Cost of Abrasive Cutting in Decommissioning Operations in the Gulf of Mexico

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Abstract: Mechanisms that inject cutting materials into a water jet and abrasively wear away steel/concrete are called abrasive cutters. The purpose of this paper is to model the cost of abrasive cutting operations associated with decommissioning offshore structures in the Gulf of Mexico. The elements of a standard abrasive cutting contract are presented and the total cost of a job is derived based on the parameters of the contract. The total cost to perform a severance operation is aggregated according to job type and normalized according to the number, size, and length of cut performed. Descriptive statistics are provided based on data collected over a three-year period from 2000–2002, and relations are derived that estimate the time and cost of a cutting operation based on various descriptor variables. A major conclusion of the analysis is that abrasive cutting is a structure-independent operation, or in other words, the total cost of performing the service does not depend on the characteristics of the structure and can only be predicted after the job is finished and the on-site time of the cutting crew is known. This is in sharp contrast to explosive cutting, where structural characteristics are very good indicators of job cost.

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Introduction

There are approximately 4,000 structures in the federally regulated Outer Continental Shelf (OCS) of the Gulf of Mexico (GOM) associated with oil and gas production. The types of structures and range of configurations vary widely, but the most common structure in the GOM is the conventionally piled platform with wells as shown in Fig. 1. In a conventionally piled platform, the platform is pinned to the seabed by long steel tubes, called piles, which pass through the legs of the structure and act like giant tent pegs. The jacket of the structure provides a protective layer around the conductors which pass from the seabed up to the topsides and serve as the conduit to the reservoir. The number of piles can vary from three to eight or more, and typically range in diameter from 24 to 96 in. (61 to 244 cm). Piling is sometimes grouted to the jacket leg near the mudline for additional stability and support. There can be as few as one or two wells per structure or as many as sixty. Fixed platforms have been used in the GOM in water depths up to 1,300 feet (396 m), but beyond this limit floating production structures are required.

Structures are installed to produce hydrocarbons and when the time arrives that the cost to operate a structure (maintenance, operating personnel, transportation, fuel, etc.) outstrips the income from the hydrocarbons under production, the structure exists as a liability instead of an asset and becomes a candidate for decommissioning. The basic aim of a decommissioning project is to render all wells permanently safe and remove most, if not all, surface/seabed signs of production activity. The general requirements for decommissioning are specified in 30 CFR Sec. 250.1703 (Federal Register 2000): "When your facilities are no longer useful for operations, you must … (b) Permanently plug all wells; (c) Remove all platforms and other facilities; (d) Decommission all pipelines; (e) Clear the seafloor of all obstructions created by your lease and pipeline right-of-way operations; …" Note that here "you" and "your" refers to the operator of the facility. In Sec. 250.1725, the removal of platforms and other facilities are specified: "(a) You must remove all platforms and other facilities within 1 year after the lease or pipelines right-of-way terminates, unless you receive approval to maintain the structure to conduct other activities. Platforms include production platforms, well jackets, single-well caissons, and pipeline accessory platforms."

During decommissioning, the piles, conductors, and caissons that attach the jacket to the seafloor and serve as a conduit to the hydrocarbon reservoir must be severed and removed at least 15 feet (5 m) below the mudline before the jacket can be removed. The manner in which structural elements are cut is based on a number of factors, such as the preference of the operator and the experience and expertise of the contractor, the characteristics of the element(s) to be cut and the schedule of the operation, the equipment available at the time of decommissioning, the amount of preparation involved, the expected cost of the proposed methods and the potential cost of failure, the disposition of the structure, and the feasibility, reliability, safety, and environmental impact of the available options.

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Fig. 1. Baldpate platform in the Gulf of Mexico (courtesy of Hess)

The purpose of this paper is to determine the cost of abrasive water jet (AWJ) cutting associated with decommissioning operations in the GOM. There are no published reports or systematic analysis on the cost of AWJ methods in decommissioning, and thus this paper should serve as a useful industry baseline. The outline of the paper is as follows. Background information on the cutting activities involved in decommissioning is outlined along with a brief description of the technology of AWJ cutting. The regulatory requirements of explosive severance provide an indication of the potential benefits of AWJ methods. The structure of abrasive severance contracts is then examined, including the general characteristics of service agreements and the elements of a standard contract. The total cost of an abrasive operation is also formally derived based on the parameters of the job and contract specification. A description of the data aggregation procedures is presented, typical contract parameters are specified, and the percentage contribution of the fixed cost of cutting to the total cost is estimated. Job data collected from AWJ service providers are then examined. Relations are derived that estimate the time and cost of abrasive cutting based on various descriptor variables, and two methods to estimate cutting cost are presented. Conclusions complete the paper.

Background Information

Decommissioning is a Severing Intensive Operation

The decommissioning of offshore structures is a severing intensive operation. Cutting is often required throughout the structure above and below the waterline and mudline on braces, pipelines, flowlines, risers, umbilicals, templates, guideposts, chains, deck equipment, and modules. More significant cutting operations are required on the elements that are driven into the seafloor, such as multistring conductors, piling, skirt piling, and stubs which need to be cut at least 15 feet (5 m) below the mudline, pulled, and removed from the seabed. Cutting piles and conductors is probably the most critical and important part of a decommissioning project since if the piles and conductors are not cut properly, a potentially dangerous condition could arise during the operation. The bottom cuts on anchor piles and conductors must be "clean" and "complete." Incomplete cuts can pose a serious danger to the stability of the vessel and crew safety during lift.

A variety of technology exists to perform severance operations and the most common cutting methods include abrasive water jet, diamond wire, diver torch, explosive charges, mechanical methods, and sand cutters (National Research Council 1996; Pulsipher 1996). For severing operations that occur above the waterline, the cutting technique is usually dictated by the potential for an explosion. Cold cut methods are used when the potential for an explosion exists; otherwise hot cuts are employed. Cutting in the air zone is conventional since it involves methods which are regularly used for dismantling onshore industrial facilities. Below the waterline cutting is more specialized. In water depths that do not exceed 200 ft (61 m) or so, divers perform cuts on simple elements such as braces and pipeline, and for shallow water structures such as caissons, diver torch cutting is sometimes the preferred severance method. In water depths exceeding 200 ft (61 m), remotely operated vehicles are employed with abrasive cutters, diamond wire, and explosive charges. Major cutting operations required on conductors, piling, and stubs normally employ AWJ, explosive charges, and mechanical methods. Explosive or mechanical methods are mainly used for conductors, while abrasive cutters or explosive charges are used for piling.

To remove the jacket from the seafloor, all the piles that run through the legs of the structure first need to be cut. Typically, the deck of the structure is cut and removed, and with the barge on-site, the piles are then cut and pulled, followed by or simultaneous with the removal of the jacket; e.g., if the piling is grouted to the jacket legs, then the piling and jacket will be removed together. After the deck of the structure is removed, access to the piles will allow abrasive tools or explosive charges to be sent downhole. Conductors and casing string that have not been cut during plug and abandonment activities will also need to be cut and removed during this time. Typically, if conductors have not been previously cut they will be explosively severed because of the short cycle time and high reliability of the procedure.

For readers requiring additional information on the activities involved throughout a decommissioning project, the case studies of Hakam and Thornton (2000) and Thornton (1989) are a good starting point, while more detailed descriptions of the overall process can be found in National Research Council (1985), Pulsipher (1996), Manago and Williamson (1997), Thornton and Wiseman (2000), and Twachtman et al. (2000).

