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DRILLING AND PREPARATION OF REUSABLE, LONG RANGE, HORIZONTAL BORE HOLES IN ROCK AND IN GOUGE

Vol. II. Estimating Manual for Time and Cost Requirements

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Final Report

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16. Abstract

The objective of this study is to assess horizontal drilling as an alternative to pilot tunneling in geological investigation prior to the design and construction of highway tunnels and to identify means to increase the penetration capability and accuracy and decrease the cost of horizontal drilling.

This volume presents a model for estimating the time and cost of drilling long horizontal holes. Sample problems are worked in detail to illustrate the application of the model to four (4) different drilling techniques. Procedures to apply the model to any combination of geological conditions are illustrated with an example problem. The logic and format of the model are adaptable to future improvements in the state-of-the-art of horizontal drilling.

This is the second of three volumes. Volume I is published as FHWA-RD-75-95, subtitle: A State-of-the-Art Assessment. Volume III is published as FHWA-RD-75-97, Subtitle: A Development Plan to Extend Penetration Capability, Increase Accuracy and Reduce Costs.

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LIST OF SYMBOLS

Symbol		Units	Reference
B	Number of bit changes	-	Sections 3.1, 3.2; Appendix B
C	Number of core samples	-	Sections 3.1, 3.3, 3.4, 3.7
D	Number of direction changes	-	Section 3.6
E	Number of drilling fluid cycles	-	Section 3.4
F_h	Fluid requirements per foot of hole	ft^3/ft (m^3/m)	Section 3.4
F	Number of fishing activities	-	Section 3.8
F_r	Fluid requirements per foot of drill rod	ft^3/ft (m^3/m)	Section 3.9
G_h	Grout requirements per foot of grouted section	ft^3/ft (m^3/m)	Section 3.9
G_n	Length of geological section	ft (m)	Sections 3.1, 3.2; Appendix B
L	Total length of hole	ft (m)	Sections 3.1, 3.2, 3.3, 3.4, 3.5, 3.6, 3.7, 3.8, 3.9
L_c	Length of core sample required	ft (m)	Sections 3.3, 3.7
L_g	Total length of hole requiring grout	ft (m)	Section 3.9
N	Number of geological sections considered	-	Sections 3.1, 3.2; Appendix B
P_c	Penetration rate during intermittent core drilling	ft/hr (cm/min)	Sections 3.3, 3.7
$P_{c,n}$	Penetration rate during wireline core drilling	ft/hr (cm/min)	Section 3.1; Appendix B
$P_{f,g}$	Penetration rate through grouted sections	ft/hr (cm/min)	Section 3.9
$P_{f,n}$	Penetration rate during full hole drilling	ft/hr (cm/min)	Section 3.2; Appendix B
P_g	Grout pump capacity	ft^3/min (ℓ/min)	Section 3.9
P_w	Water pump capacity	gal/min (ℓ/min)	Section 3.4

LIST OF SYMBOLS (Continued)

Symbol		Units	Reference
R	Number of hole stabilization activities	-	Section 3.9
S	Number of hole surveys	-	Section 3.5
t	Total time for any operation	hr.	Sections 3.1, 3.2, 3.3, 3.4, 3.5, 3.6
t_b	Time required to change bit	min.	Sections 3.1, 3.2, 3.3, 3.6, 3.7, 3.8
t_c	Time required to drill direction change	min.	Sections 3.6, 3.7
t_f	Time required to connect fishing tap to drill rod	min.	Section 3.8
t_g	Time required for grout to cure	hr.	Section 3.9
t_s	Time required to take a single shot survey	min.	Section 3.5
V_r	Rod handling velocity	ft/min. (cm/sec)	Sections 3.1, 3.2, 3.3, 3.6, 3.7, 3.8, 3.9
V_s	Survey instrument velocity through drill string	ft/min. (cm/sec)	Section 3.5
V_w	Wireline velocity	ft/min. (cm/sec)	Section 3.1

1. Introduction

The purpose of this manual is to provide a realistic method of estimating the time and cost of drilling long horizontal holes. It identifies and evaluates various drilling factors and parameters; defines and illustrates the costing logic; and provides input data needed to analyze and compare potentials of present day drilling techniques.

The input applicability of the estimating model extends to drilling holes up to 6,000 or 7,000 feet (1829 to 2134 meters) in length with diameters up to 10 inches (254 mm). These figures exceed the assessed state-of-the-art capabilities from Volume I. The logic and format used are adaptable to any set of hole dimensions which may become relevant due to improvements or extension of the state-of-the-art.

Due to a lack of factual cost or performance data pertaining to horizontal long hole drilling, it has been necessary to make various theoretical and empirical extrapolations which may or may not prove valid in future testing of the estimating model. Any adjustment which may be necessary can be made readily.

This model pertains to the initial drilling and core sampling of a directionally controlled horizontal hole. The time and cost of any other geologic investigations, testing, and sampling which might be desired is not included, although the model may easily be extended to include these operations.

Volume I of this report discusses and evaluates the capabilities and limitations of present day drilling techniques as well as many other factors pertinent to horizontal drilling. Based on the findings presented in Volume I, this estimating model considers the following four drilling techniques:

(1) Diamond Wireline Core Drilling,

(2) Rotary Drilling,

(3) Down-Hole Motor Drilling, and

(4) Down-Hole Percussive Drilling.

The model, as presented, identifies rock types on the basis of unconstrained uniaxial compressive strength and is capable of handling any combination of various rock types as well as any reasonable values for any of the drilling parameters identified.

For illustrative purposes, this manual uses an "average" rock profile. This "average" rock profile is derived from a survey of the rock type encountered in 47 tunnel projects. Rock type is classified on the basis of compressive strength as follows:

G_1 - hard rock > 22,000 psi

G_2 - medium rock 8,000-22,000 psi

G_3 - soft rock < 8,000 psi

The average profile assumes that the driller will encounter 30 percent hard rock, 59 percent medium rock, and 11 percent soft rock.

In addition to this "average" rock mix, the graphs presented assume certain recommended values for the various drilling parameters and for the frequency of periodic drilling activities. These recommended values are summarized in Tables 3.2 and 3.3 of Section 3.

For situations, where the estimator lacks information about rock type and/or drilling parameters, the entire estimate can be obtained from graphs presented within this manual. Where this information is available, the manual presents techniques for establishing more exact curves.

Although the manual provides a method of estimating the cost of long hole drilling, in actual practice the cost of drilling will depend to a large extent on the contractor's appraisal of the risks involved, the experience of his crew, and other factors which can only be generally evaluated by the model. Also, considering the present state-of-the-art, it is unlikely that a contractor would undertake the drilling of long directionally controlled holes except on a time and material or force account basis.

2. The Estimating Model

The general horizontal drilling estimating procedure is similar to that used for estimating most construction activities.

The procedure considers two basic categories of costs - direct and indirect. The direct costs reflect the actual drilling process and include:

(1) Labor,

(2) Equipment, and

(3) Materials.

The indirect costs include:

(1) Mobilization and set-up, and

(2) Overhead.

The direct costs can be related to the actual time and materials required to perform the job. The indirect costs can be expressed either as a fixed amount or as a percentage of the direct costs.

The estimated drilling cost is the sum of the direct and indirect costs plus a percentage allowance for contractors profit.

The following sections present the general estimating procedure, the drilling operations, equipment, and materials required by the different drilling techniques, and a sample cost estimate.

2.1 General Estimating Procedure

The general horizontal drilling estimating procedure is shown by the flow chart in Figure 2.1. The estimated cost is obtained in the following manner. Also included in this procedural listing are

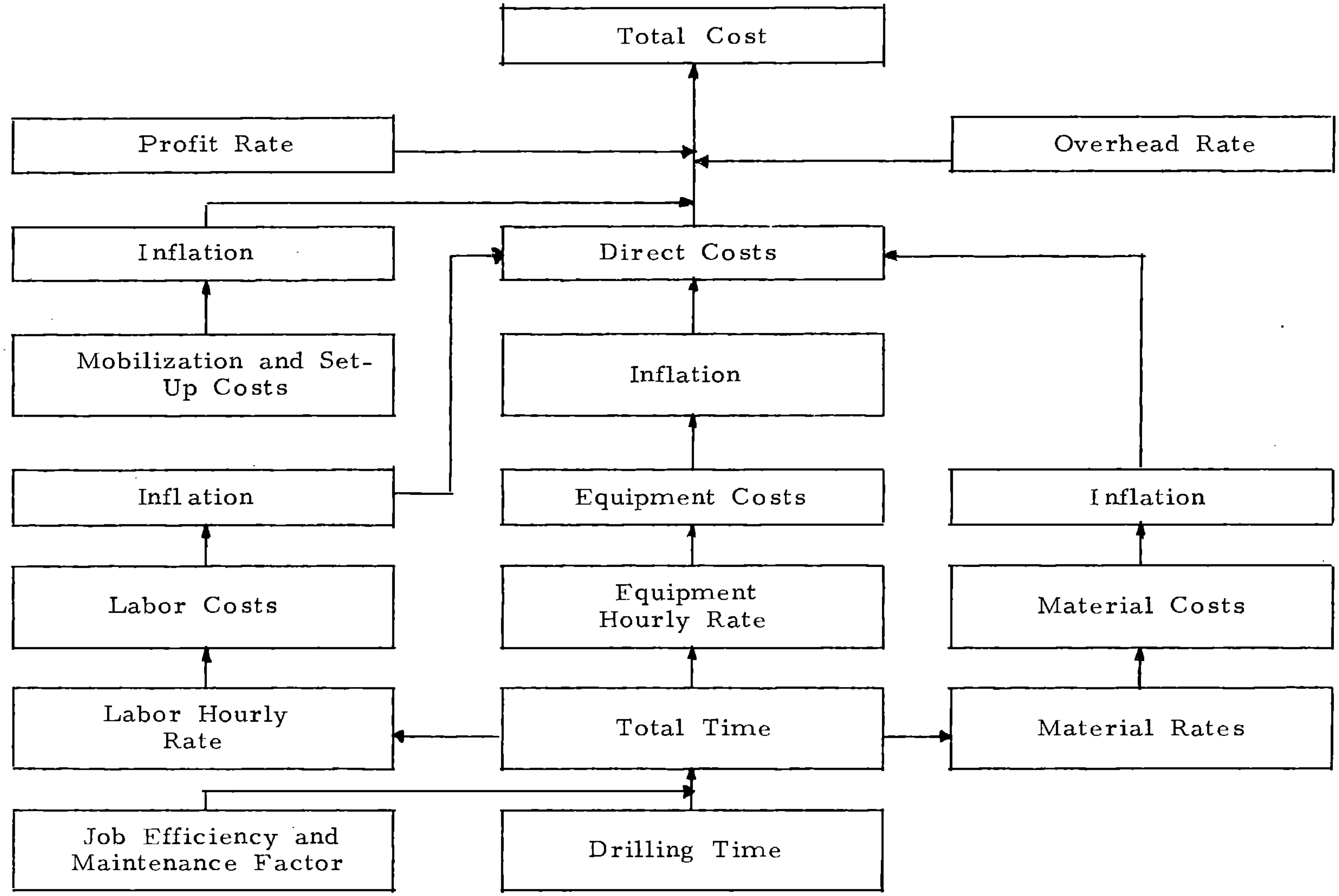

Figure 2.1 - Flow Chart of the General Estimating Model

references to later sections where more detail is provided.

(1) Determine the time required to complete all necessary drilling operations. Section 2.2 explains which operations are required by the various drilling techniques and Section 3 explains the procedure for estimating the times required for each of these operations.

