HORIZONTAL DIRECTIONAL DRILLING: PROFILE OF AN EMERGING INDUSTRY

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ABSTRACT: Perhaps the fastest growing segment in the underground trenchless construction industry is horizontal directional drilling (HDD). Currently, in North America alone, there are 17 manufacturers of HDD rigs and accessories and thousands of horizontal drilling rigs that are owned and operated by several hundred dedicated HDD contractors as well as utility companies and large pipeline outfits. Applications of HDD span across the civil engineering spectrum from mineral and oil exploration to the installation of telecommunication cables. An industry survey was conducted to gain a better understanding of this multibillion dollar industry, which is relatively unfamiliar to many in the construction sector. This paper presents the results obtained from analyzing 49 survey responses from HDD contractors in the United States and Canada. Topics investigated include company profile (e.g., annual volume, areas of activities); type of projects performed (e.g., applications, value, duration, type of product installed), and bidding and estimating practices (e.g., productivity values in various formations, cost of installation), Current and future trends in the industry are identified and discussed.

INTRODUCTION

Horizontal directional drilling (HDD) has made a significant impact in both the utility and pipeline installation industries over the past decade. The horizontal drilling industry in North America has grown from 12 operational units in 1984 to more than 2,000 units operating in 1995 (Kirby et al. 1997), with some experts placing the number of directional drilling rigs worldwide as high as 6,000 (*Guidelines* 1994). This rapid growth may be attributed, at least partially, to escalating costs involved in the installation of utility conduits in urban areas (e.g., traffic control, restoration costs, the need to dig around existing utilities), increased awareness of social costs (e.g., traffic delays, disruption of business activities), and increasing environmental regulations (e.g., placement of pipelines across rivers, wetlands, and other environmentally sensitive areas). Currently, HDD is a multibillion dollar a year industry with hundreds of contractors and thousands of drilling rigs operating on five continents. Industry applications range across the civil engineering spectrum from the installation of utility conduits and natural gas pipelines, through municipal applications (e.g., water mains, gravity sewers), to environmental and geoconstruction applications such as the remediation of contaminated sites, geotechnical investigations, and diversion channels.

The first section of this paper provides a background of the industry and a brief overview of directional drilling technology. Thereafter, the results of the survey are reported under four subsections: (1) Company profile; (2) project information; (3) bidding and cost estimating; and (4) project planning and control of operations. The paper is concluded with a discussion of current research and development needs and anticipated areas of future growth.

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BACKGROUND

The equipment and installation techniques used by HDD contractors evolved by merging technologies from the utility, oil field, and water well industries. The first known river crossing using the HDD method took place in 1971 when approximately 185 m of 100-mm-diameter steel pipe was installed across the Pajaro River near Watsonville, Calif., for the Pacific Gas and Electric Co. From 1971 to 1979, only 36 crossings were successfully made using this method (*Guidelines* 1994). Relatively complicated and inaccurate steering and navigation systems may be partially attributed to the relatively slow acceptance of the technology during those early years. The early 1980s were marked by a rapid advancement of the equipment's mechanical, hydraulic, and electronic systems. Drilling rigs were built smaller and made to drill greater distances. New systems and navigation tools were developed resulting in easier operation and decreasing capital investment. Consequently, HDD became a cost-effective method for the installation of conduits in congested urban areas and the method of choice by many utility and pipeline companies for the crossing of buried and surface obstacles. Currently, a wide range of directional boring units exist in the market place, from mini drilling rigs used for the installation of 50-mm utility conduits to maxi rigs that are capable of installing 900-mm sewer lines. The installation range is determined by many parameters including rig size, soil conditions, and product diameter. Installations as long as 1,700 m have been completed successfully. Directional drilling rigs can operate in a wide range of geological materials from soft organic soils to solid rock with an unconfined compressive strength of 140 MPa (Allouche and Como 1997).

HDD presents several advantages over traditional open-cut construction methods. One obvious advantage is that it is a trenchless technology. Installation of underground utilities in congested urban areas using open trenching can prove to be rather expensive as the contractor must dig around existing utilities to achieve the required depth, subsequently impeding the operation. Furthermore, sidewalks, pavements, brick paving, sod, or other surfaces must be repaired or replaced. In addition, open-cut construction is often associated with higher user costs, including the interruption of traffic and the disruption of nearby commercial activities (McKim 1997).

In comparison with other trenchless technologies, HDD offers several advantages: (1) No vertical shafts are required as drilling commences from the surface; (2) relatively short setup

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time; (3) the borehole alignment does not necessarily have to be straight, as HDD makes it possible to change the borehole alignment and elevation to avoid striking existing utilities and other underground obstacles along the path; and (4) the single drive installation length exceeds that of any other non-man entry trenchless method.

