Field Studies with Innovative Safe Excavation Technologies

FINAL PERFORMANCE REPORT
Grant No. 5 R01 CCR413051-03

Leonhard E. Bernold, Ph.D.
Department of Civil Engineering
North Carolina State University
Raleigh, NC 27695-7906

Phone: (919) 515 3677
Fax: (919) 515 7908
email: bernold@eos.ncsu.edu

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1. SUMMARY REPORT

ABSTRACT

On August 20, 2000 a bulldozer working on a new construction site in Charlotte, NC ripped up a primary gas transmission line that, five minutes later, exploded into a 100 high fireball, shutting down a mall and a major highway. Due to some unique circumstances, nobody was seriously injured. However, it provides the background for, and highlights the importance of the work that was undertaken to achieve the aims set for this project. The purpose of this project was to study the efficacy of innovative excavation technologies that promise to drastically reduce, or even eliminate, the many deaths and injuries that are common in excavation today. An economic impact study of underground utility damages accompanied the development and field-testing of three key technologies: a) the equipment-mounted buried utility detection system EM-BUDS, b) pipe-manipulator attachment PMA, and c) the site-integrated-backhoe-excavator SIBE.

The goal of the economic impact study was to address the question of *How Much* should be spent on protection. Surprisingly, a literature review found that little work has been done in assessing the total cost (referred to as economic impact cost) of accidental damages to utilities. However, the analysis of an actual incident showed that those costs are generally underreported because only emergency responses and repair are accounted for. Much larger than these direct costs are the consequential costs that arise from the secondary effects (of utility shutdown) on the public, business, and government. As a result, a comprehensive approach for assessing the total economic impact of such incidents was developed. Finally, a mathematical model, using marginal costs, was utilized to test an economical approach to finding an optimum amount of money that should be spent on protecting the underground infrastructure. It is believed that this method would provide an excellent means to develop a meaningful, and scientifically sound tool. However, it does require the availability of reliable data about economic impacts of accidents.

The work on EM-BUDS progressed to the point where the system was field tested on several sites. At a very congested location a power line and a phone line were correctly detected without any prior knowledge of their situations. The results also proved to be repeatable through subsequent tests.

In order to experiment with fully workable versions of the safe technologies under field conditions, the hard- and software of the first prototypes of PMA and SIBE were upgraded, ruggedized, and tested so as to ensure field-worthiness. Eventually, those two systems were integrated into one, the Pipe-Manipulator (PipeMan). At the end of September 1999, comparative field tests were conducted on a job-site at the East Park Industrial Subdivision in Raleigh, NC. A contractor was found who was willing to construct, on the same field, two equivalent pipeline sections, each with 9 concrete pipes of a 36-inch diameter and 8 feet of length. One section was constructed using the traditional pipe-laying method the other section using PipeMan. The extensive amount of data revealed the following key facts: 1) The technology worked as designed, 2) the field personnel learned quickly to operate the technology, and 3) the total costs for excavation and pipe-placement of the two sections were found to be equivalent.

After the successful field test, PipeMan was featured in the leading weekly magazine of the U.S. construction industry, the Engineering News-Record (ENR). Subsequently, it was selected as one of the 25 key news articles to receive ENR's Award of Excellence 2000.

SIGNIFICANT FINDINGS

Because of the nature of the project, the significant findings are summarized under two separate headings: 1) Economic Impact of Underground Utility Damages, and 2) Safe Pipe-Laying at Reduced Cost.