(2) Determine the job efficiency and maintenance factor. Section 4 explains the elements which must be considered in this factor.

(3) Calculate the job efficiency and maintenance time as the product of (1) and (2).

(4) Determine the total time required as the sum of (1) and (3).

(5) Determine the labor hourly rate. Section 5 explains the elements of the hourly labor rate.

(6) Determine equipment requirements and the cost per hour. Section 2.2 lists typical equipment needed for the various drilling techniques and Section 5 explains the determination of the hourly cost of this equipment.

(7) Determine material requirements and the cost per foot. Section 2.2 lists typical materials needed for the various drilling techniques and Section 5 explains the determination of the cost per foot.

(8) Determine the cost of labor as the product of (4) and (5).

(9) Correct for inflation. Section 4 explains the inflation escalation factors.

(10) Determine the cost of equipment as the product of (4) and (6).

(11) Correct for inflation. Section 4 explains the inflation escalation factors.

(12) Determine the cost of materials as the product of (3) and the hourly rate plus the hole length and per foot rate.

(13) Correct for inflation. Section 4 explains the inflation escalation factors.

(14) Determine the total direct costs as the sum of (9), (11), and (13).

(15) Determine the mobilization and set-up cost. Section 4 explains the elements of this cost.

(16) Correct for inflation. Section 4 explains the inflation escalation factors.

(17) Determine an intermediate cost as the sum of (14) and (16).

(18) Determine overhead rate. Section 4 explains factors to be considered in determining the overhead rate.

(19) Determine overhead cost as the product of (17) and (18).

(20) Determine an intermediate cost as the sum of (17) and (19).

(21) Determine the profit rate. Section 4 explains more about this factor.

(22) Determine the profit as the product of (20) and (21).

(23) Determine the total cost as the sum of (20) and (22).

These same basic steps are followed regardless of the drilling technique being employed. The major differences which arise as a result of drilling techniques are in step (1), the determination of the time required. These differences and the specific time elements involved in each drilling technique are itemized in Section 2.2. Section 3 explains the procedure for estimating the time required for each of the drilling operations.

Differences also arise in steps (6) and (7), the determination of the equipment and materials required. Section 2.2 presents typical equipment and materials lists for each of the various drilling techniques. Section 5 presents the procedure for determining the hourly and per foot costs of this equipment and materials. Section 5 also discusses the labor hourly rate required in step (5).

In addition, Section 4 discusses the job efficiency and maintenance factor required in step (3), the indirect costs of mobilization and set-up required in step (15), the overhead rate required in step (18), and the profit rate required in step (22). Section 4 also discusses the inflation escalation factors required in steps (11), (13), and (16).

A sample cost estimate is presented in Section 2.3 and more detailed cost estimates for each drilling technique are presented in Appendix A.

2.2 Drilling Operations, Equipments, and Material Requirements

This section presents, for each of the four drilling techniques, the following items:

(a) the specific drilling operations which are included in the drilling time estimate;

(b) a typical equipment list; and

(c) the typical materials required.

2.2.1 Diamond Wireline Core Drilling

The specific drilling operations required for diamond wireline core drilling are: wireline core drilling, hole survey, direction change, fishing, and hole stabilization. Figure 2.2 presents these elements in flow chart form and indicates the equation from which the estimate is obtained. These equations are found in Section 3.

Table 2.1 presents typical equipment and material requirements for diamond wireline core drilling. Specific equipment and materials required will depend on the length and diameter of the hole. More information on equipment selection for diamond wireline core drilling is available in Volume I.

2.2.2 Rotary Drilling

Rotary drilling requires that the following operations be included in the drilling time estimate: full hole drilling, intermittent core drilling, hole survey, direction, combined coring and direction change, fishing, and hole stabilization. Figure 2.3 presents these elements in flow chart form and indicates the equation in Section 3 from which each is obtained.

Table 2.2 presents typical equipment and material requirements for rotary drilling. The specific equipment and materials required will depend on the hole length and diameter. More information on equipment and material selection is available in Volume I.

2.2.3 Down-Hole Motor Drilling

Down-hole motor drilling requires that the following operations be included in the drilling time estimate: full hole

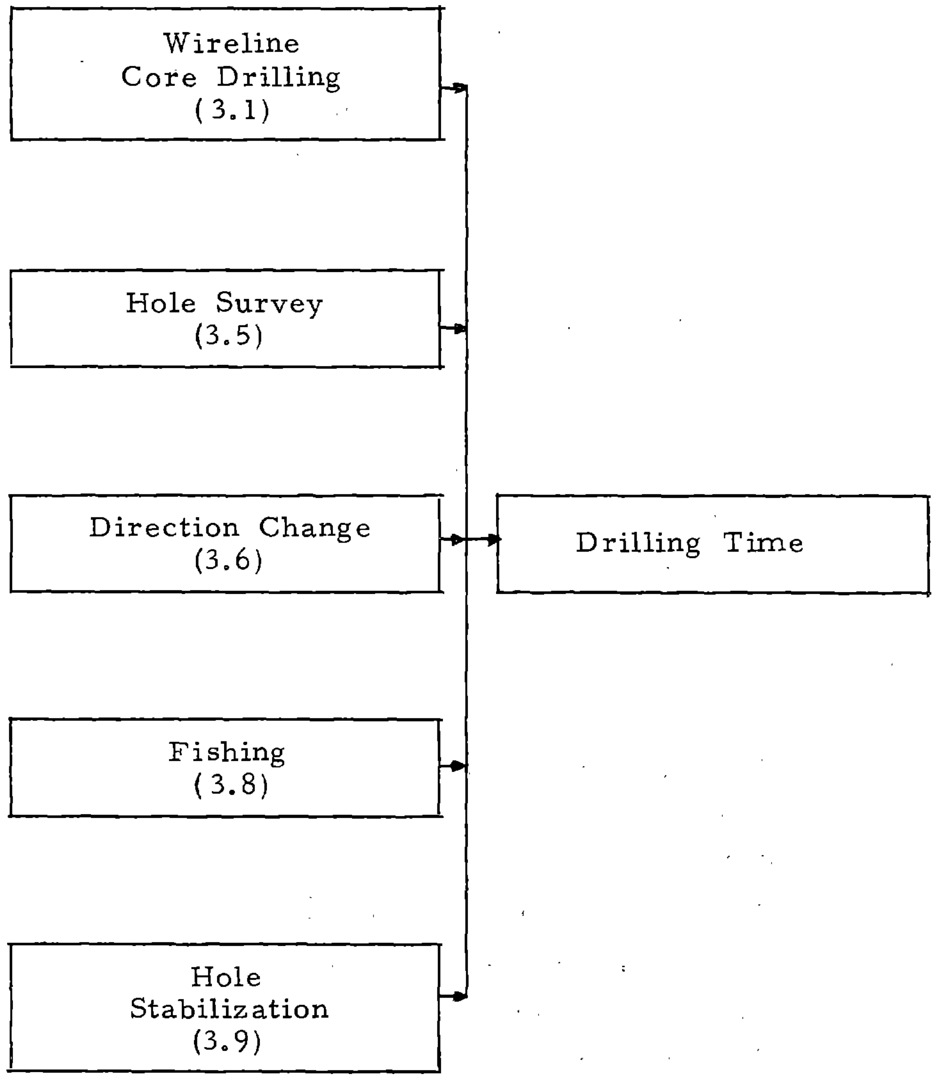

Figure 2.2 - Components of Drilling Time Estimate for Diamond Wireline Core Drilling

Table 2.1

Typical Equipment and Materials Lists for Diamond Wireline Core Drilling

Equipment

- Drill Rig
- Circulating Pump
- Supply Pump
- Hydraulic Ram
- Generator and Lights (2)
- Mud Tanks (2)
- Mud Mixer

Materials

- Core Barrel Assembly (2)
- Overshot Assembly (2)
- Wireline
- Drill Rod
- Outer Core Barrel Tubes (10)
- Inner Core Barrel Tubes (20)
- Survey Instruments
- Diamond Core Bits
- Diamond Reaming Shells
- Drilling Mud
- Grout

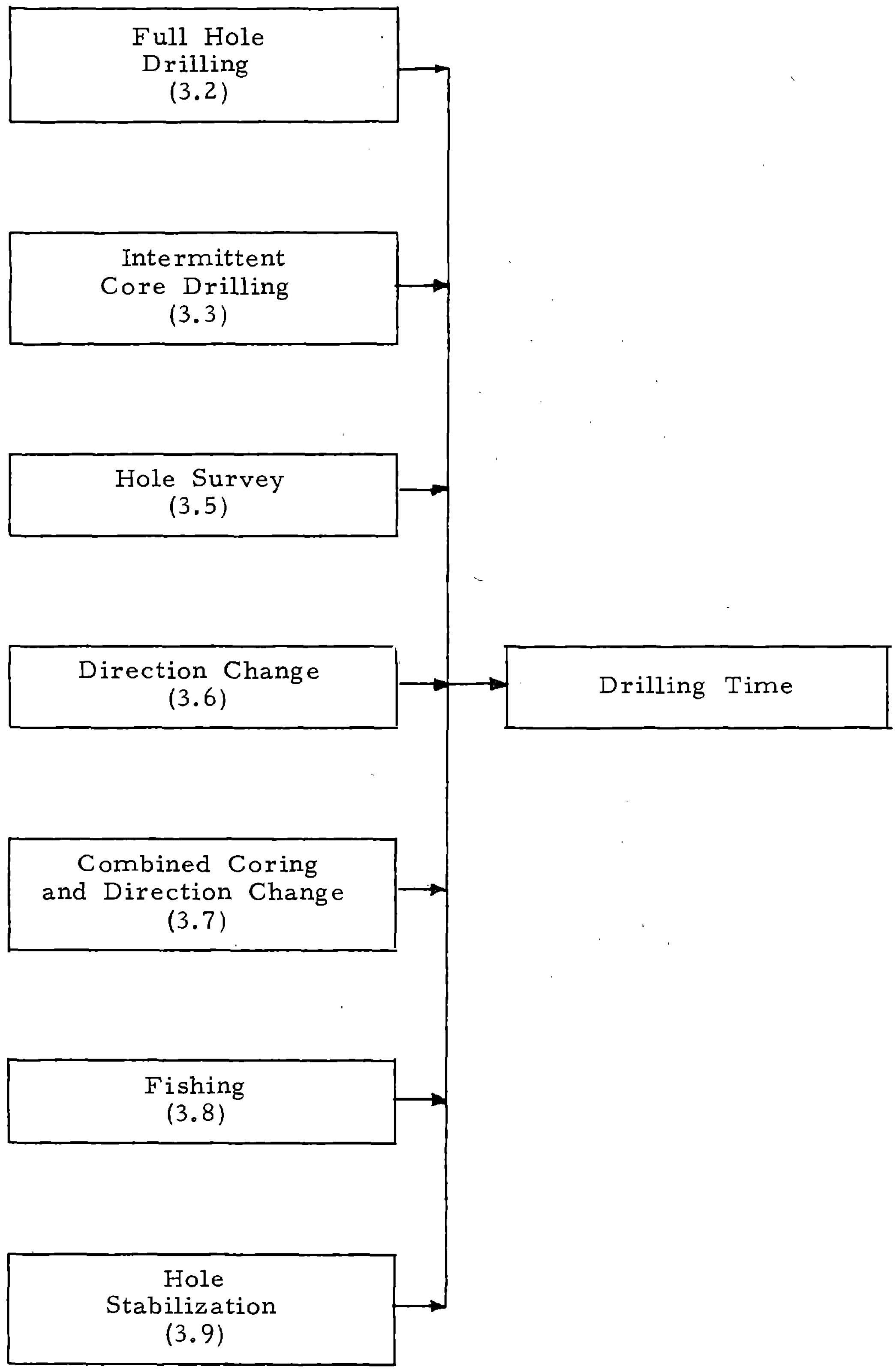

Figure 2.3 - Components of Drilling Time Estimate for Rotary Drilling

Table 2.2

Typical Equipment and Materials Lists for Rotary Drilling

Equipment

- Drill Rig
- Survey Collars (2)
- Circulating Pump
- Supply Pump
- Hydraulic Ram
- Generator and Lights (2)
- Mud Tanks (2)
- Mud Mixer

Materials

- Core Barrel Assembly
- Drill Rod
- Survey Instrument
- Outer Core Barrel Tubes (2)
- Rolling Cutter Bits
- Diamond Core Bits
- Drilling Mud
- Grout

drilling, intermittent core drilling, hole survey, direction change, combined coring and direction change, fishing, and hole stabilization. Figure 2.4 presents these elements in flow chart form and indicates the equation in Section 3 from which each is determined.