Abrasive Water Jet Technology

Mechanisms that inject cutting materials into a water jet and abrasively wear away steel/concrete are called abrasive cutters. Abrasive technology has a long history of application in industrial and manufacturing processes, and has been used in shipyards for many years. Abrasive cutters are classified as

1. Low pressure/high volume systems, or
2. High pressure/low volume systems.Cutters that use sand or slag mixed with water at low pressure 4,000–10,000 psi (28,000–69,000 kPa) and high volume 80–100 gal/min (300–380 L/min) are called sand cutters, while cutters that use garnet injected at the nozzle at high pressure 50,000–70,000 psi (346,000–482,000

J. Constr. Eng. Manage., 2005, 131(1): 137-148

Fig. 2. Abrasive water jet cutting tool for conductors and small piles (courtesy of Circle Technical Services)

kPa) and low volume 50–80 gal/min (190–300 L/min) are commonly referred to as abrasive jet cutters (National Research Council 1996). The abrasive provides the force for cutting and is introduced at the cutting nozzle and sent down a hose with air pressure or through a water-based solution. The abrasives typically used are garnet and copper slag.

Sand cutters use a turning mechanism (or power swivel), such as a mechanical cutter. The power swivel is connected to the top of an open pile and as the drill string turns, the cutting nozzle cuts the caisson and casing strings through the abrasive action of the water jet. Abrasive jet cutters produce a cutting jet of water mixed with garnet under high pressure and directed through a diamond orifice. Abrasive jet cutters can cut both internal to the tubular member as well as external to the member, although internal cutting is the preferred method if below mudline access to the foundation pile can be achieved.

A standard abrasive water jet unit consists of a cutting tool as shown in Figs. 2 and 3 to control the positioning and movement of the nozzle, the abrasive mixing or dispensing unit, high-pressure water pump(s) and hydraulic power unit, and control panels and cut monitoring systems (Brandon et al. 2000).

In a conventional internal pile cutting operation, the cutting tool is lowered into the pile from a wire line winch (deployment frame) or by a construction vessel crane. The arms of the tool's centralizing system stabilizes the tool and the cutting nozzle is positioned against the pile wall. A diesel-driven water pump supplies the high-pressure water stream to the cutting nozzle and the pressure required is determined by the cut parameters (e.g., wall thickness, cut configuration, abrasive mixing system, etc.). The cutting speed, direction of travel, and nozzle position are controlled and monitored by the operator at the surface control station. External cutting operations on legs, piles, and brace members are carried out using a diver or remotely operated vehicle installed tracks. Subsea video equipment, lights, and audio systems for cut observation and monitoring is common for both internal and external cutting.

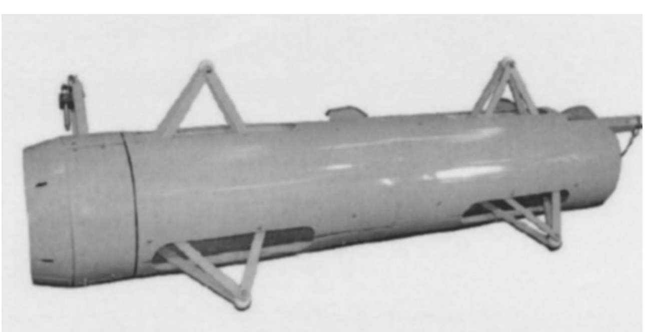

Fig. 3. Abrasive water jet cutting tool for piles or caissons from 30 to 72 in. diameter (courtesy of Circle Technical Services)

Regulatory Requirements

Lessees/operators must submit for approval an application to the Minerals Management Service (MMS)—the federal agency responsible for oil and gas development, production, and decommissioning activities in federal waters—and provide information on the structure and removal technique to be employed. All structure removals require an environmental assessment, and if explosives are to be used, an Endangered Species Section 7 Consultation.

Offshore construction contractors cannot control the marine environment as easily as land-based demolition crews, and so the MMS instigated several regulations in 1986 to protect marine mammals and sea turtles during explosive severing operations. A description of the interim regulations effective through February 2, 2004 is described in Federal Register (2002). In brief, if explosives are used for cutting, qualified observers must be used to monitor the area around the site 48 hours prior to, during and after detonation of charges; a 30-min aerial survey must be conducted within 1 h before and after each blasting episode; and detonation of explosives are allowed to occur no sooner than 1 h following sunrise and no later than 1 h prior to sunset. The time, scheduling, and expense of coordinating observers during explosive removals, the delays and cost that may occur if sea turtles or marine mammals are present, and the restrictions on using explosives encourages operators to consider alternative severance methods—when alternative methods are feasible.

For the operator and marine contractor, abrasive cutting systems thus offer some distinct advantages over explosive removal methods:

- No special permits required to employ the technology.
- National Marine Fisheries Service observers and the 48-h ocean search are not required during the severance operation.
- Pre- and postblast helicopter and diver survey requirements are eliminated.
- Daylight time restriction in the operation is eliminated.
- Potential delay due to the presence of marine life is eliminated.
- Pile flaring which may occur with explosive usage and require additional diving operations is eliminated.Abrasive cutting techniques are also considerably less certain, more time consuming and more expensive than explosive methods, and this combination of uncertainty, time, and cost, along with some of the physical limitations of the technology, continues to favor the use of explosive techniques in operator decision making (Kaiser and Pulsipher 2003, 2004).

Structure of Abrasive Severance Contracts

Cutting is a Specialty Service

Cutting is a specialty service and so most offshore contractors hire a subcontractor to supply materials and labor rather than maintain their own cutting crews. There are two principal reasons for this:

1. Subcontractors can operate more cheaply and efficiently than a contractor carrying out cutting as a noncore activity.
2. Subcontractors can develop an expertise and research and development base that contractors are not willing to pursue-.Before a contract is awarded, a tender procedure is usually carried out where companies are invited to bid for a specified amount of work. The contractor evaluates the bids and makes an award based on price and past performance.

J. Constr. Eng. Manage., 2005, 131(1): 137-148

General Characteristics of Service Contracts

The primary characteristic of a service contract is cost recovery. A general service contract must account for the cost of service plus the cost to stay in business, and all service contracts maintain the same basic cost recovery strategy (Hinze 2001). All service contractors maintain ownership (fixed) and operating (variable) costs, and the allocation of these costs into rates is typically performed by charging the customer a *portion* of the contractors ownership costs and *all* of the operating costs associated with the work requirements.

Fixed costs are those that do not vary with the service provided. Fixed costs include, but are not limited to, administration, office services, insurance, legal support, contributions to health and pension plans and social security, workers compensation, salaries, and wages, interest charges on the money tied up in the equipment, and expenses associated with maintaining and storing the equipment. Variable costs result from the cost incurred when the service is requested. Operating costs include the personnel required to operate the equipment, consumables, maintenance, wear, and equipment failure.

All costs are partially fixed and partially variable, and the allocation of these elements into one class or another is sometimes a matter of individual preference as well as convenience. The operator has many ways in which to allocate fixed and variable costs, and because fixed costs—and to a lesser extent variable costs—will vary across contractors, the terms and conditions of service contracts will vary in a market environment. In a competitive market environment, the charge to provide a service can be considered equal to the cost of performing the service plus a "risk-adjusted" market premium. In a competitive market, the market premium may be 10% or less, while in a less competitive environment, the market premium may exceed 25%.

Elements of a Standard Contract

The severance subcontractor agrees to provide cutting services as defined in the terms and conditions of work. Cutting services are usually written on a time and material basis with respect to the following elements:

- Mobilization/Demobilization to/from dock site(s), $\$K_1$,
- Equipment, $\$K_2/\text{day}$,
- Price per cut, $\$K_3/\text{cut}$,
- Personnel, $\$K_4/\text{day}$,
- Equipment standby onshore, $\$K_5/\text{day}$,
- Personnel standby onshore, $\$K_6/\text{day}$,
- Idle time, $\$K_7/\text{day}$, and
- Document preparation, $\$K_8$.The terms and conditions of each contract are unique and so the following discussion is meant only to highlight the primary terms involved in abrasive severance contracts.