Economic Impact of Underground Utility Damages

Despite the successful implementation of One-Call systems in most states of the U.S., accidents caused by damaging underground utilities are extensive, with results ranging from an inconvenience of a cut TV cable all the way to a catastrophe such as a gas explosion that causes death and destruction. The underlying factors that lead to those accidents are many. However, everybody agrees that better protection that starts with improved designs, construction methods, and line maintenance are most critical. The key premise is that it is economically prudent to invest in utility protection as long as one dollar of extra expenditure for prevention results in at least one dollar of savings from damage reduction. However, the analysis of a real incident showed that the present accounting of damages drastically underreports the actual cost, referred to as economic impact cost. The reason for this underreporting is the difficulty of assessing consequential cost for the multitude of utilities. The following two tables provide a partial account of direct and consequential cost of an incident that started with the accidental damage of a gas main during the construction of a new bookstore. An adjacent mall with approximately 130 shops, as well as a residential area, were evacuated, although the gas did not ignite.

Fire Department	$ 7,477
Police Department	$ 3,759
Dept. of Public Works & Utilities	$ 4,532
Rescue Team	$ 1,025
Repair by Gas Company	$ 20,000*
Partial Direct Cost: (Subtotal 1)	$ 36,793*

* Estimate that does not include cost of the lost natural gas

Table 1: Breakdown of Direct-Costs

Partial Direct Cost: (Subtotal 1)	$ 36,793	12%
Estimated total loss of sales for the six hour evacuation	$ 262,810	84%
Estimated total wages lost to hourly employees	$ 13,370	4%
Partial Consequential Cost: (Subtotal 2)	$ 276,180	88%
Partial Economic Impact: (Subtotals 1+2)	$312,973	100%

Table 2: Summary of Partial Direct and Consequential Costs

Unfortunately, the study did not allow the compilation of all direct costs such as the value of escaped gas, the losses incurred by the general- and sub-contractors working on the job, or the money spent for legal purposes.

The impact of the accident on the businesses and employees in the mall are displayed in Table 2. As shown, the economic impact of the incident is assessed at $ 312,973, of which 88% can be considered consequential cost. Since it is common practice to consider the $ 36,793 direct cost as the total cost of such accidents, their actual costs are underreported by a factor of almost 10. This factor is surely still much too small since the cost figures don't include large sums that are kept confidential.

Faced with the staggering risks associated with utility damages, it seems unavoidable to base decisions about how to plan, build, and maintain those critical services on sound economic approaches. It was found that the mathematical model of marginal cost/benefits would provide an excellent approach for establishing a framework, optimizing the investments in prevention for the sole purpose of mitigating accidents. Key to applying this method, however, is the computation of the true cost of accidents to the public, business, and government.

Safe Pipe-Laying at Reduced Cost.

Traditional trenching and pipe laying requires workers to enter the trench, resulting in many fatalities, due to the nature of the sometimes unpredictable behavior of the soil and many other difficult circumstances found in construction. One of the main objectives of this research was to field-test a tele-robotic approach to laying large concrete pipes that would reduce the risk to human life by keeping the worker outside of the trench. In a first step, a "field-worthy" version of an existing prototype pipe-manipulator was built and tested. Figure 1 presents schematically the structure of the system that eventually was successfully field tested on a construction site.

