services</td>
<td>S. Orange at Mary Jess Rd.</td>
<td>Orlando</td>
<td>32959</td>
</tr>
<tr>
<td>Pipe Line Const. of Fla.</td>
<td>128 Magnolia Dr.</td>
<td>Longwood</td>
<td>32750</td>
</tr>
<tr>
<td>Ric-Man International</td>
<td>P. O. Box 10229</td>
<td>Pompano Beach</td>
<td>33061</td>
</tr>
<tr>
<td>Rosa Corporation</td>
<td>750 S. E. Lake Street</td>
<td>Longwood</td>
<td>32750</td>
</tr>
<tr>
<td>Rose Engineering Contractors</td>
<td>P. O. Box 344</td>
<td>Hialeah</td>
<td>33011</td>
</tr>
<tr>
<td>Southeast Underground Const. Inc.</td>
<td>P. O. Box 1428</td>
<td>Cape Coral</td>
<td>33910</td>
</tr>
<tr>
<td>Southland Underground, Inc.</td>
<td>12570 66th Street N</td>
<td>Largo</td>
<td>33540</td>
</tr>
<tr>
<td>Token Development, Inc.</td>
<td>5401 Godfrey Rd.</td>
<td>Pompano Beach</td>
<td>33067</td>
</tr>
<tr>
<td>Village Plumbers</td>
<td>15332 N.W. 7th Avenue</td>
<td>Miami</td>
<td>33169</td>
</tr>
<tr>
<td>Waysun Underground Utilities</td>
<td>6235 Shirley Street</td>
<td>Naples</td>
<td>33940</td>
</tr>
<tr>
<td>H. E. Miller Const. Company</td>
<td>6959 NASA Blvd.</td>
<td>W. Melbourne</td>
<td>32901</td>
</tr>
</tbody>
</table>
K & L Contractors, Inc.
P. O. Box 7
Killarney, FL  32740

Poncho's Const. Company, Inc.
Route 1, Box 687
St. Cloud, FL  32769

Vannice Construction
1310 W. Colonial Drive
Orlando, FL  32804

D. L. Amici Company
5725 NW 186th Street
Miami, FL  33016

Belvedere Construction
P. O. Box 15107
W. Palm Beach, FL  33406

Capeletti Brothers
P. O. Box 4944
Hialeah, FL  33014

CGB Construction
1281 W. 62nd Street
Hialeah, FL  33012

Campenella Corporation
4101 N. Andrews Ave.
Suite 104
Ft. Lauderdale, FL  33309

Gateway Construction
1730 N. Powerline Rd.
Pompano Beach, FL  33060

Goodwin, Inc.
7275 NW 61st Street
Miami, FL  33166

A. J. House & Sons
13775 N.W. 6th Street
Miami, FL  33144

Intercounty Const. Corp.
P. O. Box 14456
Ft. Lauderdale, FL  33302

Lanzo Const. Company
Route 2, Box 904
Pompano Beach, FL  33067

Pro Contracting
7480 Fairway Drive
Suite 110
Miami Lakes, FL  33014

Rob-EL Construction
5671 NW 78th Avenue
Miami, FL  33166

Azzarelli Const. Company
P. O. Box 9097
Tampa, FL  33674

C. E. Pierce, Inc.
Utility Division
6740 Park Blvd.
Pinellas Park, FL  33565

Coastal State Utilities, Inc.
P. O. Box 862
Tampa, FL  33601

Gigliotti Pipeline, Inc.
10504 U.S. 41 N.
Palmetto, FL  33561

Woodruff & Sons, Inc.
P. O. Box 10127
Bradenton, FL  33507

West Coast Utility Const. Co.
6550 53rd St. N.
Pinellas Park, FL  33565

R. C. Cowan Const. Co.
P. O. Box 1480
Cocoa, FL  32922

Ellington Const. Company
P. O. Box 5066
Titusville, FL  32780

Ellington Const. Company
P. O. Box 5066
Titusville, FL  32780
Fearon Const. Company  
P. O. Box 112  
Rockledge, FL  32955  

Lockwood Construction Co.  
P. O. Box 177  
Pineville, NC  28134-0177  

Billings & Garrett, Inc.  
P. O. Box 58340  
Raleigh, NC  27658  

J. D. Cave Const. Company  
1239 Old Salisbury Rd.  
Winston-Salem, NC  27107  

Hobson Const. Company, Inc.  
P. O. Box 250  
Arden, NC  28704  

Frank Horne Const. Company  
P. O. Box 532  
Fair Bluff, NC  28539  

P & H Const. Company, Inc.  
Route #10, Box 226  
Lexington, NC  27292  

W. M. Paris & Associates, Inc.  
5970 Old Pineville Rd.  
Charlotte, NC  28210-3536  

Ramey, Inc.  
214 N. Spring St.  
Winston-Salem, NC  27102  

Rand Const. Company, Inc.  
P. O. Box 188  
Richfield, NC  28137  

Roanoke Const. Company, Inc.  
P. O. Box 820  
Roanoke Rapids, NC  27870  

Sam W. Smith, Inc.  
P. O. Box 428  
Eden, NC  27288  

Floyd King & Sons Inc.  
3300 Gribble Rd.  
Matthews, NC  28105  

S & S Utilities  
P. O. Box 2008  
King, NC  27021-2008  

Tar Heel Paving Company, Inc.  
2217 Chestnut Drive  
High Point, NC  27262  

Trans-State Const. Company  
P. O. Box 545  
Denver, NC  28037  

Ronny Turner Const. Company  
P. O. Box 157  
Casar, NC  28020  

Wham & Hunt Const. Co., Inc.  
P. O. Box 7  
Star, NC  27356  

John E. Jenkins, Inc.  
U.S. #29-74W  
P. O. Box 12366  
Gastonia, NC  28052  

Atlantic Coast Contr., Inc.  
P. O. Box 5402  
Charlotte, NC  28225  

Edwards Pipeline Co., Inc.  
Rt. 6, Box 646  
Charlotte, NC  28208  

McCall Brothers, Inc.  
6700 Belhaven Blvd.  
Charlotte, NC  28216  

W. M. Paris & Assoc., Inc.  
5970 Old Pineville Rd.  
Charlotte, NC  28210  

Roberts Enterprises, Inc.  
4213 Morris Field Drive  
Charlotte, NC  28208  

Nicky Construction Co., Inc.  
P. O. Box 1966  
Matthews, NC  28105