SURVEY METHODOLOGY

A survey of the HDD industry in North America was developed at the University of Alberta, Edmonton, Canada, in consultation with local contractors and practicing engineers involved in the trenchless industry. The survey was divided into four sections. The first section contained questions relating to the contractors' business activities. The second section examined project parameters including the size and duration of typical HDD projects. In the third section, contractors were asked to provide information on bidding practices including cost, markup, and contingency. The final section addressed productivity, risk management, and possible areas for future research and development.

In the summer of 1997, the Department of Civil and Environmental Engineering at the University of Alberta mailed a questionnaire to 169 HDD contractors and utility companies across Canada and the United States. Fifty-three questionnaires were returned, representing a response rate of 31%. Four of the respondents failed to complete the survey, resulting in 49 surveys being used in the analysis. Responses were received from across the continent and represent diversity in company size, economic factors, and geologic conditions. A balance between dedicated HDD contractors and underground construction divisions of general contractors and utility companies was achieved. Of the 49 HDD contractors that responded to the survey, 32 are U.S.-based companies and 17 are Canadian-based companies.

COMPANY PROFILE

Annual Sales

Approximately 47% of the companies surveyed reported annual sales of less than $3,500,000 (in U.S. dollars). These companies can be characterized as being small- to medium-sized dedicated HDD contractors with 5–20 permanent employees. They tend to act mainly as subcontractors and do little more than product installation. Thirty percent of the contractors indicated sales between $3,500,000 and $14,000,000, whereas 23% of the respondents had annual sales in excess of $14,000,000. Traditionally, the larger companies have been either national or international dedicated directional drilling contractors or underground construction divisions of more diverse construction companies. These results are not surprising because HDD is a relatively new industry with few established companies.

The specialized nature of directional drilling and the high capital investment in equipment and training tends to discourage many large construction and utility companies from purchasing HDD equipment. These companies prefer subcontract dedicated HDD contractors whenever open-cut construction is not a viable alternative or proves to be cost prohibitive. The construction of entire pipeline projects using HDD is unlikely to become common practice unless large construction companies obtain their own HDD boring units or HDD dedicated contractors diversify by acting as general contractors on municipal and utility projects.

Areas of Activity

During the 1970s and early 1980s, the utilization of HDD had been primarily in the oil and gas industries, either for exploration, production, or pipeline installation. Over the past 10 years, horizontal drilling has moved into new applications including utility installation, environmental remediation, and the installation of forcemains and gravity sewers. Ascertaining contractor experience on specific applications of HDD was done to evaluate the development of these applications. The results are exhibited in Table 1.

The survey indicates that 89% of the contractors surveyed are currently involved in underground utility installation, 74% in municipal applications, 63% in pipeline installation, and 28% in the environmental market. The number of contractors that indicated having more than 5 years of experience in a given application was 70% for underground utility installation, 53% for pipeline, and 52% for municipal applications. As previously mentioned, directional drilling evolved from the oil and gas fields that are located at selected geographical locations throughout North America (e.g., Texas, Alberta). Thus, contractors from other areas may not have access to this particular market. On the other hand, the installation of utilities is common in all urban centers and, therefore, may be considered the ''bread and butter'' of the directional drilling industry. Another reason that the majority of contractors are involved in utility installation is that most products installed are relatively small (up to 150 mm in diameter) and installation distances are relatively short (up to 200 m). Therefore, a small (or mini-) directional drilling rig is sufficient to complete these projects. Pipeline projects typically involve the installation of larger products over longer distances and subsequently require larger machinery. Many of the smaller HDD outfits do not have the capital required to enter this market.

Environmental applications of HDD are a relatively new area (Allouche et al. 1998a). This is reflected in the survey as only 28 and 17% of the contractors having undertaken remediation and soil sampling projects, respectively. Also, aside from a few contractors with several years of experience, most contractors have two or fewer years of experience in these applications.

As presented in Table 2, approximately 24% of the respondents indicated that they were specialized contractors, meaning that they worked in only one of the listed application areas, and 76% of the contractors indicated that they had undertaken projects, in two or more of the application areas. Because of the cyclic nature of the construction industry, it is important that contractors be diversified to allow continued economic

TABLE 1. Areas of Activity and Years of Experience

Experience (1)	Utility (%) (2)	Municipal (%) (3)	Pipeline (%) (4)	Environmental (%) (5)	Sampling (%) (6)
Not involve	11	26	37	72	83
Involve	89	74	63	28	17
5 years or more	70	52	53	18	4
2–4 years	15	9	4	0	4
2 years or less	4	13	8	10	9
0 years	11	26	35	72	83

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TABLE 2. Specialty versus Nonspecialty Contractors

Area(s) of activity (1)	Experience (%) (2)	Subtotal (%) (3)
Utility only	11	—
Pipeline only	11	—
Environmental only	2	24
Utility and pipeline	41	—
Three areas of activity or more	35	76
Total	100	100

support. This may account for the diversification among the majority of HDD contractors. Specialized contractors tend to be those who are just entering the field or are working exclusively for one or a few large clients. In addition, there are several companies that specialize in large-scale environmental remediation projects that require specialized knowledge and equipment. It is interesting to note that the only category in which there are no specialized HDD contractors is the municipal arena.