The mobilization/demobilization cost to/from the dock site(s) is specified at a fixed cost $\$K_1$ and covers the cost of the service provider to transport all personnel, equipment, and materials from company facilities to dockside. The value for K_1 will depend on the distance between the service facility and the dockside location(s), the size and weight of the equipment modules that need to be transported, and the form of the transportation arrangement negotiated. The total weight of an AWJ system may range from 5–15 tons and have a footprint of 200–400 ft (61–122 m). Lifting equipment and an 18-wheel truck is required for ground transportation.

The major cost elements in the operation of AWJ systems include: (1) The capital cost of the equipment, (2) the cost of maintenance, (3) the cost of power, (4) the cost of abrasive, (5) the cost of nozzles, and (6) the cost of hoses. Several different AWJ systems are commercially available ranging from \$250,000–\$500,000. The age of the system will typically determine the maintenance cost of the equipment, and generally speaking, hydraulic systems, pumps, and motors are considered high maintenance items. Water, electricity, air, and diesel fuel requirements for the AWJ equipment are provided by the barge contractor typically at no cost while the cost of consumables must be recovered through the rate structure (nozzles and hoses wear out and must be replaced, and abrasives are not recycled during the operation). The jet cutting unit and related equipment is charged at an expected usage rate $\$K_2/\text{day}$ which is intended to cover a *portion* of the capital cost and maintenance/wear of the machine over the expected lifetime of the equipment and *all* the variable costs associated with the operation. Dayrates depend on the manner in which the subcontractor needs to recover their fixed cost, which to some extent, will also fluctuate with the supply/demand for cutting services in the GOM.

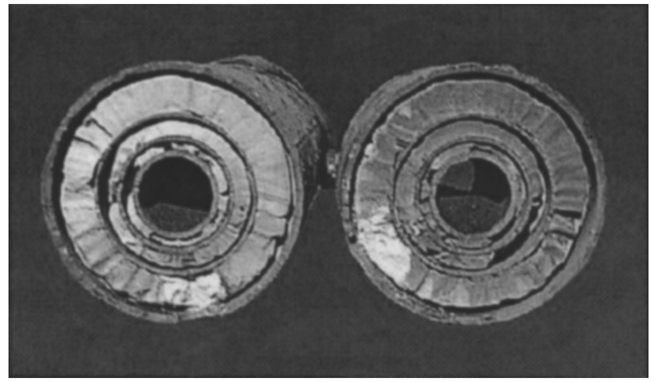

Fig. 4. Grouted conductor cross-section, concentric

A separate charge is expensed for the number of cuts that need to be performed based upon the size and type of each cut. The casing strings which line the well may or may not be grouted (see Fig. 4), and depending upon the cutting equipment employed and eccentricity of the casing, the strings may be cut in one pass and then removed or through separate cut/removal operations. There are various ways in which contractors specify the configuration charge, but typically, rates are based on the diameter $d(i)$ of element to be cut; e.g.

$$K_3(d(i)) = \begin{cases} K'_{31}/\text{cut}, & \text{if } d(i) = 24 \text{ in.} \\ K'_{32}/\text{cut}, & \text{if } d(i) = 30 \text{ in.} \\ \vdots & \\ K'_{3k}/\text{cut}, & \text{if } d(i) = 96 \text{ in.} \end{cases}$$

or through diameter classes; e.g.

$$K_3(d(i)) = \begin{cases} K_{31}/\text{cut}, & \text{if } 7 \text{ in.} \leqslant d(i) \leqslant 48 \text{ in.} \\ K_{32}/\text{cut}, & \text{if } 49 \text{ in.} \leqslant d(i) \leqslant 69 \text{ in.} \\ K_{33}/\text{cut}, & \text{if } 70 \text{ in.} \leqslant d(i) \leqslant 96 \text{ in.} \end{cases}$$

and are determined from engineering calculations based on the operational wear of the equipment and the expected time to perform the cut. The functional $K_3(d(i))$ is typically linear in $d(i)$ reflecting the fact that the time to cut steel is linearly dependent on the diameter of the element. If factors such as the thickness of the steel and/or the water depth of the cut are considered in the

J. Constr. Eng. Manage., 2005, 131(1): 137-148

rate structure, then the cost functional $K_3(d(i))$ will depart from linearity.

Personnel is charged on a per-day basis ($\$K_4/\text{day}$) to provide 24-h service availability. AWJ subcontractors in the GOM usually maintain a 3- or 4-person crew per 12-h shift. The use of equipment standby ($\$K_5/\text{day}$), personnel standby ($\$K_6/\text{day}$), and idle time ($\$K_7/\text{day}$) are charged on a "as needed" basis and the rates depend upon the personnel and equipment involved. For large abandonment projects; i.e., multiple jackets or full field removals, equipment standby essentially serve as insurance providing a backup in case of a component breakdown. Since several jobs may be performed on a single mobilization, there may not be a mob/demob cost for each job; i.e., crew and equipment may transfer barge as they move from site to site. In cases where crew and equipment transfer without returning to shore, the mob/demob cost is replaced with an idle time charge. Document preparation and a close-out report charged at a flat fee $\$K_8$ are typical components in North Sea service contracts, but for service providers operating in the GOM this cost is not normally specified.

The contractor picks up the cutting crew and equipment at dockside, provides for their meals and board while on the barge, and then delivers them back to dockside (or to another site) when the service is complete. All rates commence at the point of departure and terminate upon return to land at the point of departure. The terms and conditions of each contract is unique, but the contractor is usually responsible to ensure that the inside of all piles to be cut is free of mud, clay, and other obstructions. The cutting subcontractor may provide this service with specialized jetting equipment, but more often than not, this service is performed by the derrick barge crew. If piles are not jetted and cleared of obstructions prior to the arrival of the cutting crew, the crew will need to wait until the piles are clear to begin their operation. Accommodation and living expenses for the cutting crew are provided free or at cost plus 15%. Changes in the scope of work and technical complications—such as hangers and/or bent stabbing guides that prevent the placement of cutting tools—are charged as extra work.

Total Cost of the Job

The job specification is defined by the location of the job(s); the number, size, and type of pile that needs to be cut; and the number, size, and type of conductor that needs to be cut.

The location of the job specifies the water depth of the cutting activities, and depending upon the specific technology applied, water depth may or may not represent a technical limitation. Water depth may be a factor in the cost to provide service since increasing water depth adds to the time to go in/out of the hole and increased hydrostatic pressure may negatively impact the performance of the cutting jet. In deep water, abrasive cutting costs increase as the performance and reliability of cutting decrease.

Piling is hollow steel tubing welded together in sections and driven into the legs of the jacket to secure the structure to the seafloor. Piling is characterized by its diameter, wall thickness, and batter. Grout may be applied inside and/or outside the pile to provide additional structural support. Conductors are characterized by their diameter and wall thickness, as well as by the number and type of casing strings within the conductor, the eccentricity of the strings within the annuli, and the materials that reside between the annuli of the strings (mud, drilling fluid, water, and grout).

To describe job J, the following notation is employed:

$N_p(J)$ = total number of piles of job J;

$d_p(i)$ = outer diameter of pile i, $i = 1,\ldots,N_p$;

$N_c(J)$ = total number of conductors of job J;

$d_c(i)$ = outer diameter of conductor i, $i = 1,\ldots,N_c$;

$n_{cs}(i)$ = number of casing strings of conductor i, $i = 1,\ldots,N_c$; and

$d_{cs}(i,j)$ = outer diameter of casing string j associated with conductor i, $i = 1,\ldots,N_c$; $j = 1,\ldots,n_{cs}(i)$.