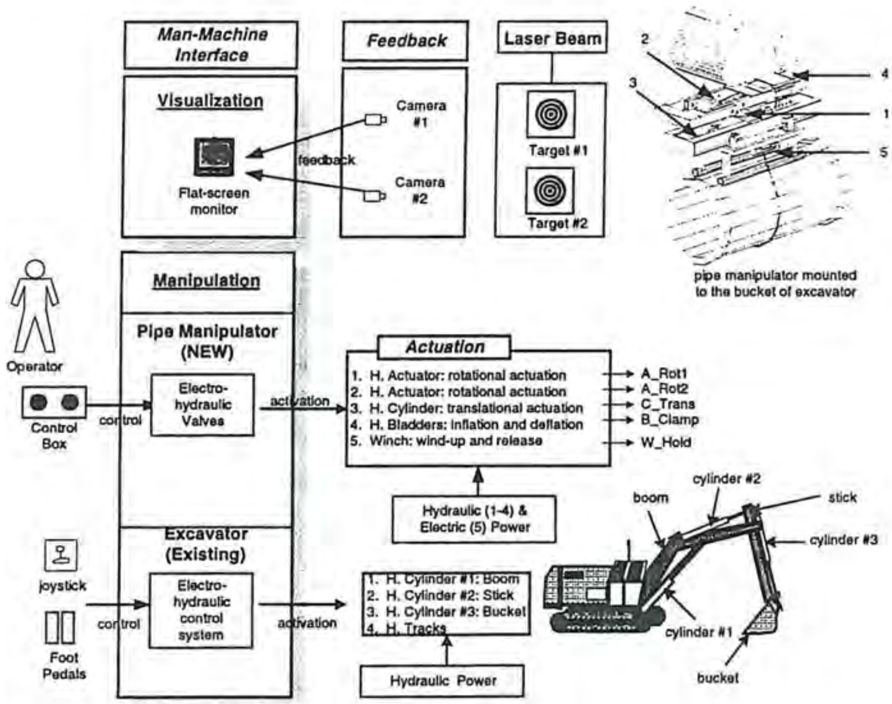
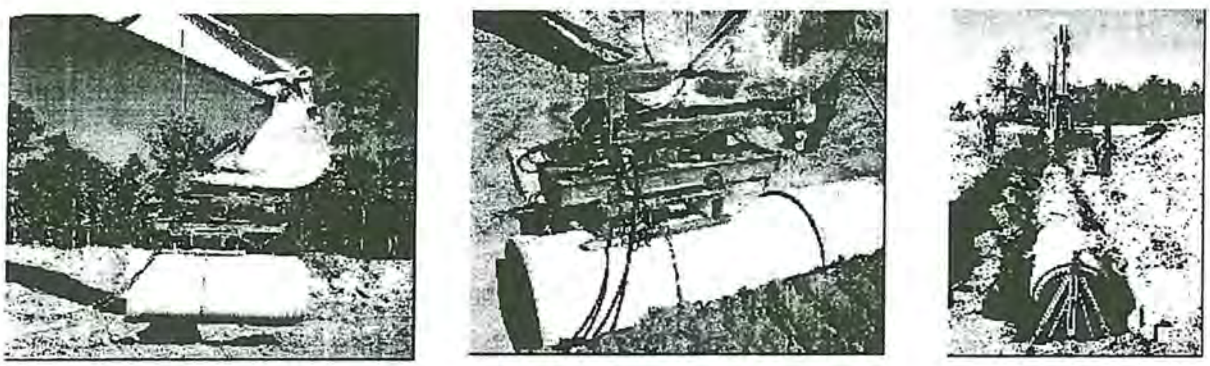


Figure 1: Structure of Tele-Robotic Pipe-Manipulator PipeMan

The PipeMan proved its technical soundness by laying 8 pieces of concrete pipes (36 inch diameter and 8 feet long) in a 6 feet (1.8 m) deep trench via remote control. It eliminated the need for 2 pipe layers to enter the trench in order to joint the pipes, resulting in fewer man-hours. A crew of 3 (1 excavator operator, 1 pipe layer, and 1 helper) was able to perform the process of excavating and pipe-laying instead of the traditional 5 workers. The excavator operator was able to line up the pipe with a control box and a vision system without any workers in the trench. Proper alignment was achieved using two different laser set-ups (inside of the pipe and on the top of the pipe). Then, the operator activated the linear actuation of the carriage of the manipulator in order to joint the bell of the new section to the spigot of the already laid pipe. Figure 2 a) shows the pipe-manipulator, attached to the bucket of the backhoe excavator, transporting a pipe from its staging location to the trench. Figure 2 b) illustrates the phase when the operator adjusts line and grade of the pipe prior to jointing it to the previous pipe, while Figure 2 c) provides an overview of the completed job.



a) Transporting Pipe b) Lining up and Jointing c) Finished Section

Figure 2: Documentation of Field Test

To ensure the safety of the observers, the benching method was used during the field testing of PipeMan. The time spent to excavate and compact that additional volume was considered in the final cost analysis.