Table 2.3 presents typical equipment and material requirements for down-hole motor drilling. The specific equipment and materials required will depend on the length and diameter of the hole to be drilled. More information on the selection of equipment and materials may be obtained in Volume I.

2.2.4 Down-Hole Percussive Drilling

The following drilling operations must be included in the time estimate for down-hole percussive drilling: full hole drilling, intermittent core drilling, cycling drilling fluid, hole survey, direction change, combined coring and direction change, fishing, and hole stabilization. Figure 2.5 presents these elements in flow chart form and indicates from which equation in Section 3 the estimate is obtained.

Table 2.4 presents typical equipment and material requirements for down-hole percussive drilling. The specific equipment and materials required for a job will depend on the length and diameter of the hole. Volume I contains more information on the selection of specific equipment and materials.

2.3 Sample Cost Estimate

As an illustration of the use of this estimating model, consider the following horizontal drilling job. A 5,000 ft (1524 m) long hole is to be drilled using diamond wireline core drilling techniques. The hole will be NX size (2.980 in./75.7 mm O.D.) and will be maintained within a $\pm$ 1% deviation.

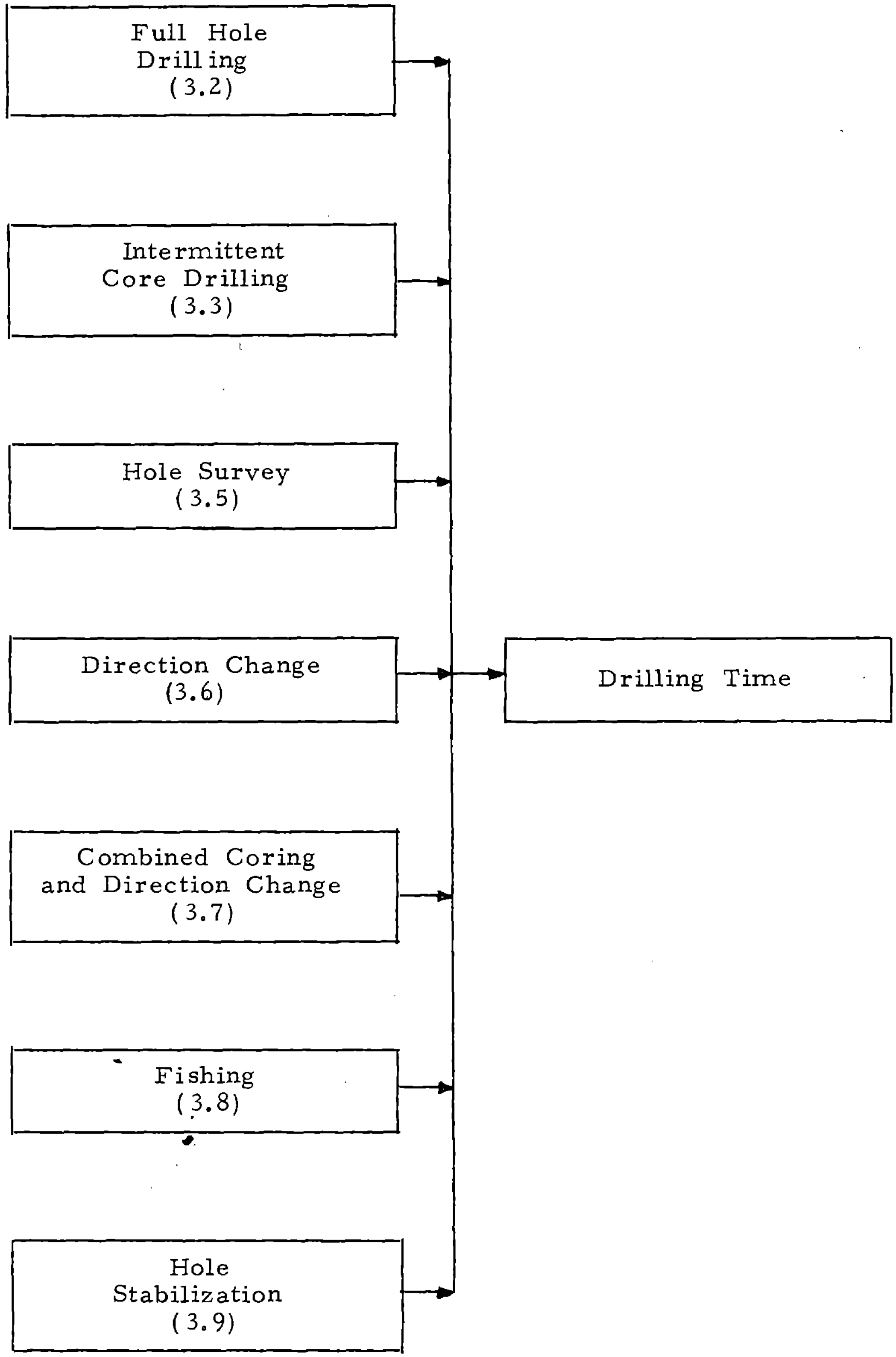

Figure 2.4 - Components of Drilling Time Estimate for Down-Hole Motor Drilling

Table 2.3

Typical Equipment and Materials Lists for Down-Hole Motor Drilling

Equipment

- Drill Rig
- Survey Collars (2)
- Circulating Pump
- Supply Pump
- Hydraulic Ram
- Generator and Lights (2)
- Mud Tanks
- Mud Mixer
- Down-Hole Motor

Materials

- Core Barrel Assembly
- Drill Rod
- Survey Instrument
- Outer Core Barrel Tubes (2)
- Rolling Cutter Bits
- Diamond Core Bits
- Drilling Mud
- Grout

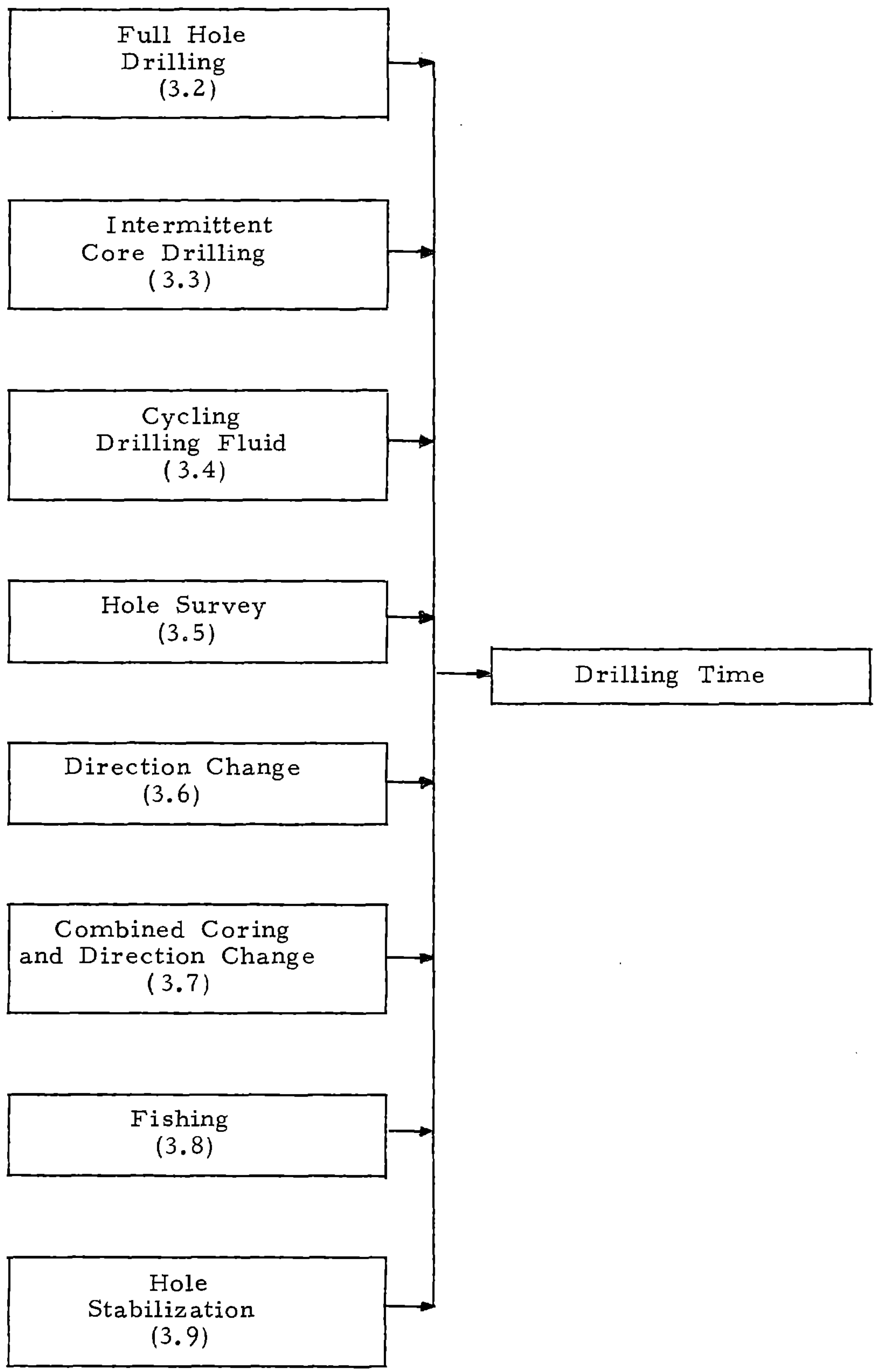

Figure 2.5 - Components of Drilling Time Estimate for Down-Hole Percussive Drilling

Table 2.4

Typical Equipment and Materials Lists for Down-Hole Percussive Drilling

Equipment

- Drill Rig
- Survey Collars (2)
- Circulating Pump
- Supply Pump
- Hydraulic Ram
- Generator and Lights (2)
- Mud Tanks (2)
- Mud Mixer
- Percussive Drill
- Air Compressor

Materials

- Core Barrel Assembly
- Drill Rod
- Survey Instrument
- Outer Core Barrel Tubes (2)
- Percussive Button Bits
- Diamond Core Bits
- Drilling Mud
- Grout

In addition to these requirements, the following assumptions are made:

(a) No geological information is available.

(b) A 10 ft (3.05 m) core barrel will be used.

(c) A direction change will be required every 90 ft (27.4 m) to maintain alignment.

(d) A hole survey will be conducted every 30 ft (9.1 m) and three additional hole surveys will be required for each direction change.