The work activity required to complete job J is specified by the following variables:

$T_1(J)$ = total number of days on-site;

$T_2(J)$ = total number of days for equipment standby;

$T_3(J)$ = total number of days for personnel standby; and

$T_4(J)$ = total amount of idle time incurred.

The total cost of job J, TC(J), is given by the value,

$$\mathrm{TC}(J) = K_1 + (K_2 + K_4)T_1 + \sum_{i=1}^{N_p} K_3(d_p(i)) + \sum_{i=1}^{N_c} (n_{cs}(i) + 1)K_3(d_c(i)) + K_5T_2 + K_6T_3 + K_7T_4 + K_8 \tag{1}$$

where the configuration charge is specified as

$$K_3(d_p(i)) = \begin{cases} K_{31}/\text{pile}, & \text{if } 7\text{ in.} \leqslant d_p(i) \leqslant 48\text{ in.} \\ K_{32}/\text{pile}, & \text{if } 49\text{ in.} \leqslant d_p(i) \leqslant 69\text{ in.} \\ K_{33}/\text{pile}, & \text{if } 70\text{ in.} \leqslant d_p(i) \leqslant 96\text{ in.} \end{cases}$$

$$K_3(d_c(i)) = \begin{cases} K_{31}/\text{string}, & \text{if } 7\text{ in.} \leqslant d_c(i) \leqslant 48\text{ in.} \\ K_{32}/\text{string}, & \text{if } 49\text{ in.} \leqslant d_c(i) \leqslant 69\text{ in.} \\ K_{33}/\text{string}, & \text{if } 70\text{ in.} \leqslant d_c(i) \leqslant 96\text{ in.} \end{cases}$$

Fixed and Variable Cost Components

The total cost of a job can be written in terms of time-independent and time-dependent cost components. The time-independent component is referred to as the "fixed" or job-dependent cost, while the time-dependent component is referred to as the "variable" or operation-dependent cost:

$$\mathrm{TC}(J) = \mathrm{FC}(J) + \mathrm{VC}(J) \tag{2}$$

where

$$\mathrm{FC}(J) = K_1 + K_8 + \sum_{i=1}^{N_p} K_3(d_p(i)) + \sum_{i=1}^{N_c} (n_{cs}(i) + 1)K_3(d_c(i))$$

$$\mathrm{VC}(J) = (K_2 + K_4)T_1 + K_5T_2 + K_6T_3 + K_7T_4$$

The fixed costs are incurred once the job is specified while the variable costs are determined once the job is complete and the crew has returned to shore. The fixed costs include mobilization/demobilization, document preparation, and the charge to cut. The variable costs include the dayrates to cover equipment, personnel,

J. Constr. Eng. Manage., 2005, 131(1): 137-148

and idle time. The relative contribution of the fixed and variable costs for a given job depends, among other factors, on the nature of the job, the success of the cutting operations, and the value of the contract parameters K_i, $i=1,\ldots,8$. The fixed costs of job J can be assessed *prior to* going offshore, while the variable costs are only known *after* the job is finished. The relative contribution of the fixed and variable costs is an important element in the determination of the total costs of the job.

Data Aggregation Methodology

Counting Tubular Elements

A typical severance job will involve cutting various size piles, skirt piles, multistring conductors, caissons, and well stubs at one or more locations. To maintain the generality of the analysis and a consistent comparison level among jobs, average cost and cut statistics are presented based on specific categorizations. A string is defined as any pile, conductor, or inner casing, and since each string is considered a separate cutting operation for the purposes of costing, strings must be counted in a consistent fashion; e.g., cutting a 36 in. pile is not equivalent to cutting a 54 in. conductor with four inner casing strings. A simple enumeration of piles and conductors will generally distort cost data unless the elements are carefully disaggregated.

Jobs are classified according to the following sets:

$$\Gamma_p = \{J | N_p(J) > 0, N_c(J) = 0\}$$

$$\Gamma_c = \{J | N_p(J) = 0, N_c(J) > 0\}$$

$$\Gamma_{pc} = \{J | N_p(J) > 0, N_c(J) > 0\}$$

$$\Gamma_s = \{J | N_p(J) \geqslant 0, N_c(J) \geqslant 0\}$$

Set Γ_p describes jobs that require only pile severance while Γ_c represents the set of jobs that only involve conductor severance. The set Γ_{pc} represents jobs that include both pile and conductor severance operations, and by definition, the set Γ_s is the union of these three mutually exclusive sets: $\Gamma_s = \Gamma_p \cup \Gamma_c \cup \Gamma_{pc}$. If $\#\Gamma_i$ denotes the number of jobs in the set Γ_i, $i=p,c,pc,s$, then it is also clear that since the categories are mutually exclusive and exhaustive, $\#\Gamma_s = \#\Gamma_p + \#\Gamma_c + \#\Gamma_{pc}$.

The number of piles, conductors, or piles and conductors within each class is counted as follows:

$$N(\Gamma_p) = \left\{ \sum_J N_p(J) | J \in \Gamma_p \right\}$$

$$N(\Gamma_c) = \left\{ \sum_J N_c(J) | J \in \Gamma_c \right\}$$

$$N(\Gamma_{pc}) = \left\{ \sum_J (N_p(J) + N_c(J)) | J \in \Gamma_{pc} \right\}$$

A normalized string count will count strings and weigh them according to their diameters, with large diameter strings carrying greater weight than small diameter strings. To count strings in a consistent fashion, three classes are defined in terms of the diameter measurement of the tubular element $\chi(i)$:

$$\mathrm{I} = \{\chi(i) | 7 \text{ in.} \leqslant d_p(i),\ d_c(i) \leqslant 48 \text{ in.}\},$$

$$\mathrm{II} = \{\chi(i) | 49 \text{ in.} \leqslant d_p(i),\ d_c(i) \leqslant 69 \text{ in.}\}, \text{ and}$$

$$\mathrm{III} = \{\chi(i) | 70 \text{ in.} \leqslant d_p(i),\ d_c(i) \leqslant 96 \text{ in.}\}.$$

Piles and conductors are then counted by class as follows:

$$N_p(\cdot, J) = \text{number of piles with diameter } d_p(i) \text{ that fall within class } \cdot\,,$$

$$N_c(\cdot, J) = \text{number of conductors with diameter } d_c(i) \text{ that fall within class } \cdot\,, \text{ and}$$

$$N(\cdot, J) = N_p(\cdot, J) + N_c(\cdot, J),$$

where the symbol $\cdot$ denotes the classes I, II, and III.

The cost to cut one pile or one casing string of the same diameter is equated under the standard contract; e.g., if a pile and a conductor both have an outer diameter of 48 in., then the cost to cut four 48–in. piles is charged at $4K_{31}$ which is "equivalent" to cutting one 48 in. conductor with three casing strings (since $n_{cs}=3$ and $n_{cs}+1=4$). Even though the length of cut of four 4–48 in. piles is strictly greater than a 48 in. conductor with three inner casing strings, complications associated with conductor severance (eccentricity, grout, voids, trip time, etc.) approximately equate the two operations.