The new technology was rapidly embraced by the equipment operators. They ascertained that the new technology was practically acceptable for: 1) lining up a pipe with accurate grade and 2) jointing pipes without any workers in the trench. Operator skill is, and will be, even more critical to the performance of the PipeMan. Thus, it is advised to emphasize the importance of operator training. It was also very interesting to observe how the workers realized the value of this innovative technology for increasing their safety. After the researchers demonstrated the system on the first pipe, the crew took control of the operation.

Table 3 summarizes the costs of the traditional and the tele-robotic approach. The total costs for laying 36 inch concrete pipes into 6 feet deep trenches are calculated to be $1.08 and $1.65 (per linear foot) for traditional and tele-operated methods, respectively. The slightly higher cost of PipeMan was mainly caused by an unexpected problem that occurred early during the field tests, namely the break-up of a brand-new electric winch. Because of time constraints the very convenient system could not be repaired and had to be substituted with a cumbersome but safe chain and a ratchet system (see Figure 2). The observed slowdown in the pipe-laying cycle, and the extra excavation volume for benching the slopes, is calculated to have cost an extra $ 0.80 per linear foot (LF). Thus, the conservatively projected total cost for laying 36 inch concrete pipes into 6 feet deep trenches tele-robotically is $0.85/LF.

Description	unit	Traditional Method		New Technology	
		RS Means [1]	Observed [2]	Observed [2]	Projected [3]
(a) Crew size		7	5	3	3
Excavating					
(b) Excavation volume [4]	CY	16	16	16	8.9
(c) Unit cost (labor)	$/CY	0.85	0.85	0.85	0.85
(d) Productivity [5]	CY/LH	30	60	60	60
(e) LH required for excavation	LH per CY	0.53	0.27	0.27	0.15
(f) Labor cost (b*c*e)	$/LF	0.90	0.45	0.45	0.14
Pipe laying					
(g) Cycle time	Min/8LF	-	2.2	6	3.6
(h) Daily output	LF/day	72	1,309	480	800
(i) Labor hours	LH per LF	0.778	0.031	0.050	0.030
(j) Unit cost (labor) [6]	$/LF	13.30	0.52	0.86	0.51
(k) Subtotal: Labor cost (f+j)	$/LF	**14.20**	**0.98**	**1.31**	**0.65**
Pipe Manipulator					
(l) Daily cost [7]	$/day	-	-	100	100
(m) Unit cost (l / h)	$/LF	-	-	0.21	0.13
Insurance					
(n) WC insurance (10% of labor)	$	1.42	0.10	0.13	0.07
Total Unit Cost (k+m+n)	$/LF	***15.62***	***1.08***	***1.65***	***0.85***

[1] RS Means: Building Construction Cost Data, 1997
[2] Observed: Based on data collected during field tests with construction crew
[3] Projected: Considers steeper trench slopes and electric winches instead of chain
[4] Excavation volume is calculated for a concrete pipe with 36 inch diameter
[5] Daily output: 480 CY/day; labor-hours per CY: 0.033, operating factor: 75%
[6] Unit cost: labor cost (17.1 $/LF) x labor hours;
labor cost (17.1 $/LF) based on RS Means Building Construction Cost Data, 1997
[7] Estimated operating cost including maintenance, repair, and depreciation

Table 3: Summary Cost Comparison

In a final effort, the effect of trench depth on the cost was assessed. This analysis took advantage of data that had been collected on several different pipe-laying jobs in the Raleigh area. The sensitivity analysis for 'excavation with a simple slope' established the following relationships between 'cost of excavation' and 'trench depth'. As expected, the cost savings increase with depth of the trench because the volume of material to be excavated and back-filled increases with depth. Table 4 shows the summarized cost comparison that includes workers' compensation insurance premiums of $10 per $100. As shown, the cost savings for the new technology reached from $ 761 to $ 5,361 for 100 LF. The selected slopes (1:1 for the new technology) indicate that these calculations are based on conservative but safe assumptions.