(e) An average of one fishing activity will be required every 300 ft (91.4 m).

(f) Hole stabilization will be required every 200 ft (61.0 m).

(g) A job efficiency factor of 0.20 will be used.

(h) An overhead rate of 15% will be used.

(i) A profit rate of 15% will be used.

(j) The parameter values recommended in Table 3.3 will be used.

The following numbered steps correspond to the general estimating procedure presented in Section 2.1.

(1) The drilling time estimates, were obtained following the flow chart presented in Figure 2.2. The estimates, as well as the equation or figure from which they were obtained, are presented in Table 2.5. The time required to complete all necessary drilling operations is estimated to be 2,598 hours.

Table 2.5

Drilling Time Estimates for Sample Cost Estimate

Item	Obtained from	Time (Hours)
Wireline Core Drilling	Eqn. 3.1 or Fig. 3.1	960
Hole Survey		
1 every 30 feet	Eqn. 3.5 or Fig. 3.7	90
3 every 90 feet	Eqn. 3.5 or Fig. 3.7	94
Direction Changes	Eqn. 3.6b or Fig. 3.9	970
Fishing	Eqn. 3.8 or Fig. 3.10	158
Hole Stabilization	Eqn. 3.9 or Fig. 3.12	326
Subtotal		2,598
Job Efficiency and Maintenance	(0.2)(Subtotal)	520
Total Time		3,118

(2) The job efficiency and maintenance factor was assumed to be 0.20.

(3) The job efficiency and maintenance 520 hours.
(0.2)(2,598) = 520 hours

(4) The total time required is 3,118 hours.
2,598 + 520 = 3,118 hours

(5) The labor hourly rate is assumed to be $36.00 per hour.

(6) Equipment costs will be assumed to be $17.00 per hour. This is the average hourly cost given in Table 5.1 for diamond wireline core drilling.

(7) Material costs will be assumed to be $17.00 per hour plus $3.00 per foot ($9.84/m). These are the average costs given in Table 5.2 for diamond wireline core drilling.

(8) The cost of labor is $112,248.
(3,118) x ($36.00) = $112,248

(9) No inflation correction is required.

(10) The cost of equipment is $53,006.
(3,118) x ($17.00) = $53,006

(11) No inflation correction is required.

(12) The cost of materials is $68,006.
(3,118) x ($17.00) + (5,000)($3.00) = $68,006

(13) No inflation correction is required.

(14) The total direct cost is $233,260.
$112,248 + $53,006 + $68,006 = $233,260

(15) The mobilization and set-up cost is estimated to be $4,400.

(16) No correction for inflation is required.

(17) The intermediate cost is $237,660.
$233,260 + $4,400 = $237,660

(18) The overhead rate was assumed to be 15%.

(19) The overhead cost is $35,649.
(0.15) x ($237,660) = $35,649

(20) The intermediate cost is $273,309.
$237,660 + $35,649 = $273,309

(21) The profit rate was assumed to be 15%.

(22) The profit is $40,996.
(0.15) x ($273,309) = $40,996

(23) The total cost is estimated to be $314,305.
$273,309 + $40,996 = $314,305

A summary of these costs is presented in Table 2.6.

Table 2.6

Sample Estimate Cost Summary

Item	Calculated from		Cost ($)
Labor	(Total time) x (Cost/hr) (3,118) x ($36.00)	=	$112,248
Equipment	(Total time) x (Cost/hr) (3,118) x ($17.00)	=	53,006
Materials per hour	(Total time) x (Cost/hr) (3,118) x ($17.00)	=	53,006
per foot	(Hole Length) x (Cost/ft) (5,000) x ($3.00)	=	15,000
Mobilization and Set-Up			4,400
	Subtotal 1		$237,660
Overhead	(Overhead rate) x (Subtotal 1) (0.15) x ($237,660)	=	35,649
	Subtotal 2		$273,309
Profit	(Profit Rate) x (Subtotal 2) (0.15) x ($273,309)	=	40,996
	Total Cost		$314,305

3. Drilling Time Estimates

Each of the four drilling techniques can be broken down into a number of basic operations which are required to complete the hole. The flow charts in Figure 2.2 through 2.5 show the operations required for each of the four drilling techniques. The estimated drilling time will be the sum of the times required for each of the necessary drilling operations. For example, from Figure 2.2, the estimated drilling time for diamond wireline core drilling will be the sum of the times required for wireline core drilling, hole survey, direction change, fishing, and hole stabilization.

In addition to indicating the drilling operations required for each technique, Figures 2.2 through 2.5 indicate the subsection which discusses the procedure for estimating the time required for that particular operation.

The following paragraphs describe the general calculations and equations used to determine the time requirements for each operation. Symbols used in the equations are listed in Table 3.1. These equations are completely general and allow the estimator to determine the specific time requirements for his particular set of hole dimensions, rock mixes, and drilling parameters.

In addition to these general equations, graphs of time required versus hole length are presented. These graphs are not as general as the equations and were obtained using the "average" rock mix presented in Section 1, the guideline for estimating the frequency of certain operations presented in Table 3.2, and the recommended values of drilling parameters presented in Table 3.3.

These graphs should be used for those situations where little if any detailed information other than hole length and diameter is available. Any time the estimator has additional information, the general equations should be used.

Table 3.1

Nomenclature

Symbol		Units	Reference
B	Number of bit changes	-	Sections 3.1, 3.2; Appendix B
C	Number of core samples	-	Sections 3.1, 3.3, 3.4, 3.7
D	Number of direction changes	-	Section 3.6
E	Number of drilling fluid cycles	-	Section 3.4
F_h	Fluid requirements per foot of hole	ft^3/ft (m^3/m)	Section 3.4
F	Number of fishing activities	-	Section 3.8
F_r	Fluid requirements per foot of drill rod	ft^3/ft (m^3/m)	Section 3.9
G_h	Grout requirements per foot of grouted section	ft^3/ft (m^3/m)	Section 3.9
G_n	Length of geological section	ft (m)	Sections 3.1, 3.2; Appendix B
L	Total length of hole	ft (m)	Sections 3.1, 3.2, 3.3, 3.4, 3.5, 3.6, 3.7, 3.8, 3.9
L_c	Length of core sample required	ft (m)	Sections 3.3, 3.7
L_g	Total length of hole requiring grout	ft (m)	Section 3.9
N	Number of geological sections considered	-	Sections 3.1, 3.2; Appendix B
P_c	Penetration rate during intermittent core drilling	ft/hr (cm/min)	Sections 3.3, 3.7
$P_{c,n}$	Penetration rate during wireline core drilling	ft/hr (cm/min)	Section 3.1; Appendix B
$P_{f,g}$	Penetration rate through grouted sections	ft/hr (cm/min)	Section 3.9
$P_{f,n}$	Penetration rate during full hole drilling	ft/hr (cm/min)	Section 3.2; Appendix B
P_g	Grout pump capacity	ft^3/min (ℓ/min)	Section 3.9
P_w	Water pump capacity	gal/min (ℓ/min)	Section 3.4

Table 3.1 (Continued)

Symbol		Units	Reference
R	Number of hole stabilization activities	-	Section 3.9
S	Number of hole surveys	-	Section 3.5
t	Total time for any operation	hr.	Sections 3.1, 3.2, 3.3, 3.4, 3.5, 3.6
t_b	Time required to change bit	min.	Sections 3.1, 3.2, 3.3, 3.6, 3.7, 3.8
t_c	Time required to drill direction change	min.	Sections 3.6, 3.7
t_f	Time required to connect fishing tap to drill rod	min.	Section 3.8
t_g	Time required for grout to cure	hr.	Section 3.9
t_s	Time required to take a single shot survey	min.	Section 3.5
V_r	Rod handling velocity	ft/min. (cm/sec)	Sections 3.1, 3.2, 3.3, 3.6, 3.7, 3.8, 3.9
V_s	Survey instrument velocity through drill string	ft/min. (cm/sec)	Section 3.5
V_w	Wireline velocity	ft/min. (cm/sec)	Section 3.1

Table 3.2

Guidelines for Estimating Activities

Hole Survey

Every 30 ft (9.1 m)

$$S = \frac{\text{Length of Hole}}{30 \text{ ft.}} \qquad \left(\frac{\text{Length of Hole}}{9.1 \text{ m}}\right)$$

Direction Change

Every 90 ft (27.4 m)

$$D = \frac{\text{Length of Hole}}{90 \text{ ft.}} \qquad \left(\frac{\text{Length of Hole}}{27.4 \text{ m}}\right)$$

Fishing

Rock Type	Activity Interval
Soft	every 200 ft (61.0 m)
Medium	every 500 ft (152.4 m)
Hard	every 800 ft (244 m)

Hole Stabilization

Rock Type	% of Length Requiring Stabilization	Activity Interval
Soft	20%	every 100 ft (30.5 m)
Medium	10%	every 300 ft (91.4 m)
Hard	2%	every 800 ft (244 m)

NOTE: These guidelines represent current rule-of-thumb estimates obtained from discussions with equipment manufacturers and contractors.

Table 3.3

Recommended Values for Estimating Parameters

G_h	1 ft^3/ft (0.093 m^3/m)
L_c	10 ft (3.05 m)
P_c	16 ft/hr (8 cm/min)
$P_{f,g}$	50 ft/hr (25 cm/min)
t_b	7.5 min
t_c	20 min
t_f	10 min
t_g	8 hr
t_s	10 min
V_r	20 ft/min (10 cm/sec)
V_s	200 ft/min (100 cm/sec)
V_w	150 ft/min (75 cm/sec)

NOTE: These values represent current rule-of-thumb estimates obtained from discussions with equipment manufacturers and contractors.

3.1 Wireline Core Drilling

The time required for continuous wireline core drilling is given by:

$$t_1 = \sum_{n=1}^{N} \left(\frac{G_n}{P_{c,n}}\right) + Bt_b + \frac{L}{V_r}(B + 1) + \frac{3}{2}\frac{L}{V_w}(C + 1) \qquad (3.1)$$

From left to right, these terms represent: the time required for drilling the hole, the time required for changing worn out drill bits, the time required for running the drill rod in and out of the hole for bit changes, and the time required for wirelining the core barrel. The number of core samples, C, is equal to the total length of hole, L, divided by the length of the core barrel, L_c. For example, a 5,000 ft hole (1524 m) using a 10 ft (3.05 m) core barrel requires C = 500 core samples. Appendix B explains and illustrates the actual calculation of this equation.

For illustration purposes, the time required for wireline core drilling is presented in Figure 3.1 as a function of hole length and hole diameter. This figure assumes the "average" rock profile and, from Table 3.3, a bit changing time, t_b, of 7.5 minutes, a wireline velocity, V_w, of 150 ft/min (75 cm/sec), a core barrel length of 10 ft (3.05 m), and a rod handling velocity of 20 ft/min (10 cm/sec).