Clients

The survey results indicate that most projects undertaken by HDD contractors are privately owned. On average, 67% of the projects undertaken by the survey participants were for private clients, 24% for municipal clients, and 9% for federal clients.

PROJECT INFORMATION

Work Soliciting Practices

Projects in the construction industry are typically obtained through a competitive bidding process. Though there are some exceptions, the HDD industry follows this norm. As shown in Table 3, 74% of the contractors surveyed obtain between 75 and 100% of their work through a competitive bidding process. Projects not obtained through competitive bidding typically fall under two categories: work that is highly specialized, and work obtained through strategic alliances.

Highly specialized jobs are traditionally conducted using a design-build approach. These jobs may consist of complex environmental installations or long crossings of large diameter pipeline. Typically, there are few contractors that have the experience or machinery to perform this work. It is common for owners to approach contractors and privately negotiate the terms of the contract. Strategic alliances are a growing trend in the directional drilling industry, particularly in the utility market. These relationships are usually defined by a contract and extend over a period of 3–5 years. The owner is generally a large utility company that contracts a selected directional drilling contractor to perform all of its installation needs for the contract period. Under such an arrangement, the owner trains the contractor on specialized work related directly to the owner's infrastructure network and facilities, with the contractor effectively becoming an extension of the client's own forces. Through this method, the owner receives the advantage of not having to retrain a new contractor for each project undertaken.

TABLE 3. Breakdown of Work Obtained from Competitive Bidding

Percent of total work (%) (1)	Number of contractors (2)	Percent obtained (3)
<25%	4	8
25–49	6	12
50–74	3	6
75–100	36	74
Total	49	100

Type and Diameter of Product Installed

Pipeline products installed using HDD must demonstrate high tensile and buckling strengths. Additionally, the installed products must be sufficiently flexible so that they are not adversely affected by the curved alignment typically followed in horizontal drilling installations. Therefore, it is not surprising that most pipe products installed using directional drilling are manufactured either from steel or high-density polyethylene (HDPE). Nevertheless, other product pipes are also installed using HDD methods, notably polyvinyl chloride (PVC). The size of pipe that can be installed by a particular drilling rig is a function of several parameters including the rig's pull-push and torque capacities, soil conditions, length of bore, weight of pipe, and borehole profile. As a general rule of thumb, mini rigs are used to install pipes and conduits with diameters up to 150 mm and midi rigs up to 400 mm. Maxi rigs are used to install pipeline products with maximum diameters ranging between 600 to 900 mm, depending on the borehole length and soil conditions. Table 4 summarizes the length of pipeline products installed by the 49 contractors surveyed with a breakdown on the basis of diameter and material. The 49 contractors surveyed installed over 1,650,000 m of pipe in 1995–1996. Considering that there are over 600 dedicated HDD contractors currently operating in Canada and the United States, the annual amount of pipe installed per year using the directional drilling method in North America may be estimated to be approximately 20,000,000 m.

It can be seen that 72% of the total pipe product installed by HDD during 1995-1996 was 100 mm or smaller in diameter. Products in this diameter range are typically utilized in telecommunication (e.g., fiber-optic), electrical conduits, and natural gas distribution systems. These markets form the core of the directional drilling industry. Environmental applications are another area where small diameter pipelines are often used. Sixteen percent of the total product line installed was in the range of 150–300 mm. Pipe in this diameter range is utilized mainly in municipal applications (e.g., forcemain water and sewer lines), crude oil and natural gas delivery systems, and industrial applications. Pipe and conduit over 300 mm in diameter account for approximately 12% of all projects under-

TABLE 4. Breakdown of Pipeline Product Installed by Diameter and Material

	Pipeline Product Material					
Diameter (1)	PVC (2)	HDPE (3)	Steel (4)	Other (5)	Total (6)	Percent of Total (7)
50–100 mm	241,428 m	891,494 m	64,573 m	4,500 m	1,201,994 m	72
150–200 mm	6,686 m	11,688 m	55,717 m	0 m	179,288 m	11
250–300 mm	457 m	7,730 m	72,042 m	0 m	80,229 m	5
>300 mm	0 m	13,146 m	180,144 m	0 m	193,290 m	12
Total installed	248,572 m	1,029,253 m	372,476 m	4,500 m	1,654,800 m	—
Percent of total	15	62	23	0.3	—	—

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taken. These pipes are typically used for installing gravity sewers, water trunk lines, and transmission lines.