Once the values of the configuration charge K_{3i} are selected, it is also possible to count "cuts" across classes. A weighted count is straightforward if the values of K_{32} and K_{33} are a multiple of K_{31}. For example, if $K_{32}=pK_{31}$ and $p=2$, then the cost to cut one class (II) pile is equated to the cost of cutting two class (I) piles, or one class (II) conductor with two strings is cost equivalent to six class (I) piles. More generally, on a string equivalent basis, if $\sigma(\cdot)$ denotes a string that belongs to class $\cdot$, then $\sigma(\mathrm{III}) = q\,\sigma(\mathrm{I})$, $\sigma(\mathrm{II}) = p\,\sigma(\mathrm{I})$, and $\sigma(\mathrm{III}) = q/p\,\sigma(\mathrm{II})$. After the values of p and q are specified, a normalized class of cuts is determined as

$$N(\mathrm{I}, J)^* = N_s(J) = N(\mathrm{I}, J) + pN(\mathrm{II}, J) + qN(\mathrm{III}, J) \tag{3}$$

If the values of p and q are selected as $p=2$ and $q=3$, then the normalized string-count factor is defined as

$$\begin{aligned} N(\Gamma_s) &= \left\{ \sum_J N_s(J) | J \in \Gamma_s \right\} \\ &= \left\{ \sum_J (N(\mathrm{I}, J) + 2N(\mathrm{II}, J) + 3N(\mathrm{III}, J)) | J \in \Gamma_s \right\} \end{aligned} \tag{4}$$

Total Length of Cut

A precise description of the work requirements associated with job J computes the total length of cut performed in the operation. The total length of cut is a precise measure of the cutting requirements of a job, but since cut length is *not* how abrasive severance contracts are written or priced, this variable is used to provide an alternative descriptor of the normalization process. The total length of cut per class is determined as

$$L(\Gamma_i) = \left\{ \sum_J L(J) | J \in \Gamma_i \right\}, \quad i = p, c, pc, s \tag{5}$$

where the total length of cut associated with job J, $L(J)$, is determined as

J. Constr. Eng. Manage., 2005, 131(1): 137-148

$$
L(J)=\begin{cases}\pi\sum_{i=1}^{N_p} d_p(i), & J\in\Gamma_p\\ \pi\sum_{i=1}^{N_c} d_c(i), & J\in\Gamma_c\\ \pi\sum_{i=1}^{N_p} d_p(i)+\pi\sum_{i=1}^{N_c} d_c(i), & J\in\Gamma_{pc}\\ \pi\sum_{i=1}^{N_p} d_p(i)+\pi\sum_{i=1}^{N_c}\left(d_c(i)+\sum_{j=1}^{n_{cs}(i)} d_{cs}(i,j)\right), & J\in\Gamma_s\end{cases}
$$

Parameter Specification

The values of the parameters $N_p(J)$, $N_c(J)$, $n_{\text{cs}}(i)$, $d_p(i)$, $d_c(i)$, and $d_{\text{cs}}(i,j)$ are determined by the scope of the work and, in theory, is known prior to the start of the job. The values of $N_p(J)$, $N_c(J)$, and $d_p(i)$ are available from public records, while data on $n_{\text{cs}}(i)$, $d_c(i)$, and $d_{\text{cs}}(i,j)$, and more specific information on the wall thickness of the tubular elements, the application of grout, the eccentricity of the casing strings, etc., are available from blueprints, operator records, and on-site inspection. The values of $N_s(J)$ and $L(J)$ are derived from the number and size of piles and conductors to be cut: $N_s(J)$ counts the total number of piles, conductors, and casing strings, and then normalizes the value to account for the different size strings; $L(J)$ measures the total cut length of the piles, conductors, and casing string directly.

The values of $T_1(J)$, $T_2(J)$, $T_3(J)$, and $T_4(J)$ are known after the job is complete and are determined in part by the characteristics of the structure and exogenous factors, such as the schedule/success of the cutting and the weather conditions during the operation. $T_1(J)$ is defined as the number of days the subcontractor is on-site, and this value is always recorded, while $T_2(J)$, $T_3(J)$, and $T_4(J)$ define the number of days for equipment standby, personnel standby, and idle time, respectively. Contractors may bring on the cutting crew on a "just-in-time" basis, while other contractors may allow the service provider a larger time window to perform their activities. The subcontractor will usually record some of these values in the work log, but as a practical matter, they are not generally accessible. Hence, as a matter of necessity we shall assume $T_2(J)=T_3(J)=T_4(J)=0$ and write $T_1(J)=T(J)$. The value of $T(J)$ is expected to vary with the contractor since some contractors may "hold" the cutting crew until all removal work at the site is complete, and so even a simple job may appear to take an excessive amount of time to finish. If the cutting operation is not successful on the first attempt, then either the contractor or operator (usually the operator) assumes the cost of failure and the additional time required to recut.

The values of $K_1,\ldots,K_7$ are determined through the terms of the contract. A range of typical values for K_i, $i=1,\ldots,8$ is depicted in Table 1.

Percentage Contribution of Fixed Cost to Total Cost

The percentage contribution of the fixed cost of an AWJ job to the total cost can be estimated based on the contract parameters and the job specification. Specifically, the total cost function can be expressed in terms of the expected fixed and variable cost components:

$$E[\text{TC}(J)]=E[\text{FC}(J)]+E[\text{VC}(J)] \tag{6}$$

where

Table 1. Typical Abrasive Water Jet Contract Parameters for Gulf of Mexico Severance Subcontractors (2002)

Contract parameter (units)	Parameter value ($1,000)
K_1 ($)	6–10
K_2 ($/day)	3–5
K_{31} ($/string)	1–3
K_4 ($/day)	3–4
K_5 ($/day)	2–3
K_6 ($/day)	0.3–0.5
K_7 ($/day)	1–3
K_8 ($)	3–5

$$E[\text{FC}(J)]=E[K_1]+E[K_8]+E\left[\sum_{i=1}^{N_p} K_3(d_p(i))+\sum_{i=1}^{N_c}(n_{\text{cs}}(i)+1)K_3(d_c(i))\right]$$

$$E[\text{VC}(J)]=E[(K_2+K_4)T_1]+E[K_5T_2]+E[K_6T_3]+E[K_7T_4]$$

The contract parameters vary with each subcontractor, but if the parameter values are averaged across service providers, it is possible to estimate the contribution of $E[\text{FC}(J)]$ and $E[\text{VC}(J)]$. If $K_5=K_6=K_7=K_8=0$, $T_2=T_3=T_4=0$, and we consider the average values of the parameters from Table 1, $E(K_1)=\$8,000$, $E(K_2)=\$4,000$, $E(K_3)=\$2,000$, and $E(K_4)=\$3,500/\text{day}$, then

$$E[\text{FC}(J)]=\$8,000+\$2,000N_s(J)$$

$$E[\text{VC}(J)]=\$7,500E[T(J)]$$

The expected fixed, variable, and total costs are illustrated in Fig. 5 as a function of $N_s(J)$. As a percentage of the total cost,

$$\frac{E[\text{FC}(J)]}{E[\text{TC}(J)]}=\frac{\$8,000+\$2,000N_s(J),}{\$8,000+\$2,000N_s(J)+17,250N_s(J)^{0.37}} \tag{7}$$

as shown in Fig. 6.

The relation between the fixed and variable costs of abrasive cutting is interesting since it indicates the interplay between the time variant (e.g., service) and time invariant (e.g., structural) components of the contract. As the structure complexity increases, the percentage of the fixed cost to total cost will increase. For low values of $N_s(J)$, the variable costs are marginally greater than the fixed cost component.