Depth (feet)	**5**	**12**	**19**	**Slope**
Traditional (simple slope)	2,090	4,364	*8,156*	1½(h): 1(v)
New technology (simple slope)	970	1,589	*2,795*	1(h): 1(v)
COST SAVING simple slope	**1,120**	**2,775**	**5,361**	
Traditional (trench box)	1,740	2,702	5,204	1½(h): 1(v)
New technology (trench box)	979	1,189	*1,399*	1(h): 1(v)
COST SAVING trench box	**761**	**1,513**	**3,805**	

Table 4: Cost Sensitivity for 100 LF of Pipe at Different Depths

USEFULNESS OF FINDINGS

In TEA 21, the congressional Transportation Equity Act for the 21st Century, it is noted that the public, businesses, and critical public services such as air traffic control, are experiencing significant negative effects from accidents involving our utilities. The Common Ground Report (1999) calls for a collective effort: "Protecting this essential infrastructure is a top priority for the people who plan, install, operate, repair, and regulate underground facilities." The findings of this research demonstrate the fact that the economic impact of accidents involving utilities are far greater then commonly reported. The study verifies the need for a comprehensive effort to study the total effect such incidents have on the public, business, industry, and government. It was shown that only if such data is available will it be possible to apply mathematical models to optimize the investment into protecting underground utilities.

A second set of findings provides the evidence for the fact that trenching and pipe-laying operations can be made safer without adding extra cost to the contractor. The findings are of extreme practical use because the data that support the conclusions have been collected while observing real equipment and an actual crew in a comparative field test. Because such evaluations are generally done using CAD or other computer based simulators their results are hard to validate.

References

Common Ground (1999). "Study of One-Call Systems and Damage Prevention Best Practices," U.S. Dept. of Transportation, Office of Pipeline Safety, Washington, DC.

National Institute for Occupational Safety and Health. (1995). Preventing Deaths and Injuries From Excavation Cave-ins, NIOSH Alert, DHHS Publication No. 85-110.

LIST OF PUBLICATIONS

Bernold LE: Spatial Integration in Construction. Construction Engineering and Management, in press, 2000

Bernold LE: An Optimization Model for Underground Utility Protection. Construction Engineering and Management, in press, 2000

Lee J, Lorenc SJ, Bernold LE: A Comparative Performance Evaluation of Tele-Operated Pipe Laying. Construction Engineering and Management, in press, 2000

Lee J, Lorenc SJ, Bernold LE: Saving Lives and Money with Robotic Trenching and Pipe Installation. Aerospace Engineering, Volume 12, No. 2: 43-49, 1999

Lee J, Lorenc SJ, Bernold LE: Breaking Even with Robotic Trenching and Pipe Installation. Proc of American Nuclear Society 8th International Topical Meeting and Exposition Robotics and Remote Systems, Pittsburgh, PA, CD, April 25-29, 1999

Lee J, Lorenc SJ, Bernold LE: Tele-Operated Pipe Manipulation. Proc of 1998 American Society of Civil Engineers Conference on Robotics for Challenging Environments Conference, Albuquerque, NM, 188-194, April 26-30,1998

Lorenc SJ, Bernold LE: 'Smart' Attachment for Utility Damage Prevention. Proc of 1998 American Society of Civil Engineers Robotics for Challenging Environments Conference, Albuquerque, NM, 26-30,140-146, April 26-30, 1998

Carver C, Bernold LE, Lorenc CJ: Averting Excavation Disaster. Management in Engineering, Vol. 14, No. 1: 29-30, 1998

Lee J: Comparative Performance Evaluation of Tele-Operated Pipe Laying, Ph.D. Thesis, North Carolina State University, 1999

COVERAGE OF SPECIFIC AIMS BY PUBLICATIONS

The following section provides a complete explanation of how the different aims were covered by our publications. Several publications, such as the Ph.D. dissertation by Lee, cover several aims

Aim 1: Preparation of the prototype hardware and software for field experiments.