The material of choice for horizontal drilling installations without doubt is HDPE, which accounts for approximately 62% of the total length of pipe installed. HDPE is most commonly used for installations under 150 mm in diameter, mainly representing utility applications. It is preferred by contractors because of its high tensile strength and flexibility, which lends itself well to the steering ability of directional drilling rigs. Additionally, butt-fusion of HDPE eliminates the potential problem of weak joint connections often exhibited by glue-joints common in PVC pipes.

The second most common material indicated was steel, accounting for 23% of the total length of pipe installed. Steel pipe has high tensile and buckling strengths and is commonly used in the pipeline industry and on projects where the product is delivered under high pressure. The utilization of steel pipe was found to be more common in the larger pipe sizes representing 31% of all pipe products installed in the 150–200-mm diameter category and 92% of all pipe with 250-mm or larger diameter.

PVC pipe accounts for 15% of the total length of pipe installed during 1995-1956. Ninety-seven percent of all PVC pipe installed had diameters equal to or smaller than 100 mm. Pipes manufactured of PVC are mainly used in water distribution networks, sewer laterals, and environmental remediation applications. PVC has the advantage of being less expensive than HDPE; however, it has a lower tensile strength due to the use of threaded couplings or glue-joints between individual sections, which require shorter installation lengths. In addition, PVC is less flexible than HDPE, thus imposing tighter bend radius limits on the borehole profile. Currently, PVC manufacturers are striving to develop new coupling mechanisms that exhibit the higher tensile strength required in HDD installations. Pipe materials different from the three discussed above account for only 0.3% of the total length installed.

Project Duration and Dollar Value

Depending on project characteristics, directional drilling may only be economical for sections of the project, whereas traditional open-cut methods (e.g., backhoe, plows or trenchers) might be better suited for the majority of the work. Thus, it is not uncommon for a directional drilling contractor to complete two or three different projects, at locations hundreds of kilometers apart, in vastly different ground conditions, in a single week. Consequently, aspects of project management in HDD differ significantly from more traditional horizontal or vertical construction activities.

The survey sampled project duration and magnitude, as shown in Table 5. It can be seen that approximately 47% of the projects undertaken by HDD contractors were under $70,000. Shallow depths and relatively short installation lengths (up to 300 m for any single drive) would generally characterize projects in this category with product diameters up to 300 mm. Most projects in this category are completed using a mini- or midi-sized rigs. Project duration typically ranges from 1 day to a couple of weeks. In such projects, the HDD contractor is typically employed as a subcontractor, and the majority of the cost represents drillings fees. Pipe and support equipment are commonly provided by the general contractor.

Projects in the cost range of $70,000–$350,000 represent 28% of the total number of projects undertaken by the contractors surveyed. Projects in this range tend to consist of large utility installation contracts or the installation of large diameter pipelines (up to 600 mm in diameter). Projects that range in size over $350,000 typically involve the installation of large

TABLE 5. Duration and Magnitude of Horizontal Directional Drilling Projects

Project dollar value (1)	Percentage (2)	Project duration (days) (3)	Percentage (4)
Up to $70,000	47	up to 2	21
$70,001–$180,000	15	3 to 7	16
$180,001–$350,000	13	8 to 14	14
Over $350,000	25	over 14	49
Total	100	—	100

diameter products (450 mm and over) over substantial distances (500 m and greater), large utility projects, complex projects or projects where the HDD contractor is acting as a general contractor, responsible for supplying all materials and support equipment.

Type of Contract

The survey revealed that the most common type of contract used in the directional drilling industry is unit price. Approximately 98% of the respondents had utilized the unit price contract in their operations. Unit price contracts are best suited for utility installation projects. These projects can be characterized as having an open-ended contract where the contractor quotes a cost per length of installation and the owner decides the lengths and locations of the installations. Typically, several unit rates will be shown in the quote for each product diameter, representing different types of soil conditions expected to be encountered on the project.

The second most common type of contract utilized was lump sum with 75% of the respondents indicating its utilization. Lump sum contracts are used primarily on public projects, where the scope of the work is well defined.

Per diem, or daily rate, contracts are typically employed when the risk borne by the contractor is considered above normal, or when the chances of successful installation are deemed slim. Examples of high-risk projects are crossings of major rivers, drilling in cobble or gravel, or crossings that were unsuccessfully attempted by a previous contractor. Approximately 35% of the respondents indicated that they had worked under this type of contract.

An alternative to the per diem contract is an hourly rate. Though common practice in the vertical drilling industry, the hourly rate contract is not as well accepted in the HDD industry. Only 29% of the contractors indicated they had operated under an hourly contractual arrangement. These projects are typically of short duration and performed using small drilling rigs, Twenty-one percent of the respondents indicated that they had used cost plus contracts. This type of contract is typically utilized on projects where ground conditions are considered complex or little geotechnical information is available.

As a rule of thumb, the more complex and uncertain the ground conditions are, the greater the tendency to shift the contract type from unit price/lump sum to per diem and then to cost plus.