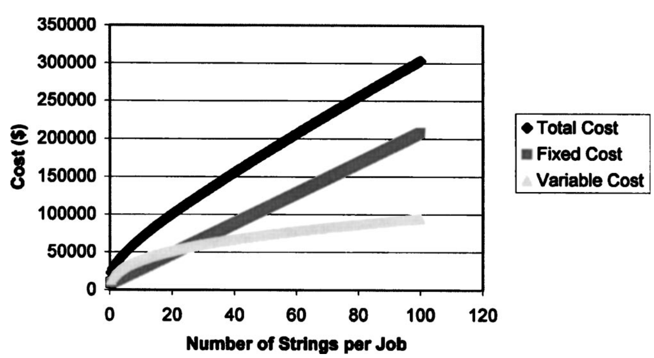

Fig. 5. Expected fixed, variable, and total cost functionals for abrasive water jet cutting services

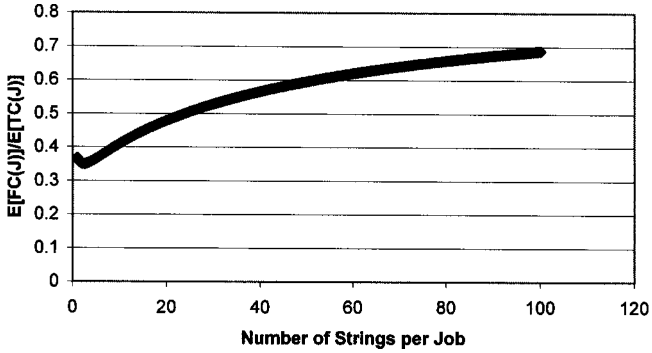

Fig. 6. Expected fixed cost to total cost ratio of abrasive water jet services

Empirical Cost Analysis

Data Source

Fifty-four AWJ jobs performed in the GOM over a three-year period, 2000–2002, were identified and processed. The sampling was reasonably uniform across subcontractors, and the restricted time frame minimized the impact of technology change while reflecting costs of the current operating environment. The sample set is comprised of 351 piles totaling 10,477 feet cut length and 68 conductors totaling 3,346 feet cut length.

Descriptive Statistics

A summary of the descriptive statistics provides insight on the manner in which abrasive cutting technology is applied (see Tables 2 and 3). Abrasive technology is used to cut piling roughly four times more frequently than conductors, which is generally supportive of the industry consensus that AWJ technology is a feasible option for piles but does *not* work well for conductors. The majority of piles severed with abrasive technology have an outer diameter of 48 in. or less, while the majority of conductors that were severed have an outer diameter of 42 in. or less. The diameter of the tubular element is not usually considered a constraint for the application of abrasive technology. Indeed, for medium and large diameter piles and conductors, AWJ technology is sometimes the best method for severance.

The diameter range and frequency of application of abrasive cutting jobs as a function of water depth are depicted in Table 3. The minimum and maximum diameter range is shown for piles and conductors and we observe that the application of abrasive cutting in the sample set drops off rapidly as water depths exceed 150–200 ft. This is reflective of the shallow water caissons and fixed platform structures removed in the GOM over the past three years as well as the technical limitations/operator preferences associated with abrasive technology.

Table 3. Typical Diameter Range and Frequency for Pile and Conductor Severance Using Abrasive Water Jet Technology as a Function of Water Depth (2000–2002)

	Pile[a]		Conductor[b]	
Water depth range (ft)	(Min, Max) (in.)	Frequency (%)	(Min, Max) (in.)	Frequency (%)
0–50	(36, 48)	53	(7, 30)	17
51–100	(30, 60)	16	(7, 48)	55
101–150	(36, 48)	24	(7, 72)	17
151–200	(30, 60)	5	(10, 42)	10
201–250	(30, 60)	1		
251–300	(48, 54)	1		
301–350	(42, 48)			

[a]Based on 351 piles and 10,477 feet cut length.

[b]Based on 68 conductors and 3,346 feet cut length.

Average Cost and Cut Measures

The cost to cut one pile or one conductor on a job that *only* involves piles or conductors is defined as the cost of the job, AC(J), divided by a count of the number of cuts performed on the job:

$$\text{Cost-pile}(J) = \frac{\text{AC}(J)}{N_p(J)}, \quad J \in \Gamma_p \tag{8}$$

$$\text{Cost-conductor}(J) = \frac{\text{AC}(J)}{N_c(J)}, \quad J \in \Gamma_c \tag{9}$$

where $N_p(J)$ and $N_c(J)$ count the total number of piles and conductors of the job. Jobs that involve severing piles *and* conductors are counted and analyzed separately:

$$\text{Cost-pile/conductor}(J) = \frac{\text{AC}(J)}{N_p(J) + N_c(J)}, \quad J \in \Gamma_{pc} \tag{10}$$

The normalized cost to cut a string is defined as

$$\text{Cost-string}(J) = \frac{\text{AC}(J)}{N_s(J)}, \quad J \in \Gamma_s \tag{11}$$

The average cost to cut a pile, conductor, pile and conductor, or string is determined according to job classification. The average cost to cut an element in the set Γ_i is defined as

$$\text{Cost-cut}(\Gamma_i) = \frac{\text{AC}(\Gamma_i)}{N(\Gamma_i)}, \quad i = p,c,pc,s \tag{12}$$

where $\text{AC}(\Gamma_i) = \{\Sigma_J \text{AC}(J) \mid J \in \Gamma_i\}$. The average number of cuts achieved per day is estimated as

Table 2. Frequency of Application of Abrasive Water Jet Technology in the Gulf of Mexico as a Function of the Diameter of the Tubular Member (2000–2002)

Parameter	Pile[a]					Conductor[b]		
Outer diameter	⩽30 in.	36 in.	42 in.	48 in.	⩾54 in.	<26 in.	26–42 in.	>42 in.
Frequency	15%	26%	17%	32%	9%	59%	36%	5%

[a]Based on 351 piles and 10,477 feet cut length.

[b]Based on 68 conductors and 3,346 feet cut length.

Table 4. Summary Statistics of Abrasive Water Jet Severance Technology in the Gulf of Mexico (2000–2002)

Parameter (unit)	Γ_p	Γ_c	Γ_{pc}	Γ_s
Cost-cut ($/element)	9,019	12,147	4,313	4,561
Cut-day (cut/day)	0.97	0.83	2.48	2.05
Cost-day ($/day)	8,737	10,003	10,686	9,362
Cost-length ($/foot)	979	848	521	787
Cost-job ($/job)	52,142	51,286	53,444	52,706
Cut-job (cut/job)	5.8	4.8	11.9	11.6
# (element)	32	8	14	54

$$\text{Cut-day}(\Gamma_i) = \frac{N(\Gamma_i)}{T(\Gamma_i)}, \quad i = p,c,pc,s \tag{13}$$

where $T(\Gamma_i)=\{\Sigma_J T(J) \mid J \in \Gamma_i\}, \quad i=p,c,pc,s$.

The average dayrates associated with AWJ severance is defined as the total cost of the operation divided by the total on-site time to perform the operation:

$$\text{Cost-day}(\Gamma_i) = \frac{\text{AC}(\Gamma_i)}{T(\Gamma_i)}, \quad i = p,c,pc,s \tag{14}$$

The cost per length of material cut provides a measure to compare against the average cost to cut an element. The cost per length is defined as

$$\text{Cost-length}(\Gamma_i) = \frac{\text{AC}(\Gamma_i)}{L(\Gamma_i)}, \quad i = p,c,pc,s \tag{15}$$

The values of the Cost-cut, Cut-day, Cost-day, and Cost-length statistics based on the empirical data are shown in Table 4 categorized according to job specification. Descriptive statistics on the value of Cost-job and Cut-job within each category are also shown, along with a count of the number of elements within each class.

The collected data represent a majority of the abrasive cuts performed in the GOM over 2000–2002, and so the frequency of application of the job types is itself an interesting statistic: Pile-only jobs represent 59% of the sample set, followed by pile/conductor jobs (26%), and conductor-only jobs (15%). The application of AWJ cutting is primarily aimed at pile-only and pile/conductor type jobs, and is not frequently used on conductor-only job types. The average cost per job across each data set is also surprisingly uniform indicating that the jobs within each class are comparable in terms of the absolute scope and magnitude of work.

The unit cost and time to perform a cut vary with the level of categorization, so from Table 4 we observe that the cost to cut piling on a pile-only job is $9,019/pile, while the cost to cut a conductor on a conductor-only job is $12,147/conductor. On a cut length basis, the cost statistics yield $979/ft to abrasively cut a pile versus $848/ft to cut a conductor. The reason for the dichotomy is due to the fact that most conductors are composed of a number of casing strings which add length (and thus time and cost) to the cut but are not counted in a simple element enumeration. The values of the cost per cut and the cost per length adjust downward as expected if the number of inner casing strings is accounted for through Γ_s or $L(\Gamma_i)$. The most cost effective cutting occurs when both piles and conductors are severed together, and since this occurs in conjunction with an increase in the number of cuts per job, it is likely that abrasive cutting operations are subject to scale economies.