Bernold LE: Spatial Integration in Construction. Construction Engineering and Management, in press, 2000
In this paper, the author gives not only a historic review of spatial integration in construction but describes specifically the hard- and software of SIBE, the Spatially-Integrated-Backhoe-Excavator.

Lee J: Comparative Performance Evaluation of Tele-Operated Pipe Laying, Ph.D. Thesis, North Carolina State University, 1999
The thesis gives a detailed account of all the improvements that were made to the prototype system.

Lee J, Lorenc SJ, Bernold LE: Saving Lives and Money with Robotic Trenching and Pipe Installation. Aerospace Engineering, Volume 12, No. 2: 43-49, 1999
Lee J, Lorenc SJ, Bernold LE: Breaking Even with Robotic Trenching and Pipe Installation. Proc of American Nuclear Society 8th International Topical Meeting and Exposition Robotics and Remote Systems, Pittsburgh, PA, CD, April 25-29, 1999
Lee J, Lorenc SJ, Bernold LE: Tele-Operated Pipe Manipulation. Proc of 1998 American Society of Civil Engineers Conference on Robotics for Challenging Environments Conference, Albuquerque, NM, 188-194, April 26-30,1998
These three conference papers explain the progress made on designing, developing, and testing the innovative technology to be used in the comparative field tests at the end of the project.

Carver C, Bernold LE, Lorenc CJ: Averting Excavation Disaster. Management in Engineering, Vol. 14, No. 1: 29-30, 1998
The authors of this paper discuss the efforts of the first phase in upgrading existing prototype hardware and software.

Aim 2: In-depth re-evaluation of excavation accidents and their effects on the safety/health of construction workers and the public. An additional critical element of this study is the assessment of the full economic impact of utility damages (e.g., gas lines) on the area of the accident (e.g., lost revenues of businesses and their employees when a mall has to be evacuated due to a gas line break).

Bernold LE: An Optimization Model for Underground Utility Protection. Construction Engineering and Management, in press, 2000
As the title indicates, this journal paper presents the findings of an economic impact study and discusses an economic model to optimize investments for damage prevention.

Lee J: Comparative Performance Evaluation of Tele-Operated Pipe Laying, Ph.D. Thesis, North Carolina State University, 1999
Lee provides the newest information about excavation accidents, their causes, and the relevant OSHA regulations that cover trench excavation and pipe-laying.

Carver C, Bernold LE, Lorenc CJ: Averting Excavation Disaster. Management in Engineering, Vol. 14, No. 1: 29-30, 1998
This publication discusses not only the ongoing work on upgrading the hardware and software for PMA and EM-BUDS, it also presents first results of the economic impact study.

Aim 3: Comparative study on construction sites where a baseline measure of the occupational process will be defined. The new/improved approach will be implemented, and an assessment oft the impacts made.

Lee J, Lorenc SJ, Bernold LE: A Comparative Performance Evaluation of Tele-Operated Pipe Laying. Construction Engineering and Management, in press, 2000
Indicated by its title, the paper presents the design and execution of the comparative field study. It also discusses the results of the assessment.

Lee J: Comparative Performance Evaluation of Tele-Operated Pipe Laying, Ph.D. Thesis, North Carolina State University, 1999
The highlight of the dissertation is a minute documentation of the comparative field study with a large amount of analyzed data collected during the tests.

Aim 4: Evaluation of technical, safety, quality related utility and cost/benefit analysis of the new technologies.

Lee J, Lorenc SJ, Bernold LE: A Comparative Performance Evaluation of Tele-Operated Pipe Laying. Construction Engineering and Management, in press, 2000
As the title of this paper indicates, it contains the main findings of this project concerning the technical feasibility and utility of the new technologies. Also covered is a cost comparison for laying concrete pipes using the tele-robotic and the traditional methods.