BIDDING AND COST ESTIMATING

Percent Markup

The contractors were asked to identify the percent markup in their projects that account for the risk associated with project uncertainty (e.g., soil conditions). A distinction was made between utility and environmental projects to compare these industries. The percent markup reported in this section accounts for unexpected conditions only (e.g., contingency), as overhead and profit are excluded. The results are shown in Table 6.

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TABLE 6. Percent Markup to Account for Contingency

Markup (%) (1)	Percentage of respondents (2)
(*a*) Utility project	
0–5	5
6–10	14
11–15	27
16–20	23
>20	32
Total	100
(*b*) Environmental projects	
0–9	12
10–19	24
20–29	44
30–40	12
>40	8
Total	100

The mean markup for utility projects appears to be approximately 15%, whereas the mean markup value for environmental projects is approximately 25%. Furthermore, it can be seen that although only 32% of the respondents indicate a markup >20% to account for site related risks in utility projects, this value increases to 64% for environmental projects. The tendency of HDD contractors to view environmental projects with more caution than utility projects can be partially attributed to the following factors:

- The crew may be exposed to greater risk when working in contaminated soils and ground water, increasing the contractors' liability and insurance costs.
- In the case of hazardous contaminants, costs associated with equipment decontamination and productivity losses due to the use of protection gear may be substantial.

Cost of Installation

The cost of installation may vary significantly depending on a number of factors, including product diameter, length of installation, subsurface conditions, number and type of utilities to be crossed or paralleled, depth of installation, accessibility to locations directly above the bore path, placement tolerances regarding alignment and profile, type of project (e.g., municipal versus environmental), and proximity to home base. Although the large number of variables involved makes it difficult to develop an equation to predict the cost of installation for a particular project, it is possible to determine a cost range for the installation of a particular product diameter.

Contractors were asked to mark the appropriate cost range for the installation of a product of a particular diameter. The data collected was processed to calculate the percentage of responses that selected a particular range for a particular product diameter. The results as well as the mean and average prices for each product diameter are listed in Table 7. It can be seen that the cost of installation increases significantly with the product diameter. The larger the product, the larger the boring unit required for the installation, which typically extends the setup time and reduces the drilling rate. Because the borehole's size required for a safe installation is typically 1.5 times the product diameter, and the borehole cross-sectional area is a quadratic function of the borehole diameter, the amount of soil to be removed or compacted significantly increases as product diameter increases. In addition, the increase in the amount of drilling fluid and cuttings washed out of the borehole during the drilling of large diameter sections requires the implementation of an extensive drilling fluids management program and, consequently, increasing costs for the contractor.

Both the average price and the median price for each product diameter was calculated. In most categories the values of the mean and the average are in close agreement indicating a normal distribution is expected. The discrepancy in the 50-mm category may be partially attributed to the fact that many environmental projects employ products of this size; thus the values in this category may represent the combination of two distinct distributions (one for utility conduits and one for environmental installations). It should be noted that regardless of the product diameter, the average cost of installing a pipeline product using HDD is in the range of \$0.65–\$0.95/mm diameter per meter. These values are similar to those reported by Iseley and Gokhale (1997).

Factors Effecting Contingency and Bid Price

During the preparation of the survey questionnaire, discussions and interviews with practicing professionals were conducted to establish a list of factors that were believed to influence the contingency and/or final bid price. The survey asked the contractors to indicate the importance of each factor from 4 (very important) to 1 (not at all important). The score for each factor was obtained by multiplying the number of answers for each category by the category's assigned value, totaling the sums and dividing by the number of responses. The results are provided in Table 8.

It can be seen in Table 8 that the most important factor in estimating contingency is the availability of adequate soil data. Soil conditions are of utmost importance in selecting the type of downhole drilling tools, drilling fluid composition, and rig size. Even a short section of adverse soil conditions along the alignment can result in failure of the installation or a loss of the entire drill string. The more information is made available regarding local soil conditions, the lower the average bid price is expected to be. The next two factors are previous experience and location. When conducting a specialty type of work such as gravity sewers or environmental wells, the availability of personnel with experience in the area is a critical factor to the

TABLE 7. Cost of Installation for Various Product Diameters

Cost (dollars/m) (1)	Product Diameter (mm) 50 (2)	100 (3)	150 (4)	200 (5)	250 (6)	300 (7)
\$15–\$44	63%	27%	5%	5%	8%	5%
\$45–\$79	23%	37%	39%	7%	0%	3%
\$80–\$159	3%	22%	27%	44%	32%	19%
\$160–\$239	10%	10%	20%	17%	19%	19%
\$240–\$325	3%	2%	7%	22%	27%	22%
>\$325	0%	2%	2%	5%	14%	32%
Total	100%	100%	100%	100%	100%	100%
Average	\$64.39	\$66.98	\$127.67	\$173.11	\$202.16	\$233.18
Median	\$40.00	\$65.57	\$105.00	\$164.00	\$203.00	\$252.00

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technical and financial success of the project. On-the-job learning may prove to be expensive as productivity rates may drop and several attempts may be required to achieve a successful installation. As for location, urban environments present special risks including unmarked utilities, traffic, and public relations. On the other hand, the crossing of large bodies of water or environmentally sensitive areas present different types of risks related to containment of drilling fluids and lack of accessibility to the drill path. The owner and project size were also identified as important factors. Type of contract and proximity to home base were considered to be of less importance by the survey respondents when compared with the other categories.