3.2 Full Hole Drilling

The time required for full hole drilling is expressed as:

$$t_2 = \sum_{n=1}^{N} \left(\frac{G_n}{P_{f,n}}\right) + Bt_b + \frac{L}{V_r}(B + 1) \qquad (3.2)$$

From left to right, these terms represent: the time required for drilling the full diameter hole, the time required for changing worn out bits, and the time needed for running the drill rod in and out of the hole for each

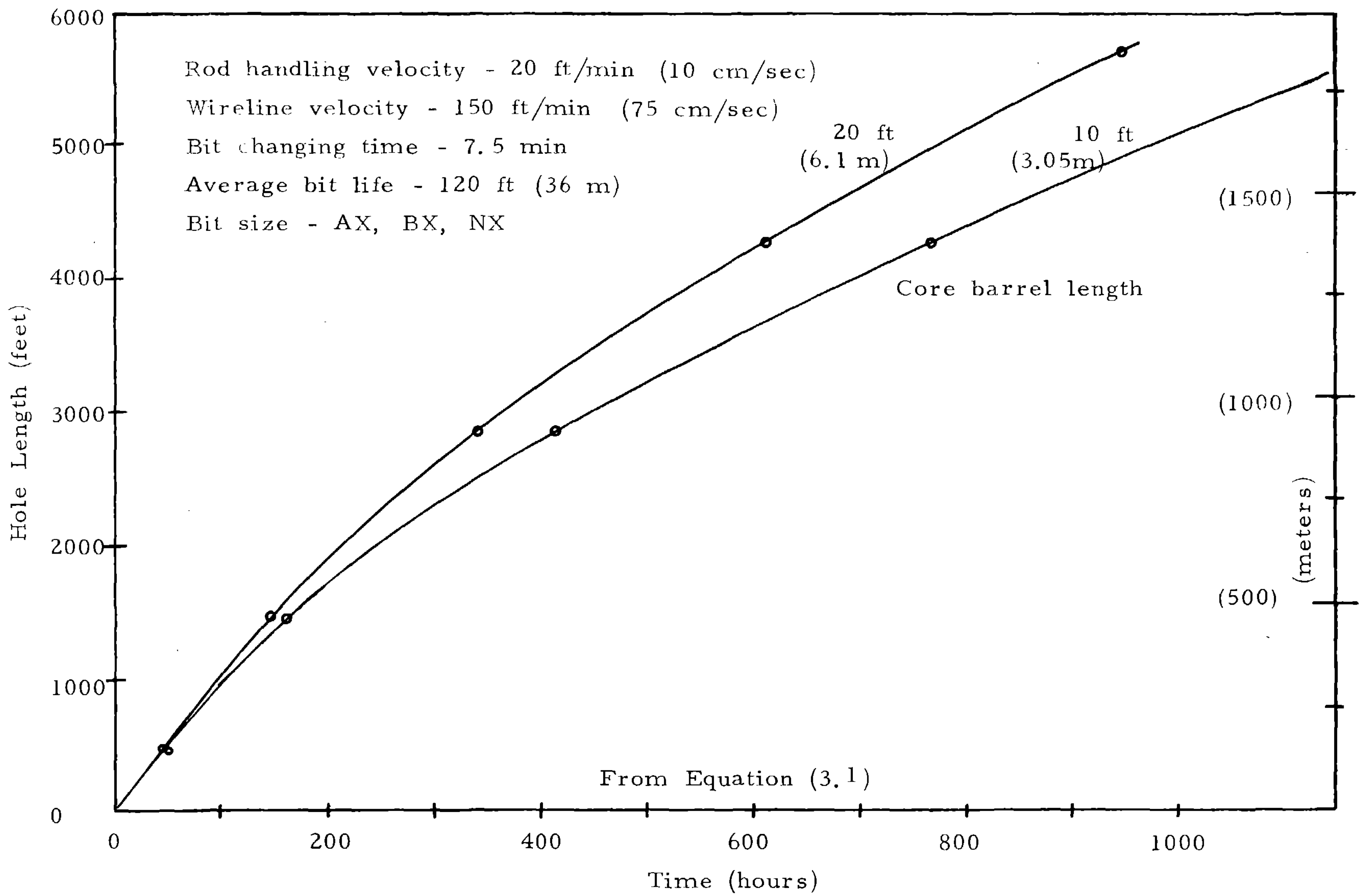

Figure 3.1 - Diamond Wireline Core Drilling Time

bit change. This equation is used for those parts of the hole where coring is not required. Appendix B presents and illustrates the detailed use of this equation.

For illustration purposes, the time required for full hole drilling is presented as a function of hole length and diameter in Figures 3.2, 3.3, and 3.4. These figures assume the "average" rock profile and, from Table 3.3, a bit changing time, t_b, of 7.5 minutes, and a rod handling velocity, V_r, of 20 ft/min (10 cm/sec). Figure 3.2 is for rotary drilling with rolling cutter bits. Figure 3.3 is for down-hole motor drilling utilizing a Dyna-Drill with rolling cutter bits. Figure 3.4 is for down-hole percussive drilling using button bits.

3.3 Intermittent Core Drilling

When full hole drilling is used, intermittent coring is required. The time required for this coring is:

$$t_3 = \frac{L_c C}{P_c} + 2\ C\ t_b + 2\ \frac{L}{V_r}\ (C + 1) \qquad (3.3)$$

The terms in this equation represent, from left to right: the time to drill the core sample, the time required to put on and remove the diamond core bit, and the time required for running the drill in and out of the hole twice. For this case, the number of core samples, C, is equal to the total length of the hole, L, divided by the distance between core samples. For example, a 6,000 ft hole (1829 m) with a 5 ft (1.52 m) core sample every 60 ft (18.3 m) will require C = 100 core samples.

For illustration purposes, Figure 3.5 presents intermittent core drilling time versus hole length. In accordance with Table 3.3, this figure assumes an average core penetration rate, P_c, of 16 ft/hr (8 cm/min), a rod handling velocity, V_r, of 20 ft/min (10 cm/sec), and