Table 5. Regression Model Results—I

Descriptor	$T(\Gamma_i)=\alpha N(\Gamma_i)^\beta$ α	β	R^2
$N(\Gamma_p)$	3.1	0.29	0.06
$N(\Gamma_c)$	2.4	0.47	0.27
$N(\Gamma_{pc})$	1.7	0.47	0.58
$N(\Gamma_s)$	2.3	0.37	0.23
Descriptor	$T(\Gamma_i)=\gamma L(\Gamma_i)^\delta$ γ	δ	R^2
$L(\Gamma_p)$	0.65	0.52	0.16
$L(\Gamma_c)$	0.51	0.58	0.50
$L(\Gamma_{pc})$	0.49	0.51	0.68
$L(\Gamma_s)$	0.67	0.49	0.30

The total cost of pile-only jobs per day was the least expensive of all the job types, while on a per cut basis, pile/conductor cutting jobs exhibited the lowest cost per cut and the greatest number of cuts per day. The cost to cut a string is roughly $4,500/string or $787/ft. The cost per day for AWJ cutting is on the order of $10,000/day regardless of the job type.

Regression-Based Cost Functionals

On-Site Time Cannot be Predicted Using Structural Characteristics

For a given job J, the structure characteristics are known prior to the start of the job, while the time to complete the operation and return to shore is known only after the job is finished. The relationship between the time on-site, excluding weather delays, and the characteristics of the structure would be a useful indicator of cost if the model results are robust. Unfortunately, the on-site time cannot be reliably predicted using the characteristics of the structure.

A linear relation between the time to cut and the number of cuts is a reasonable hypothesis, but such relations yield unusually poor fits. and so power relations of the form

$$T(\Gamma_i) = \alpha N(\Gamma_i)^\beta \tag{16}$$

$$T(\Gamma_i) = \gamma L(\Gamma_i)^\delta \tag{17}$$

for $i=p,c,pc,s$, was employed. The model results remain quite weak, however, as shown in Table 5, leading to the conclusion that knowledge of the structure does *not* provide a reasonable basis to predict the time a crew will be on-site to perform a job. This is in sharp contrast to explosive cutting where structural characteristics are very good indicators of the job time (Kaiser and Pulsipher 2003). The functional relation that employs the cut length is superior to a simple count of tubular elements, but for the most part, the improvement is marginal. The on-site time of an abrasive cutting crew is a stochastic quantity which, in general, cannot be predicted prior to performing the job.

Total Cost is Correlated to On-Site Time

The two primary variables that determine the cost of AWJ service are the dayrate charged for the equipment and personnel and the configuration charge related to the number of cuts that have to be made. The total cost to cut elements is developed in stages using

J. Constr. Eng. Manage., 2005, 131(1): 137-148

Table 6. Regression Model Results—II

	$TC(\Gamma_i)=\varepsilon+\eta T(\Gamma_i)$		
Descriptor	ε	η	R^2
$T(\Gamma_p)$	8,925	7,240	0.74
$T(\Gamma_c)$	1,974	9,692	0.63
$T(\Gamma_{pc})$	8,103	8,994	0.78
$T(\Gamma_s)$	7,412	8,046	0.68

	$TC(\Gamma_i)=\mu N(\Gamma_i)^{\theta}$		
Descriptor	μ	θ	R^2
$N(\Gamma_p)$	20,207	0.47	0.13
$N(\Gamma_c)$	17,015	0.71	0.49
$N(\Gamma_{pc})$	18,345	0.45	0.65
$N(\Gamma_s)$	16,595	0.49	0.35

	$TC(\Gamma_i)=\nu L(\Gamma_i)^{\varphi}$		
Descriptor	ν	φ	R^2
$L(\Gamma_p)$	2,615	0.72	0.26
$L(\Gamma_c)$	2,343	0.77	0.73
$L(\Gamma_{pc})$	4,561	0.55	0.67
$L(\Gamma_s)$	3,475	0.64	0.45

one- and two-variable models based on the descriptor variables $T(\Gamma_i)$, $N(\Gamma_i)$, and $L(\Gamma_i)$. The one-variable models explain the total cost through the on-site time of the crew, $T(\Gamma_i)$, an enumeration of the number of elements to be cut, $N(\Gamma_i)$, and a calculation of the total length of cut to be made, $L(\Gamma_i)$:

$$TC(\Gamma_i) = \varepsilon + \eta N(\Gamma_i) \tag{18}$$

$$TC(\Gamma_i) = \mu T(\Gamma_i)^{\theta} \tag{19}$$

$$TC(\Gamma_i) = \nu L(\Gamma_i)^{\varphi} \tag{20}$$

while the two-variable models combine the on-site time and configuration specification as follows:

$$TC(\Gamma_i) = \psi + \kappa T(\Gamma_i) + \xi N(\Gamma_i) \tag{21}$$

$$TC(\Gamma_i) = \rho + \sigma T(\Gamma_i) + \chi L(\Gamma_i) \tag{22}$$

for $i=p,c,pc,s$. Model results are depicted in Tables 6 and 7.

There is a fairly strong relation between the total cost of a job and the on-site time of the crew as shown in Table 6. This result is both reasonable and understandable since time *is* a primary factor in the cost of service contracts. It is interesting to note that the slope parameter of the regression models is fairly stable across classes indicating that the same fundamental driver is acting across each class. The total cost to cut piles and/or conductors can be predicted with reasonable accuracy given the knowledge of the total on-site time of the operation.

The knowledge of the structural characteristics of a job, however, does *not* provide a good indicator of the total cost, and considering the results from Table 5, this is not surprising. The total cost of a job can be predicted by the on-site time of the cutting crew, but the on-site time cannot be predicted by the characteristics of the structure, and so it is reasonable to surmise that the total cost is not readily predicted through the structure characteristics. Specification of $N(\Gamma_i)$ and/or $L(\Gamma_i)$ does not provide a useful means to predict the total cost of the operation as indicated by the relatively low values of the fit parameters in Table 6. (The high values of the fit parameter for Γ_c and Γ_{pc} in Table 6 are likely due to the small number of elements within each categorization.)

Table 7. Regression Model Results—III

	$TC(\Gamma_i)=\psi+\kappa T(\Gamma_i)+\xi N(\Gamma_i)$			
Descriptor	ψ	κ	ξ	R^2
$T(\Gamma_p)$, $N(\Gamma_p)$	5,430(1.1)	7,041(9.1)	810(1.8)	0.75
$T(\Gamma_c)$, $N(\Gamma_c)$	−5,345(−0.6)	5,778(4.64)	1,463(6.4)	0.94
$T(\Gamma_{pc})$, $N(\Gamma_{pc})$	18,549(1.6)	4,632(1.3)	745(1.3)	0.77
$T(\Gamma_s)$, $N(\Gamma_s)$	7,330(16)	6,562(9.6)	729(5.2)	0.78

	$TC(\Gamma_i)=\rho+\sigma T(\Gamma_i)+\chi L(\Gamma_i)$			
Descriptor	ρ	σ	χ	R^2
$T(\Gamma_p)$, $L(\Gamma_p)$	−676(−0.12)	6,779(9.2)	232(2.8)	0.78
$T(\Gamma_c)$, $L(\Gamma_c)$	−7,053(−0.8)	5,661(4.5)	473(6.4)	0.94
$T(\Gamma_{pc})$, $L(\Gamma_{pc})$	19,604(1.5)	2333(0.7)	212(2.2)	0.81
$T(\Gamma_s)$, $L(\Gamma_s)$	3,590(0.7)	6,476(9.2)	189(5.0)	0.78

[a]The t statistics of the multiple regression model are presented in parentheses.