As for the factors that influence the total bid price, innovation in design and construction method and experience received the highest ratings. This is not surprising as these factors enable the contractor to more confidently bid a project. Other factors of importance were the owner and the quality of the cost estimate. The number of competitors appeared to have little effect on bid price.

TABLE 8. Relative Importance of Factors in Estimating Contingency and Bid Price

Factor (1)	Score (2)
(*a*) Contingency	
Availability of soil data	3.6
Previous experience	3.4
Location (urban/rural)	3.4
Project size	3.2
Owner	3.2
Type of contract	2.9
Proximity to home base	2.6
(*b*) Bid price	
Innovative in design or construction methods	3.4
Experience	3.3
Owner	3.2
Quality of cost estimate	3.2
Number of competitors	2.6

PROJECT PLANNING AND CONTROL OF OPERATIONS

Productivity

In HDD, as in other types of construction works, productivity is the key to a profitable operation. Two of the main factors that affect productivity in utility projects are subsurface conditions and product diameter. Contractors were asked to identify the two types of soil formations most commonly found in their area from the following formations: clay, silt, sand, gravel, cobbles, hard-pan, sandstone, and bedrock. Next, the contractors were asked to identify the average productivity rate in terms of meters per day (based on an 8-h day) for these two soil types for a range of product diameters. The productivity values for each of the four diameter ranges in each of the eight types of soils were added and divided by the number of data points to obtain an average productivity value. The results are summarized in Table 9.

The quality and reliability of the data in Table 9 can be considered proportional to the number of data points available for the specific category of interest. Even though the values obtained for clay and sand are statistically relevant (e.g., 14–27 observations in each category), the value for cobbles, sandstone, and bedrock may or may not reflect the industry average. The following observations can be made based on the productivity data obtained:

- Productivity tends to decrease when product diameter increases.
- The highest productivity is attained while drilling in clay and silty clay.
- Lower productivity is expected while drilling in cobble and gravel.
- Reasonably satisfactory advancement rates can be achieved in sand and sandstone formations.

Problems Encountered during Drilling

During the preparation of the survey, interviews were held with practicing professionals to determine problems or diffi-

TABLE 9. Average Productivity (m/Day) in Various Subsurface Formations

Diameter (mm) (1)	Clay (2)	Silty clay (3)	Sand (4)	Gravel (5)	Cobbles (6)	Hard pan (7)	Sandstone (8)	Bedrock (9)
50–100	180 (26)	221 (3)	133 (17)	80 (8)	38 (3)	95 (6)	149 (2)	103 (2)
150–200	128 (27)	131 (4)	100 (16)	49 (7)	23 (1)	41 (5)	80 (2)	69 (2)
250–300	102 (20)	—[a]	90 (16)	41 (5)	23 (1)	35 (4)	45 (2)	45 (2)
>300	67 (17)	—[a]	65 (14)	40 (5)	23 (1)	23 (4)	45 (2)	23 (2)

Note: Values in parentheses are number of data points used to calculate average productivity for each category.
[a]Not applicable.

TABLE 10. Typical Problems and Frequency Encountered during HDD Projects

Problem or difficulty (1)	Frequency of Encountering Problem/Difficulty: Often (%) (2)	Sometimes (%) (3)	Seldom (%) (4)	Never (%) (5)	Rank (6)
Loss of circulation	23	40	36	0	1
Inclement weather	13	62	17	9	2
Tracking device	15	38	38	9	3
Buried obstacles	4	51	38	6	4
Breakdown of drill	2	39	59	0	5
Cave-in of borehole	4	30	57	9	6
Bending of rods	0	32	51	17	7
Voids in the ground	2	22	56	20	8

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culties that may be anticipated on directional drilling projects. Eight scenarios were identified in the survey and are listed in the first column of Table 10. The survey participants were asked to identify the frequency with which these problems were encountered on their projects. Each frequency received a weight ranging from 4 (often) to 1 (never). The rank for each problem/difficulty was determined by multiplying the data points assigned to each frequency by the frequency weight, adding the sums from all frequencies for the particular problem, and dividing the total by the number of data points. The higher the value obtained, the higher the frequency with which the problem was encountered, and the greater the effort that should be exercised in the development of measures to avoid it or mitigate its negative impact.