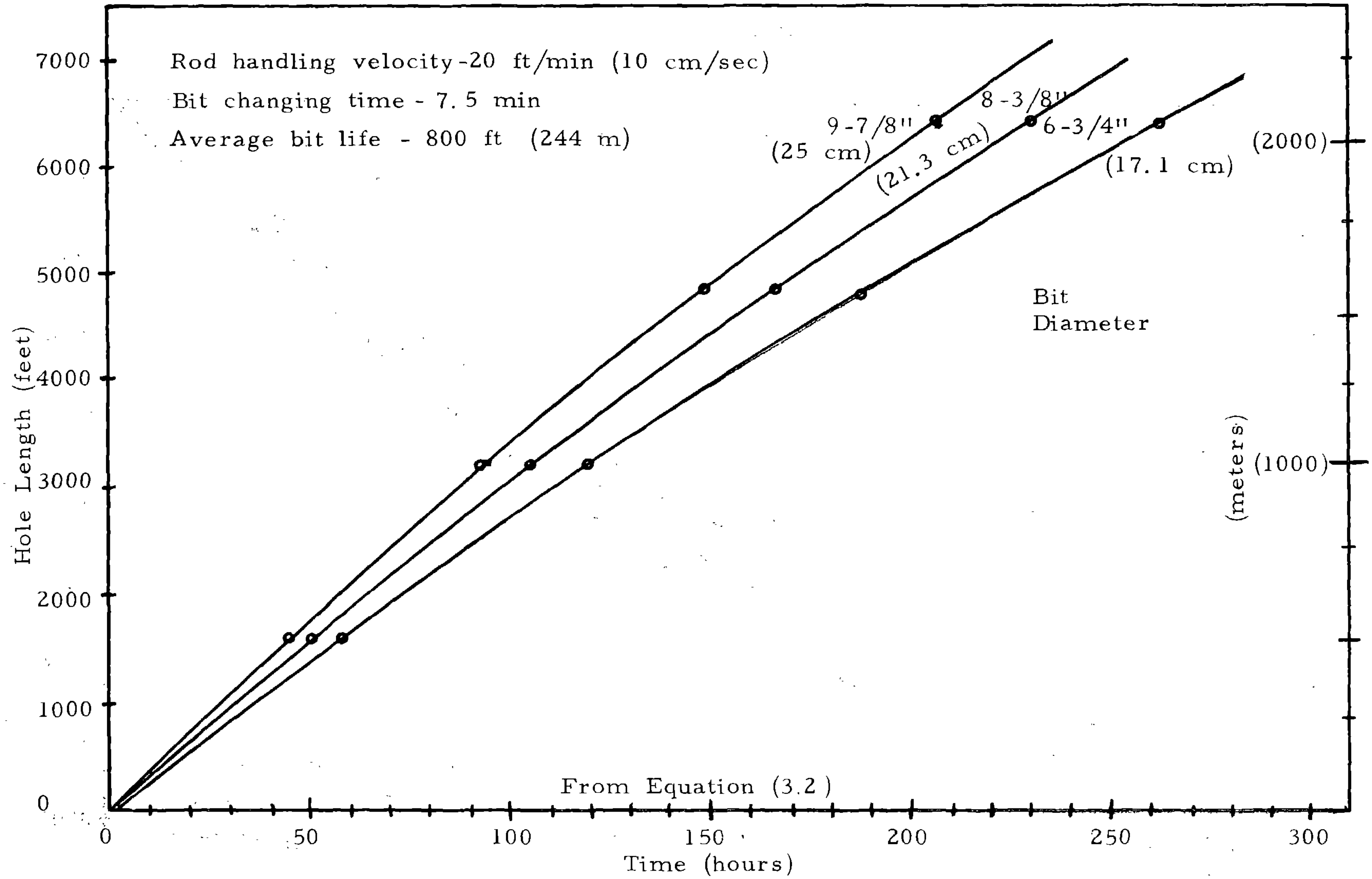

Figure 3.2 - Full Hole Drilling Time - Rotary Drilling

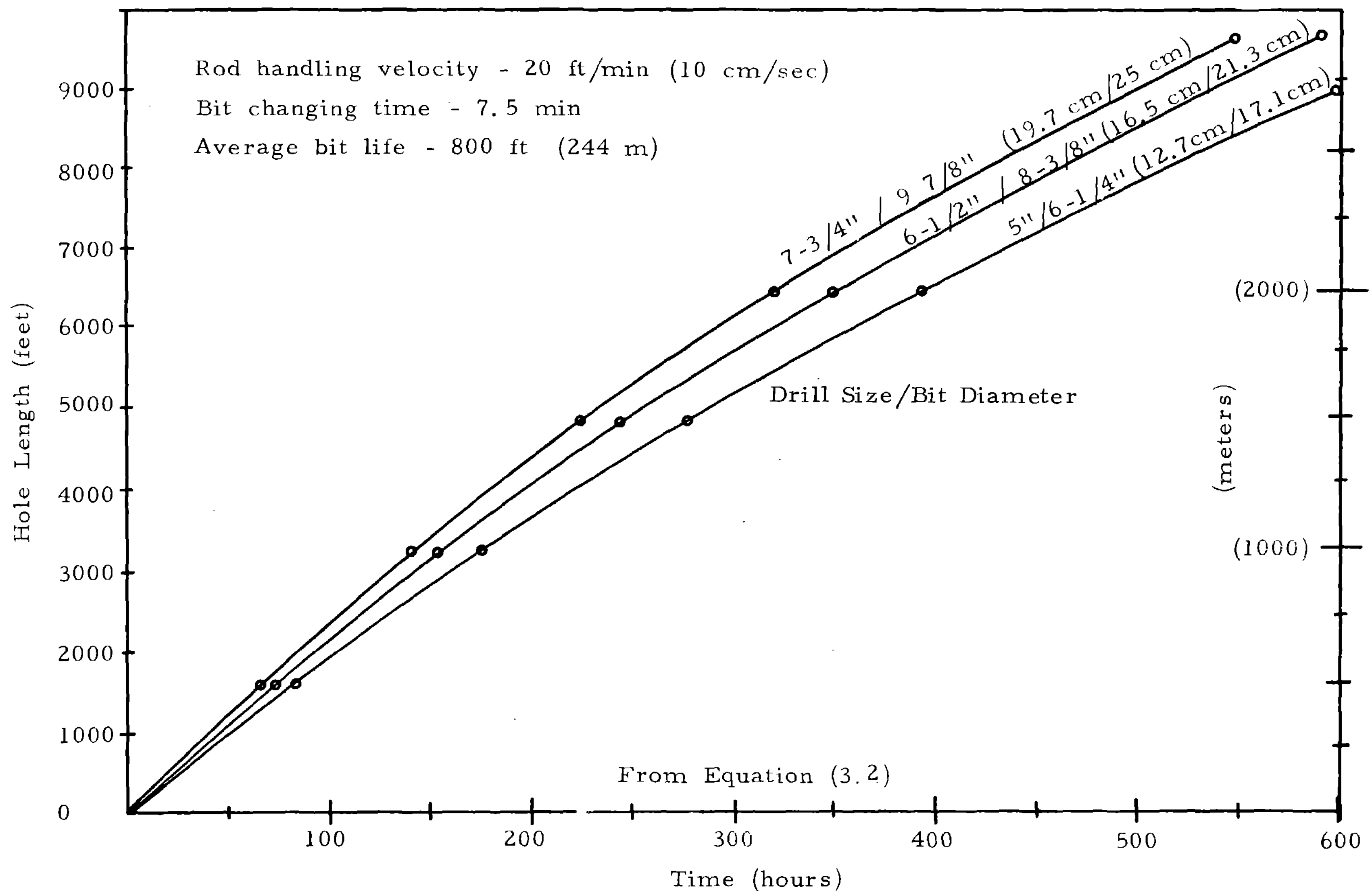

Figure 3.3 - Full Hole Drilling Time - Down-Hole Motor Drilling

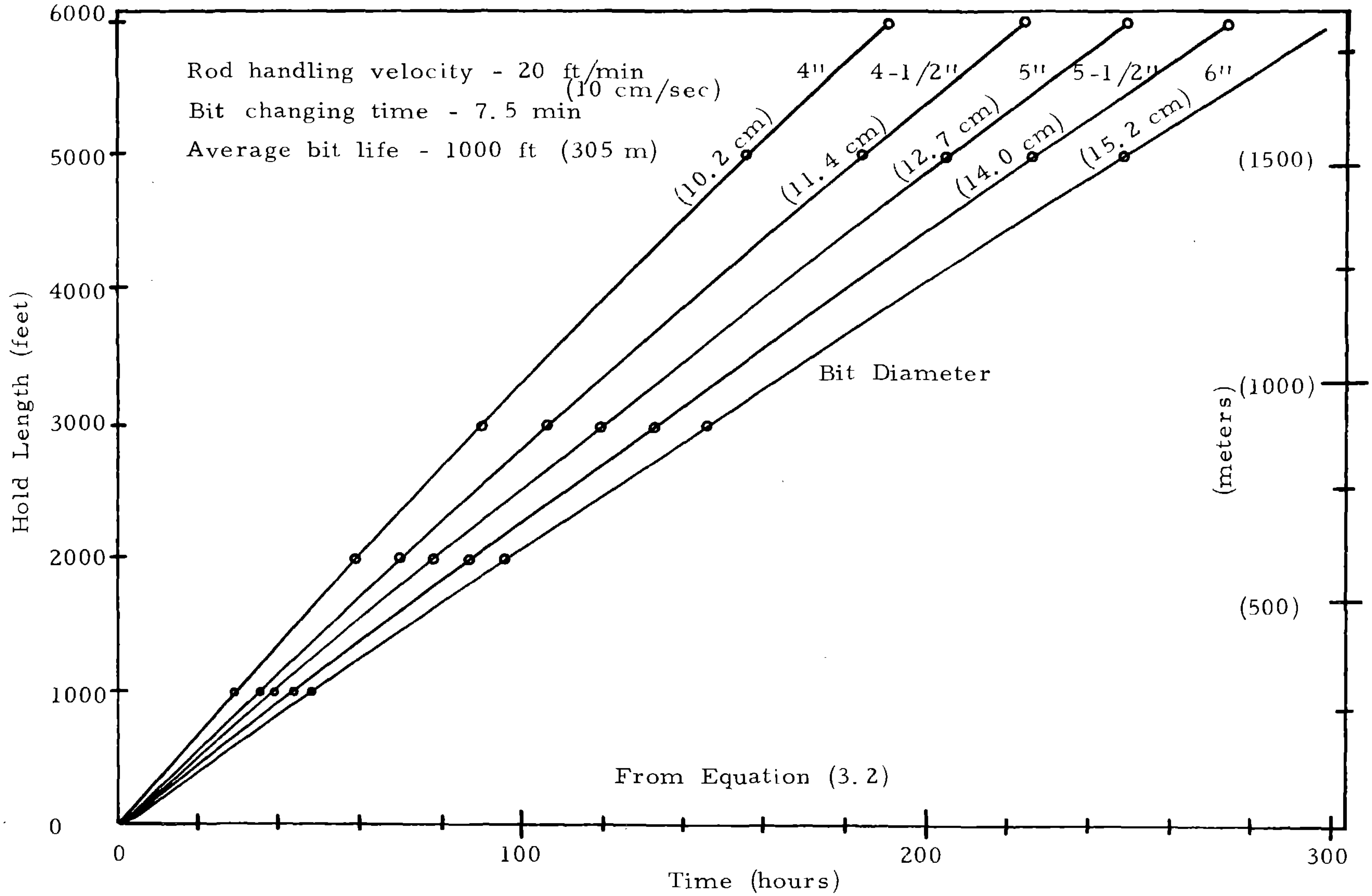

Figure 3.4 - Full Hole Drilling Time - Down-Hole Percussive Drilling

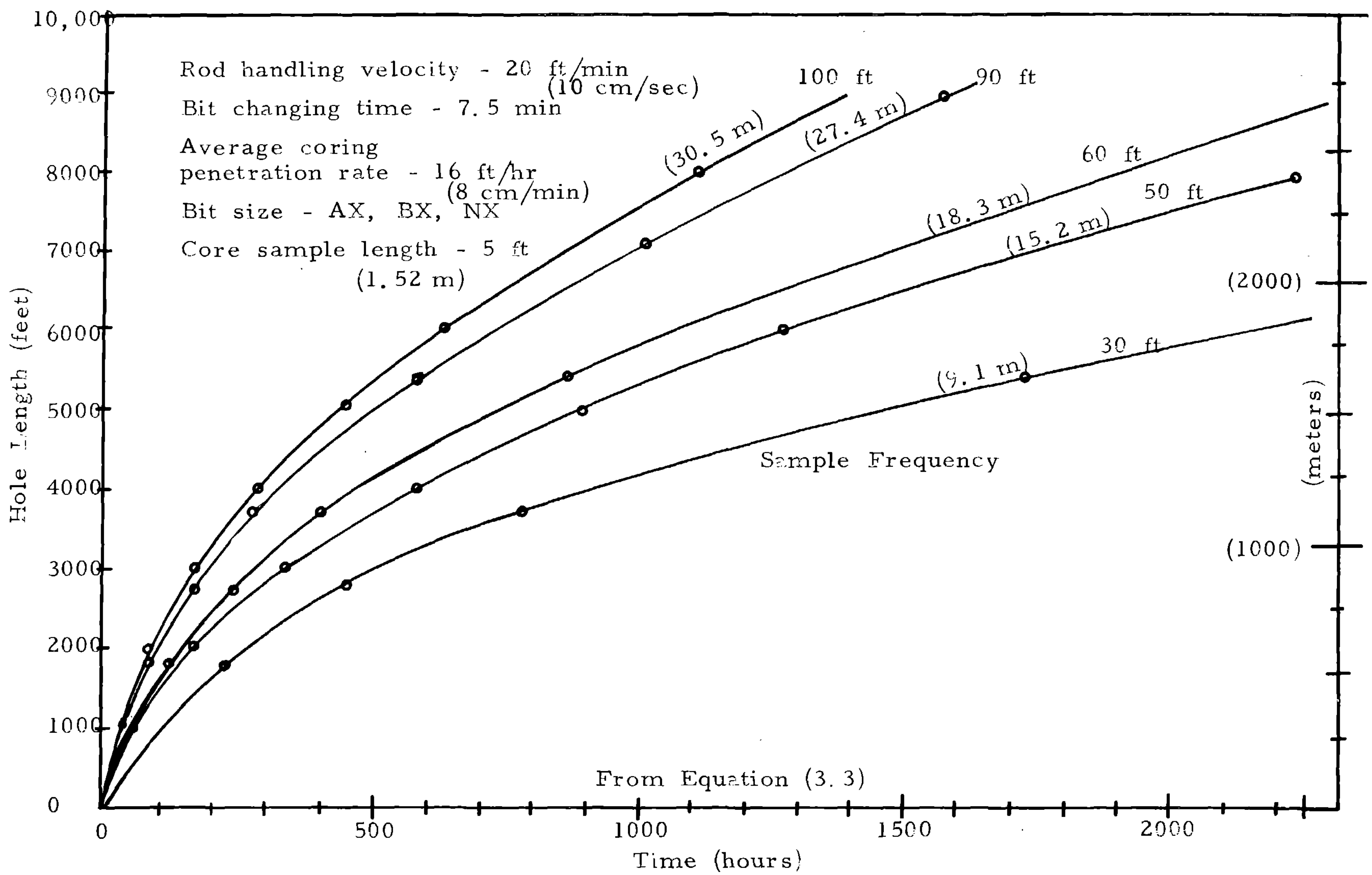

Figure 3.5 - Intermittent Core Drilling Time

a bit changing time, t_b, of 7.5 minutes. Core sampling frequency is a parameter.

If intermittent core drilling can be combined with direction changes, this section does not apply. Section 3.7 estimates the time required for this situation.

3.4 Cycling Drilling Fluid

This variable is included for down-hole percussive drilling where it is necessary to cycle drilling fluid into and out of the hole whenever a core sample or direction change is to be made. It is necessary because the percussive drilling uses air flushing while the core sample or direction change drilling utilizes liquid flushing. The time needed is expressed as:

$$t_4 = \frac{F_h L}{P_w} (E + 1) \tag{3.4}$$

This equation includes the time required to pump in and blow out the liquid. The fluid requirement per foot of hole, F_h, is equal to the volume of hole per foot minus the volume of drill steel per foot. E is the total number of times that the drilling liquid must be cycled into the hole. If all direction changes are made at the same time as core samples are drilled or vice versa, then the number of fluid cycles, E, will equal the number of core samples required, C, or the number of direction changes, D, whichever is larger. If direction changes are made separately from any core sample drilling then the number of fluid cycles, E, will equal the sum of the number of core samples required and the number of direction changes, C + D.

For illustration purposes, the time required for fluid cycling is presented in Figure 3.6 versus hole length with hole diameter as a parameter. In accordance with Table 3.3, this figure assumes a water pump capacity, P_w, of 80 gpm (303 ℓ/min).