Lee J: Comparative Performance Evaluation of Tele-Operated Pipe Laying, Ph.D. Thesis, North Carolina State University, 1999
The thesis provides extensive information about technical feasibilities, utility and cost/benefits of the new technologies.

Lorenc SJ, Bernold LE: 'Smart' Attachment for Utility Damage Prevention. Proc of 1998 American Society of Civil Engineers Robotics for Challenging Environments Conference, Albuquerque, NM, 26-30,140-146, April 26-30, 1998
This conference paper offers an overview of the causes of utility damages and a review of common practices in utility locating. It also presents the results of the newest efforts in increasing the quality of EM-BUDS.

Aim 5: Demonstrations of the technology at various sites and locations.

Lee J, Lorenc SJ, Bernold LE: A Comparative Performance Evaluation of Tele-Operated Pipe Laying. Construction Engineering and Management, in press, 2000
This paper is based on Lee's dissertation and gives an account of the fieldwork.

Lee J: Comparative Performance Evaluation of Tele-Operated Pipe Laying, Ph.D. Thesis, North Carolina State University, 1999
Lee includes several of the demonstrations that were made in his thesis.

Bernold LE: Spatial Integration in Construction. Construction Engineering and Management, in press, 2000
This paper documents how SIBE and PMA were demonstrated in the field.

2. FINANCIAL STATUS REPORT

Will be submitted by The North Carolina State University Accounting Office.

3. EQUIPMENT INVENTORY (ITEMS OVER $1000)

Item	ID number	Acquisition Date	Total Cost	% Federal Funds	Condition of Item	Wish to Retain?
Spectra-Physics Laserplane	1160/1201	10/1/97	$ 2490.00	100%	Functional	Yes
Gateway P5-200 MMX Laptop	0006960288	4/14/97	$ 2912.88	100%	Functional	Yes

4. FINAL INVENTION STATEMENT

No inventions were conceived under the assistance award.

DEPARTMENT OF HEALTH AND HUMAN SERVICES

Public Health Service
Centers for Disease Control
and Prevention (CDC)

Memorandum

Date: April 16, 2001

From: Roy M. Fleming, Sc.D., Director, Research Grants Program RMF
Office of Extramural Programs, NIOSH, D30

Subject: Final Report Submitted for Entry into NTIS for Grant 5 R01 CC413051-03.

To: William D. Bennett
Data Systems Team, Information Resources Branch, EID, NIOSH, P03/C18

The attached final report has been received from the principal investigator on the subject NIOSH grant. If this document is forwarded to the National Technical Information Service, please let us know when a document number is known so that we can inform anyone who inquires about this final report.

Any publications that are included with this report are highlighted on the list below.

Attachment
cc: Sherri Diana, EID, P03/C13

List of Publications

Bernold LE: Spatial Integration in Construction. Construction Engineering and Management, in press, 2000

Bernold LE: An Optimization Model for Underground Utility Protection. Construction Engineering and Management, in press, 2000

Lee J, Lorenc SJ, Bernold LE: A Comparative Performance Evaluation of Tele-Operated Pipe Laying. Construction Engineering and Management, in press, 2000

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Title: Field Studies with Innovative Safe Excavation Technologies
Investigator: Leonhard E. Bernold
Affiliation: North Carolina State University
City & State: Raleigh, NC
Telephone: (919) 515-3677
Award Number: 5 R01 CC413051-03
Start & End Date: 9/30/1996–8/31/2000
Total Project Cost: $318,653
Program Area: Control Technology
Key Words:

Abstract:
The purpose of this project was to study the efficacy of innovative excavation technologies that promise to drastically reduce, or even eliminate, the many deaths and injuries that are common in excavation today. An economic impact study of underground utility damages accompanied the development and field-testing of three key technologies: (a) the equipment-mounted buried utility detection system (EMBUDS), (b) pipe-manipulator attachment (PMA), and (c) the site-integrated-backhoe-excavator (SIBE).

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