It appears that the most common problem encountered during HDD projects was loss of circulation. Loss of circulation refers to the discontinuation of the flow of drilling fluids in the borehole between the location of the drilling-head or reamer and the entry pit. Loss of circulation may occur due to natural fractures in the formation or ''frac-out,'' a leak to the surface due to overpressurizing fluids in the borehole. Depending on the circumstances, loss of circulation may have a minor effect on the drilling operation or may result in catastrophic consequences such as loss of the entire borehole together with the drill stem and downhole equipment. Although loss of circulation may not be avoided on all projects, the frequency of occurrence may be greatly reduced by employing proper drilling practices.

Inclement weather was the second most common problem identified in the survey. Proper gear and the availability of a sheltered operator shack can help mitigate the effect of inclement weather on productivity.

Tracking a disturbance refers to the presence of metallic objects or sources of magnetic fields on-site, that create ''background noise,'' thus reducing the reliability of information obtained by the locating system. Experience and proper-locating practices can typically overcome most problems caused by magnetic interference. In difficult situations, a wire-line system together with a tru-track interference overriding system can be used.

The presence of unknown buried obstacles is a risk that is present on every directional drilling project. It is expensive as well as potentially dangerous to drill into buried utilities. Subsequently, locating existing utilities is a mandatory step before commencing any HDD project. The drill operator may also encounter other buried objects such as train cars, vehicles, or foundations. Preventive measures that can help reduce the risk of encountering unmarked buried obstacles include walking the alignment with a ''walk-over'' locating system to identify possible buried metallic obstacles; searching for depressions in the ground or for above-ground facilities that may indicate the presence of a pipeline or conduit; and having a conversation with nearby residents.

Breakdown of the drilling rig or the bending of drilling rods can be traced in most cases to operator error, poor maintenance, or extending the drilling rig to its limits. Bending of rods typically occurs when the rods' maximum bending radius is exceeded. Mechanical breakdowns are a part of any project where heavy equipment is employed intensively; however, they can be minimized using scheduled maintenance and proper drilling practices.

Cave-ins of boreholes tend to occur when drilling through unconsolidated formations (e.g., sand, gravel, and cobble) or in locations where the ground water table is fast moving, making it difficult to build a sound ''filter-cake'' around the borehole wall. The results of a cave-in can be disastrous, leading to partial loss of the drill string and abandonment of the borehole. Proper drilling practices, the use of stabilizing agents, and proper selection of borehole tools can help in minimizing borehole collapse in most circumstances.

Voids in the ground can be neither predicted nor avoided. When a void is encountered an immediate loss of circulation occurs. If the void is sufficiently small the drill string can be pushed across it, otherwise, the drilling string should be withdrawn and a new alignment selected.

Concerns in Relation to Directional Drilling Projects

In the survey, contractors were asked to list concerns that they commonly considered when entering an environmental or a utility project. These concerns are listed below in order of importance.

For utility projects:

- Location of existing utilities
- Soil conditions
- Safety conditions on site (e.g., traffic)
- Accessibility
- Reliability of client (e.g., payment, soil data provided)
- Type of product
- Containment and disposal of drilling fluids
- Length of bore
- Time of the year
- Quality of design

For environmental projects:

- Type(s) of contamination
- Soil conditions
- Location of buried obstacles
- Location of plume
- Method and site for disposal of drilling fluids/cuttings
- Contract and local regulations
- Level of risk/public exposure
- Expected level of performance
- Site hydrogeological conditions
- Accessibility

Location of existing utilities, local soil conditions, safety on-site (particularly traffic control), and accessibility appear to be the main concerns on any HDD utility projects. Payment provisions are another concern, as an increasing number of clients utilize an approach of ''no hole no pay.'' In other words, in the case of an unsuccessful installation, the contractor receives no compensation for his efforts.

The type of pipe product may be of a concern if it lacks the required tensile or buckling strengths (Ariaratnam et al. 1998). Containment and disposal of drilling fluids is a growing issue as the number of directional drilling rigs increases steadily. Regulations and bylaws in many municipalities place strict restrictions on drilling fluid runoff and discharge into the local storm and sanitary sewer systems. These regulations may substantially increase the cost of the project, particularly when large diameter products are installed in soil formations with low hydraulic conductivity. Time of the year is a concern in areas where the soil freezes, thus reducing productivity.

In relation to environmental projects, the type of contaminants involved, soil conditions, location of buried obstructions, and the location of the plume are obvious concerns. Disposal of drilling fluids must be addressed as the returned drilling fluids may be considered a contaminated substance, which can be disposed of only at licensed sites. Depending on the type of contaminants involved, the cost associated with the disposal of contaminated drilling fluids might be substantial. Contract provisions should address local regulations, development ef-

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forts, and acceptance criteria. Other aspects reported by the contractors include verifiable contacts with surrounding landowners and the degree of public exposure.