Multiple regression models built from the variables $T(\Gamma_i)$, $N(\Gamma_i)$, and $L(\Gamma_i)$ are depicted in Table 7. The inclusion of on-site time improves the model fits indicating that the variable is relevant, but since the time to perform a job is uncertain from the outset (and cannot be predicted), the application of these relations remain limited. Functional relations that employ the cut length as a descriptive factor are slightly superior to using a count of tubular elements.

Abrasive Water Jet Operations Exhibit Scale Economies

Economies of scale exist for abrasive cutting since the average cost per unit of output decreases with increasing output levels. The average cost per cut as a function of the total number of cuts and the total length of cut is defined as

$$ACN(\Gamma_i) = \frac{TC(\Gamma_i)}{N(\Gamma_i)} = \mu_i N(\Gamma_i)^{\theta_i - 1} \tag{23}$$

$$ACL(\Gamma_i) = \frac{TC(\Gamma_i)}{L(\Gamma_i)} = \nu_i L(\Gamma_i)^{\varphi_i - 1} \tag{24}$$

for $i=p,c,pc,s$. From Table 6, since $\theta_i < 1$ and $\varphi_i < 1$ for $i = p,c,pc,s$, the average costs per unit of output are decreasing functions of $N(\Gamma_i)$ and $L(\Gamma_i)$.

Estimating the Direct Cost of Abrasive Cutting

The average cost per cut provides a quick means to estimate the direct cost of abrasive cutting operations. Using average cost multipliers, it is possible to provide a quick estimate of the cost of job J by first classifying the job by its cutting specification, computing the total number of cuts per class or the total cut length, and then evaluating the expected total cost of the job, $E[TC(J)]_a$, using one of the following relations:

$$E[TC(J)]_{a_1} = \text{Cost-cut}(J) N(J) \tag{25}$$

$$E[TC(J)]_{a_2} = \text{Cost-length}(J) L(J) \tag{26}$$

where Cost-cut(J) and Cost-length(J) are determined from Table 4.

J. Constr. Eng. Manage., 2005, 131(1): 137-148

An alternative realization of the expected cost of job $J \in \Gamma_i$ is based on the multiple regression models:

$$E[\mathrm{TC}(J)]_{r_1} = \psi + \kappa E[T(J)] + \xi N(J) \tag{27}$$

$$E[\mathrm{TC}(J)]_{r_2} = \rho + \sigma E[T(J)] + \chi L(J) \tag{28}$$

where the coefficients of the relations are provided in Table 7. Application of the regression models requires an estimate of the expected on-site time of job J, $E[T(J)]$, which as we have shown previously, can be considered a stochastic quantity. Ultimately, the veracity of cost estimation depends upon the user's preference of which model to apply and the ability to predict the on-site time for the operation.

- *Example 1.* For job J specified by 3–48 in. piles, $J \in \Gamma_p$ and

  $$\{N(J) = 3, L(J) = 3(48\text{ in.})(3.14)(\text{ft}/12\text{ in.}) = 37.7\text{ ft}\}$$

  The average cost models yield the estimates

  $$E[\mathrm{TC}(J)]_{a_1} = \$9{,}019/\text{cut } (3\text{ cuts}) = \$27{,}057$$

  $$E[\mathrm{TC}(J)]_{a_2} = \$979/\text{ft } (37.7\text{ ft}) = \$36{,}889$$

  To apply the regression model, we first estimate the time to complete the job,

  $$E[T(J)] = 3.1N(\Gamma_p)^{0.29} = 0.65L(\Gamma_p)^{0.52} = 4.3\text{ days}$$

  and then apply the relations

  $$E[\mathrm{TC}(J)] = \$5{,}430 + \$7{,}041\ E[T(J)] + \$801N(J) = \$38{,}109$$

  $$E[\mathrm{TC}(J)] = -\$676 + \$6{,}779\ E[T(J)] + \$232L(J) = \$37{,}220$$

- *Example 2.* For job J specified by 4–36 in. piles, 1–65 in./36 in./20 in. conductor with two inner casing strings and 1–74 in. caisson, $J \in \Gamma_{pc}$ and

  $$\{N_p(J) = 4, N_c(J) = 2, N_{pc}(J) = N_p(J) + N_c(J) = 6, L(J) = 60.4\text{ ft}\}$$

  $$E[T(J)] = 1.7N(\Gamma_{pc})^{0.47} = 0.49L(\Gamma_{pc})^{0.51} = 4.0\text{ days}$$

  The average cost and regression model for $J \in \Gamma_{pc}$ yield an expected service cost bound between \$25,878 and \$41,647:

  $$E[\mathrm{TC}(J)]_{a_1} = \$4{,}313/\text{cut } (6\text{ cuts}) = \$25{,}878$$

  $$E[\mathrm{TC}(J)]_{a_2} = \$521/\text{ft } (60.4\text{ ft}) = \$31{,}468$$

  $$E[\mathrm{TC}(J)]_{r_1} = \$18{,}549 + \$4{,}632(3.94) + \$745(6) = \$41{,}362$$

  $$E[\mathrm{TC}(J)]_{r_2} = \$19{,}604 + \$2{,}333(3.96) + \$212(60.4) = \$41{,}647$$

  In terms of $J \in \Gamma_s$,

  $$\{N_p(\mathrm{I},J) = 4,\ N_c(\mathrm{II},J) = 3,\ N_c(\mathrm{III},J) = 1,\ N_s(J) = 13\}$$

  $$E[T(J)] = 2.3N(\Gamma_s)^{0.37} = 5.9\text{ days}$$

The average cost and regression model for $J \in \Gamma_s$ yield an expected service cost range given by

$$E[\mathrm{TC}(J)]_{a_1} = \$4{,}561/\text{cut } (13\text{ cuts}) = \$59{,}293$$

$$E[\mathrm{TC}(J)]_{a_2} = \$787/\text{ft}(60.4\text{ ft}) = \$47{,}535$$

$$E[\mathrm{TC}(J)]_{r_1} = \$7{,}330 + \$6{,}562(5.9) + \$729(13) = \$55{,}794$$

$$E[\mathrm{TC}(J)]_{r_2} = \$3{,}590 + \$6{,}476(5.9) + \$189(60.4) = \$53{,}214$$

Conclusions

The offshore environment is a potentially hazardous location which presents special risk to the personnel involved in cutting operations and potential harm to the marine environment. Abrasive cutting offers significant regulatory relief in application, but the technology is also considerably less certain, more time consuming, and more expensive than explosive methods, and operators and marine contractors continue to favor the use of explosive techniques. The expected time required to perform an operation, and more importantly, the cost of failure and exposure time, are important parameters that drive decision making. The use of derrick barge spreads typically run on the order of \$100,000–\$200,000 a day, and so time delays—especially unexpected delays—are priced at a premium. Time is *big* money in offshore operations and increased exposure equates to increased risk.

Empirical relations for the cost of AWJ cutting in the GOM were derived as a function of the characteristics of the structure and the amount of on-site time of the operation. There are no published reports or systematic analysis of the cost of AWJ cutting, and so the primary task of this paper was to provide the foundational basis for an empirical analysis of the cost of abrasive cutting. It was shown that the total cost of an abrasive operation is closely correlated to the amount of time on-site but only weakly correlated to the characteristics of the structure. The primary implication of this result is that the total cost to perform abrasive cutting cannot be reasonably predicted *prior* to performing the job. It is only *after* the job is complete and the total on-site time known that the total cost can be predicted with reasonable certainty.

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