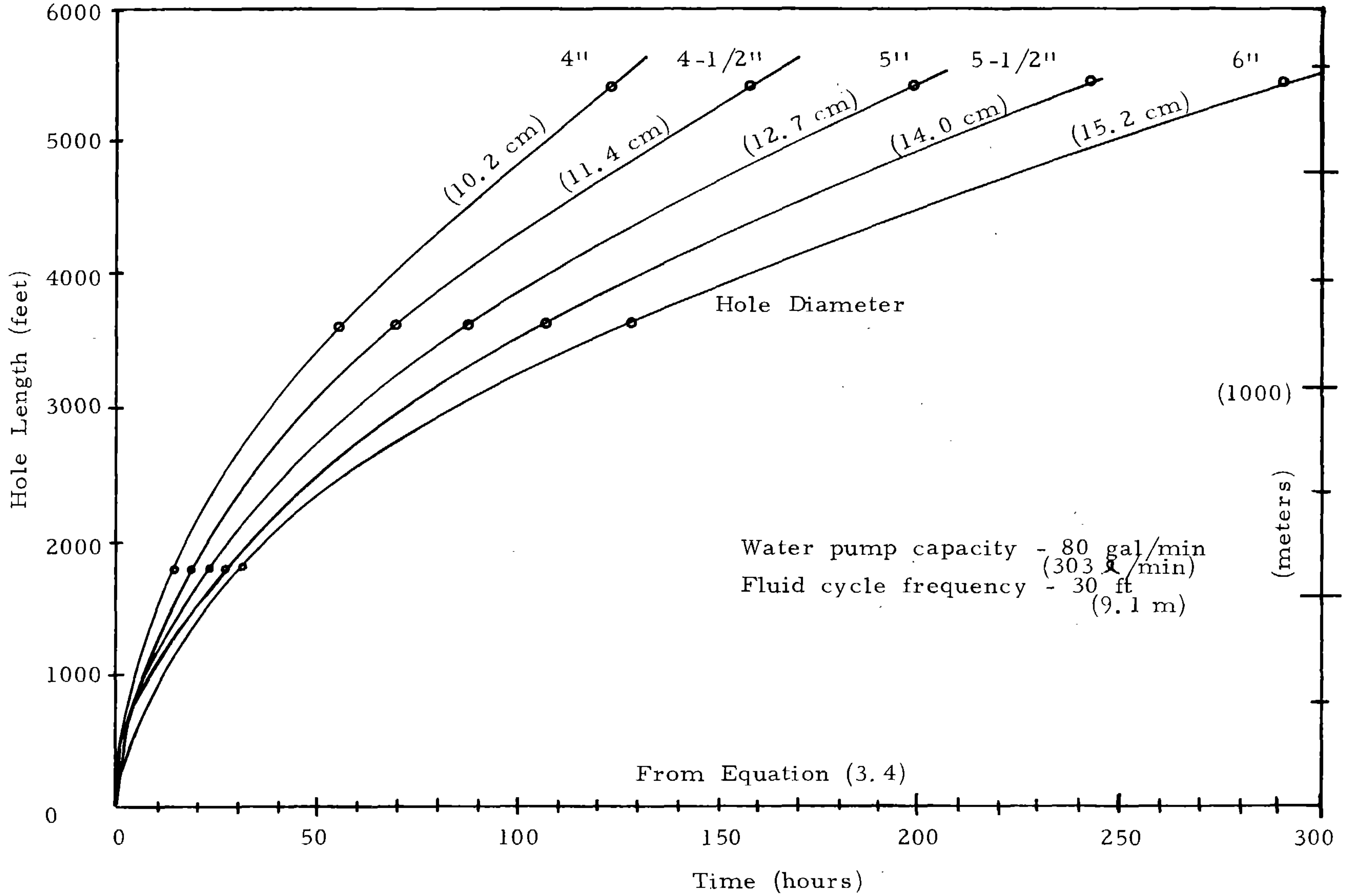

Figure 3.6 - Cycling Drilling Fluid Time - Down-Hole Percussive Drilling

3.5 Hole Survey

The time required for one single shot survey is expressed as:

$$t_5 = St_s + \frac{L}{V_s} (S + 1) \tag{3.5}$$

This equation includes running the survey instrument in and out of the hole and taking one single shot survey at each interval. If more than one survey is required, the time calculated should be multiplied by the number of surveys required at each interval. The number of surveys per total length of hole, S, must be estimated according to the directional accuracy required.

Figure 3.7 shows the time required to make one survey at 30, 60, and 90 foot (9.1, 18.3, and 27.4 m) intervals assuming, from Table 3.3, that the survey instrument velocity, V_s, is 200 ft/min (100 cm/sec) and the time required for a survey, t_s, is 10 minutes.

3.6 Direction Change

Direction changes may be made by means of either a down-hole motor (Dyna-Drill) or a wedge.

When a Dyna-Drill is employed to make the direction change, the time required is expressed as:

$$t_6 = D(t_c + 2t_b) + \frac{2L}{V_r} (D + 1) \tag{3.6a}$$

The terms of this equation, from left to right, represent: the time required to drill the direction change, the time required to attach and remove the Dyna-Drill, and the time required to run the drill rod in and out of the hole twice. If a down-hole motor is being used to drill

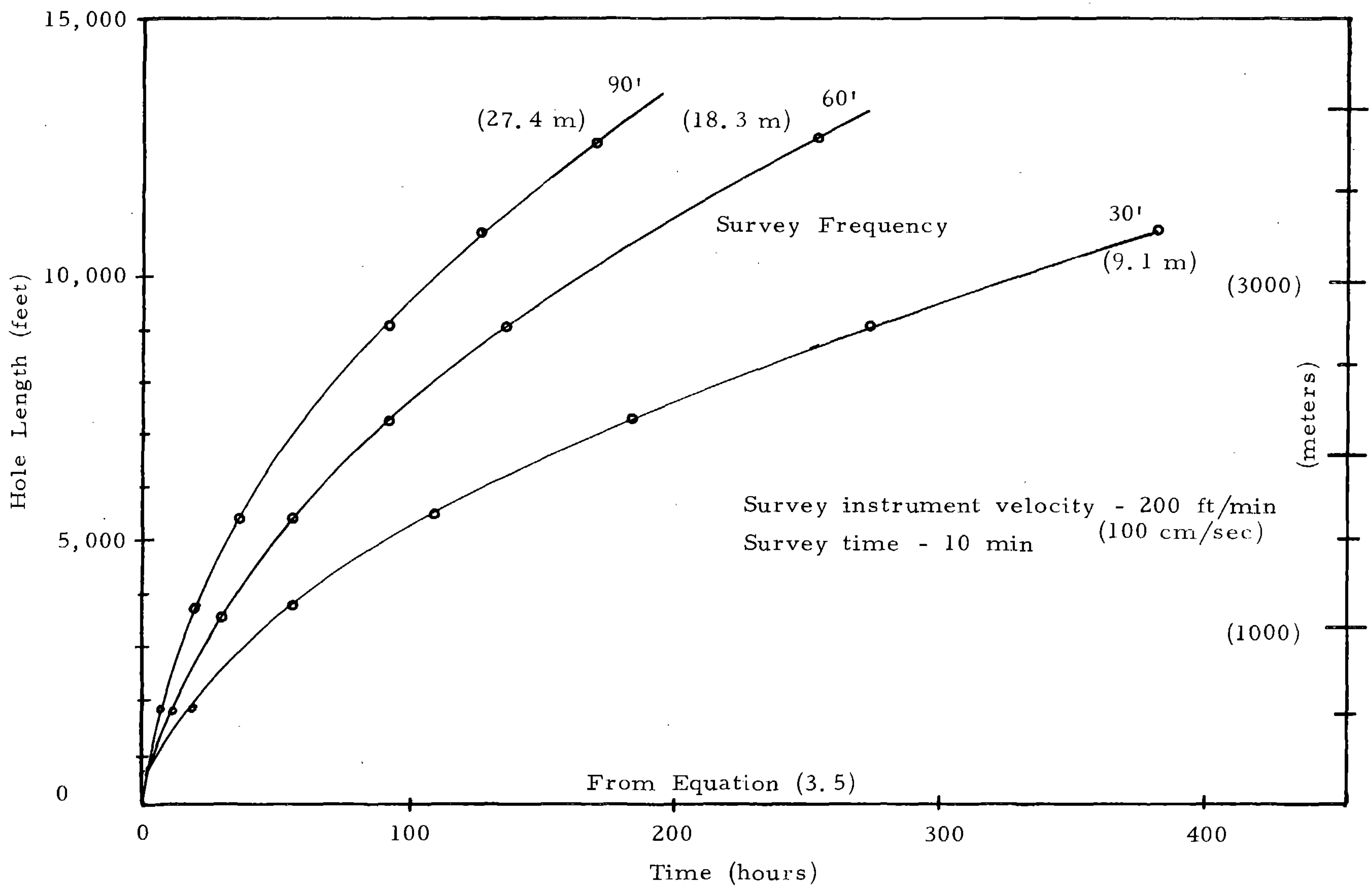

Figure 3.7 - Hole Survey Time

the full hole, the time to add a bent sub should be substituted for the time to change a drill bit and then the equation can be applied directly. The number of direction changes per total length of the hole, D, should be estimated according to the directional accuracy required. The time required to drill the direction change, t_c, must also be estimated.

When a wedge is used to make direction changes, two additional bit changes and round trips of the drill rods are required and the time is expressed as:

$$t_6 = D(t_c + 4t_b) + \frac{4L}{V_r}(D + 1) \qquad (3.6b)$$

Figure 3.8 presents the time required for direction changes using a Dyna-Drill and Figure 3.9 shows the time required when wedges are employed. These graphs assume, from Table 3.3, that the time to change a bit, t_b, is 7.5 minutes, the time required to drill the direction change, t_c, is 20 minutes, and the rod handling velocity, V_r, is 20 ft/min. (10 cm/sec). Frequency of direction changes is a parameter.

If direction changes are combined with intermittent core sampling, this section does not apply. Section 3.7 covers this situation.

3.7 Intermittent Coring and Direction Change Combined

If intermittent coring and direction changes can be combined at the same interval, the time for one round trip of the drill rods can be saved at each interval. The equation for this combination is:

$$t_7 = \frac{L_c C}{P_c} + C\ (t_c + 3t_b) + \frac{3L}{V_r}(C + 1) \qquad (3.7)$$

From left to right the terms of this equation represent: the time required to drill the core samples, the time required to drill the direction changes, the time required to change the bit three times, and the time