DISCUSSION OF FUTURE GROWTH IN HDD INDUSTRY

Over the past 15 years, HDD industry exhibited an extraordinary rate of growth expanding its applications in traditional markets, while entering new ones. It was desired to explore the direction and rate of future growth in the industry as seen by HDD contractors themselves. In response to the survey, 85% of contractors indicated that they were considering the purchase of new equipment, 84% indicated that they were considering the hiring of new personnel, and 74% intended to increase their region of business in the near future.

As for the markets in which future growth can be expected, it was unanimous among contractors that the utility and environmental markets will continue to expand into the next century. Recent reports in professional literature and trade magazines support the survey results (Allouche et al. 1998a; Clarke 1998; Scialdon 1997; Krzyrs 1996). The second most promising applications were the municipal markets and pipeline industry. The installation of deep gravity sewers using HDD holds substantial cost savings even in comparison to traditional open-cut. In comparison to microtunneling, the use of directional drilling may result in savings as high as 50% of the cost of installation (Berzins et al. 1998). Another municipal application in which HDD may be proven to be cost effective is the installation of water forcemains, particularly in congested urban areas, northern regions where water lines are placed at depth of 3 m or more, or in areas where the bedrock is extremely close to the surface.

The pipeline industry has a cyclic nature and is heavily dependent on local activities in the natural gas and oil fields. However, on average across the continent, the pipeline industry is expected to experience a substantial growth as the deregulation of the energy market boosts the construction of local cogeneration plants, thus increasing the demand for natural gas.

The next most promising application is horizontal sampling and logging, a field still in its infancy, but sure to grow as more reliable horizontal sampling tools and more accurate borehole geophysics tools are developed (Allouche et al. 1998b).

Closing the list are specialized applications including dewatering, slope stabilization, and cathodic protection. A promising new market, overlooked by the survey, is the industrial market. Expansion of industrial facilities becomes increasingly difficult, as the number of buried utilities to be crossed can be substantial. On a recent project in an industrial facility near the city of Edmonton, Alberta, Canada, a 50-m-long pipe section installed using HDD had to cross 42 utilities along its path. Utilizing the cut-and-cover method to cross this congested pipeline corridor would have been not only expensive but also a safety concern, as many of these product lines contained potentially hazardous materials.

In conclusion, a comprehensive insight into a new and rapidly growing underground pipe and conduit installation industry was presented. It might be said that HDD has outgrown its infancy stage but is yet to achieve the status of a mature industry. Ongoing technological improvements and increased competition among HDD contractors have resulted in increased technical capability and decreased installation fees. This, combined with increasing environmental regulations and awareness of social costs, resulted in the industry steadily expanding its market share in applications such as underground utility and pipeline installations over the last 10 years. More recently, HDD contractors, seeking to improve their rate of return, ventured into new, more lucrative applications such as gravity sewers and water intakes, partially replacing more established methods such as cut-and-cover and microtunneling. Finally, emerging applications, such as horizontal wells and horizontal sampling and logging, are gaining increased acceptance as alternative methods for solving a wide range of environmental and geotechnical problems.

Consultants, owners, contractors, and researchers should strive to increase their knowledge of this industry, as it is likely to play an increasing role in the underground pipe and conduit installation industry in North America as we enter the next century.

APPENDIX I. PARTICIPATING COMPANIES

The following contractors participated in the survey:

Abbett Electrical Corp.
B. Fair Contracting Ltd.
Balkema, Inc.
Berco Services, Inc.
B-Line Contracting
Bob Hull Inc.
C&B Associates
Cliffside Utility Contractors
Commercial Trenching
D+K Horizontal Drilling Ltd.
Desa Pipeline
Drilex Systems, Inc.
Florida Boring, Inc.
Gator Brothers Boring, Inc.
Gleason Construction Co., Inc.
Golden State Utility Co.
Han Mar Energy, Inc.
Harding Directional Drilling
Harford Cable Contracting, Inc.
Hemlock Directional Boring
Horizontal Directional Drilling International
Intercom Construction
J. D. Dayley and Sons, Inc.
Jakmas Plumbing & Heating, Inc.
Kamloops Augering, Ltd.
Land & Marine, Inc.
Layne, Inc.
Michael's Limited
Michigan Trenching Services, Inc.
Mid-East Oilfield Services
Miller The Driller
Prarie Pipeline Contractors Ltd.
Premeci, Inc.
Pro Bore, Inc.
Skookum Trenchless Systems
Southern Directional Services
SubTerra Corporation
Sunland Construction, Inc.
T. C. Backhoe Services Ltd.
T. W. Johnstone Co. Ltd.
Target Directional Drilling
The Charles Machine Works
Trenchless Replacement Services
Volkens Utility Construction
Weber Contracting
R2 D2 Construction Ltd.
Rachwalski Excavating Ltd.
Robinson Trenching
Santa Rita Directional Drilling Services LLC

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