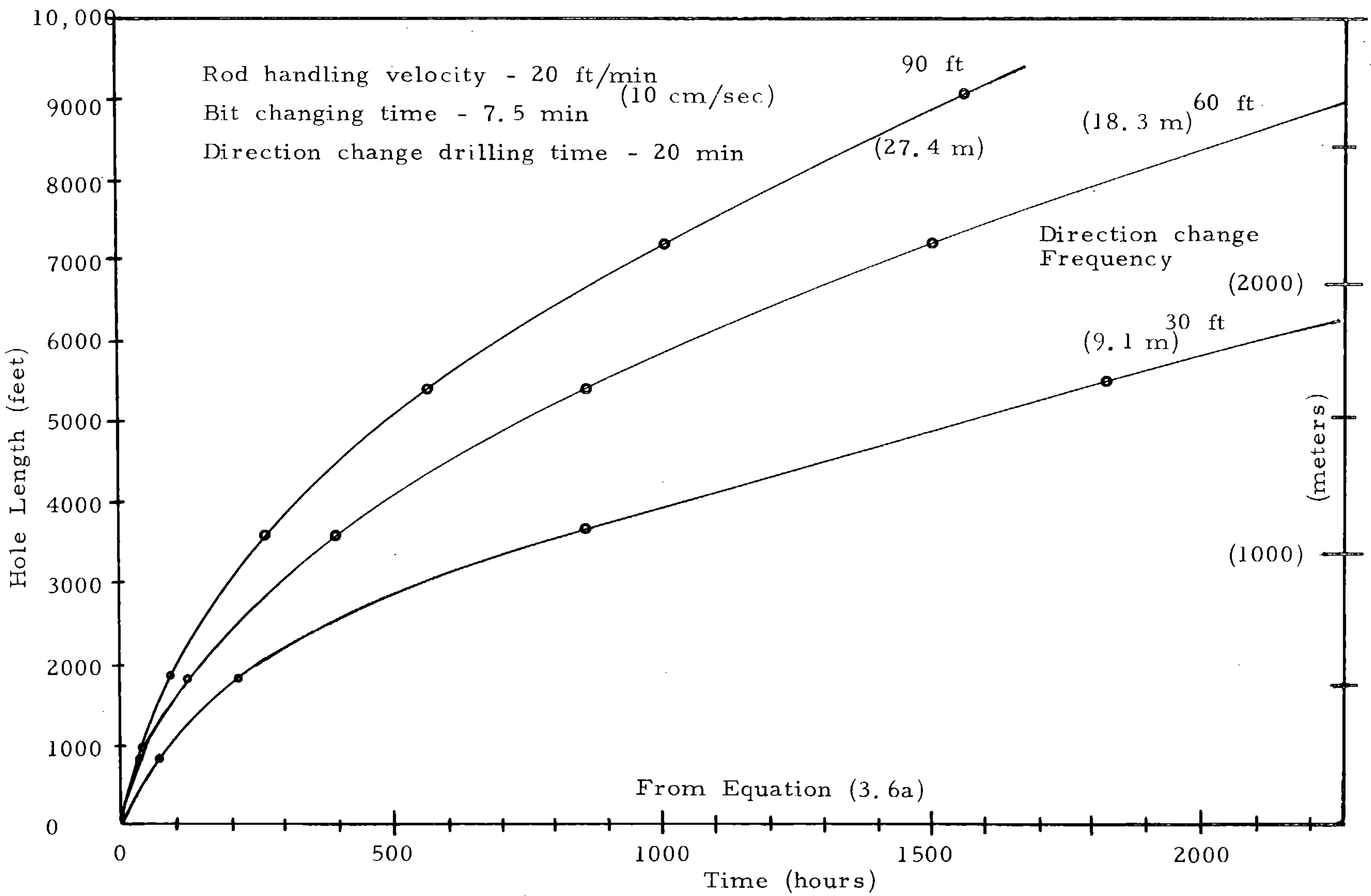

Figure 3.8 - Direction Change Time Using Dyna-Drill

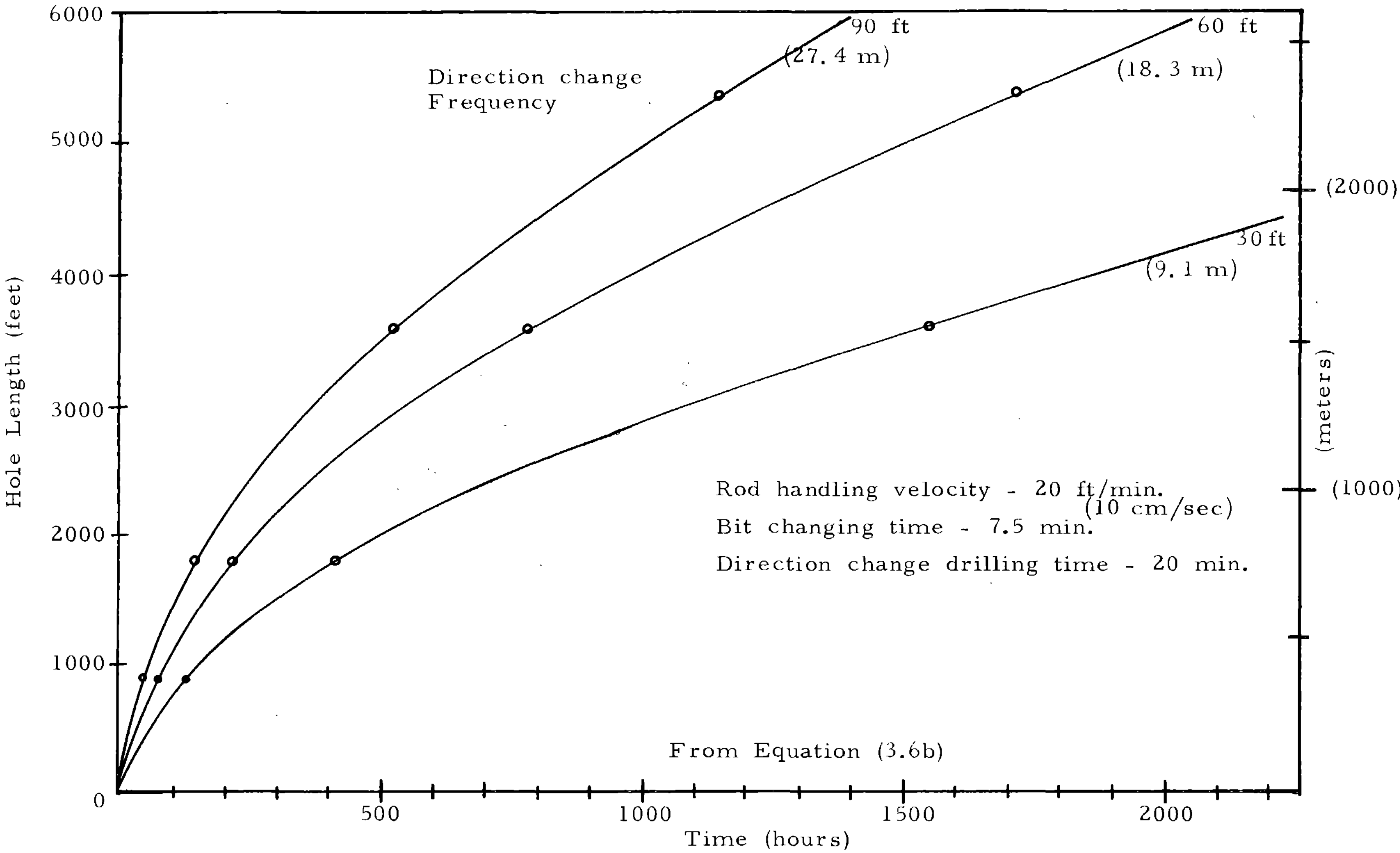

Figure 3.9 - Direction Change Time Using Wedges

required to run the drill rod in and out of the hole three times.

For illustration purposes, Figure 3.10 presents the time required as a function of hole length and core sampling frequency. This figure assumes, from Table 3.3, a rod handling velocity of 20 ft/min (10 cm/sec), a bit changing time, t_b, of 7.5 minutes, a direction change drilling time, t_c, of 20 minutes, and an average core drilling penetration rate, P_c, of 16 ft/hr (8 cm/min).

3.8 Fishing for Broken Tools

The time required for fishing for broken tools may be expressed as:

$$t_8 = F\ (t_f + 2t_b) + \frac{2L}{V_r}\ (F + 1) \qquad (3.8)$$

This equation includes, from left to right, the following elements: the time spent actually fishing, the time required to attach and remove the fishing tap, and the time required for two round trips of the drill rod.

The number of fishing activities, F , must be estimated, and would generally be based on the predicted geological structure. In poor ground conditions more fishing activities are likely to be required than in competent rock. Table 3.2 presents some guidelines for estimating the number of fishing activities. The time required to connect the fishing tap to the broken tools, t_f, must also be estimated. Table 3.3 recommends a value of 10 minutes.

For illustration purposes, Figure 3.11 presents fishing time requirements versus hole length with frequency of fishing activity as a parameter. This figure assumes, from Table 3.3, a fishing time, t_f, of 10 minutes, a bit changing time, t_b, of 7.5 minutes, and a rod handling velocity, V_r, of 20 ft/min (10 cm/sec).

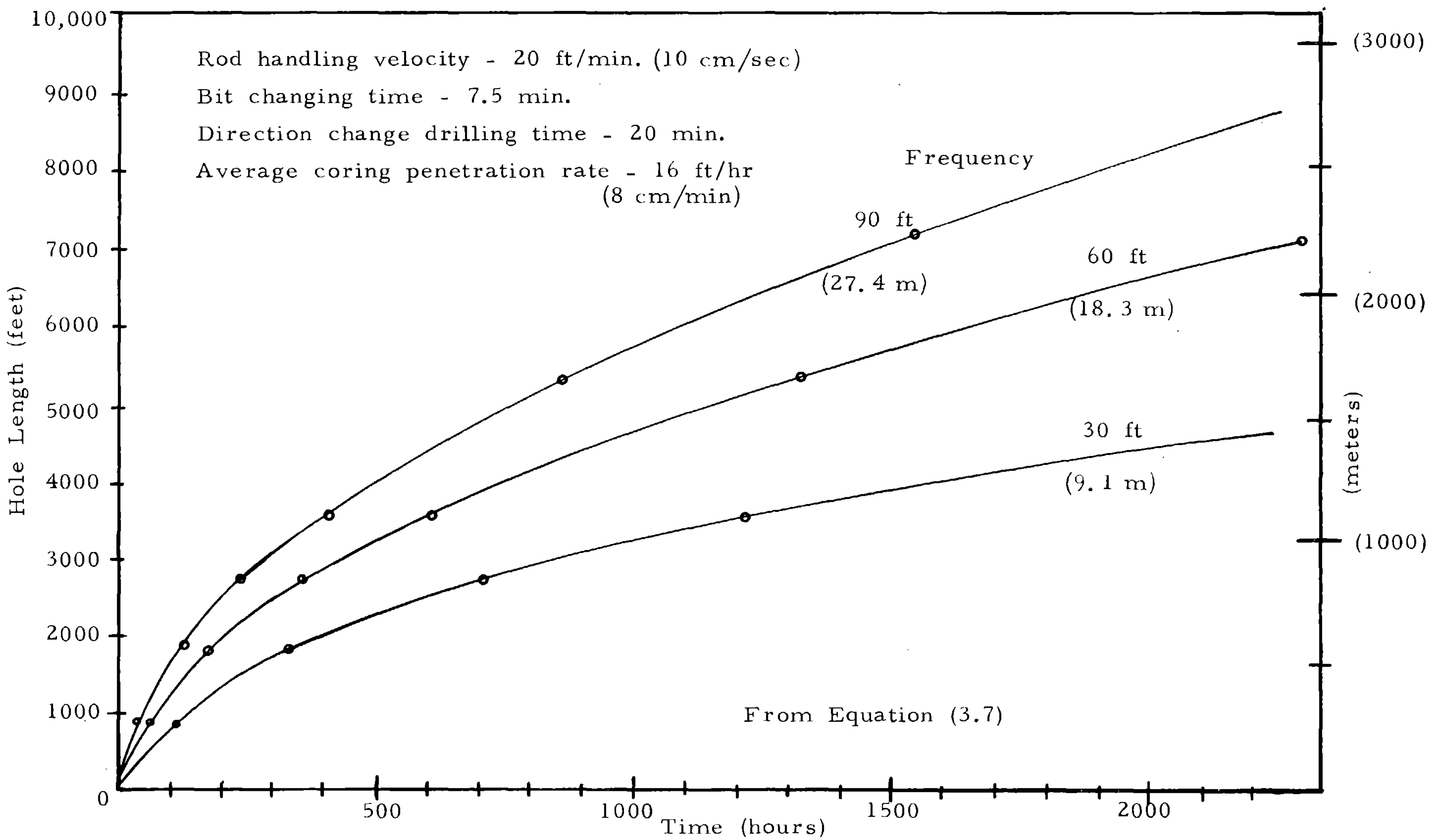

Figure 3.10- Time for Combined Intermittent Core Sampling and Direction Change

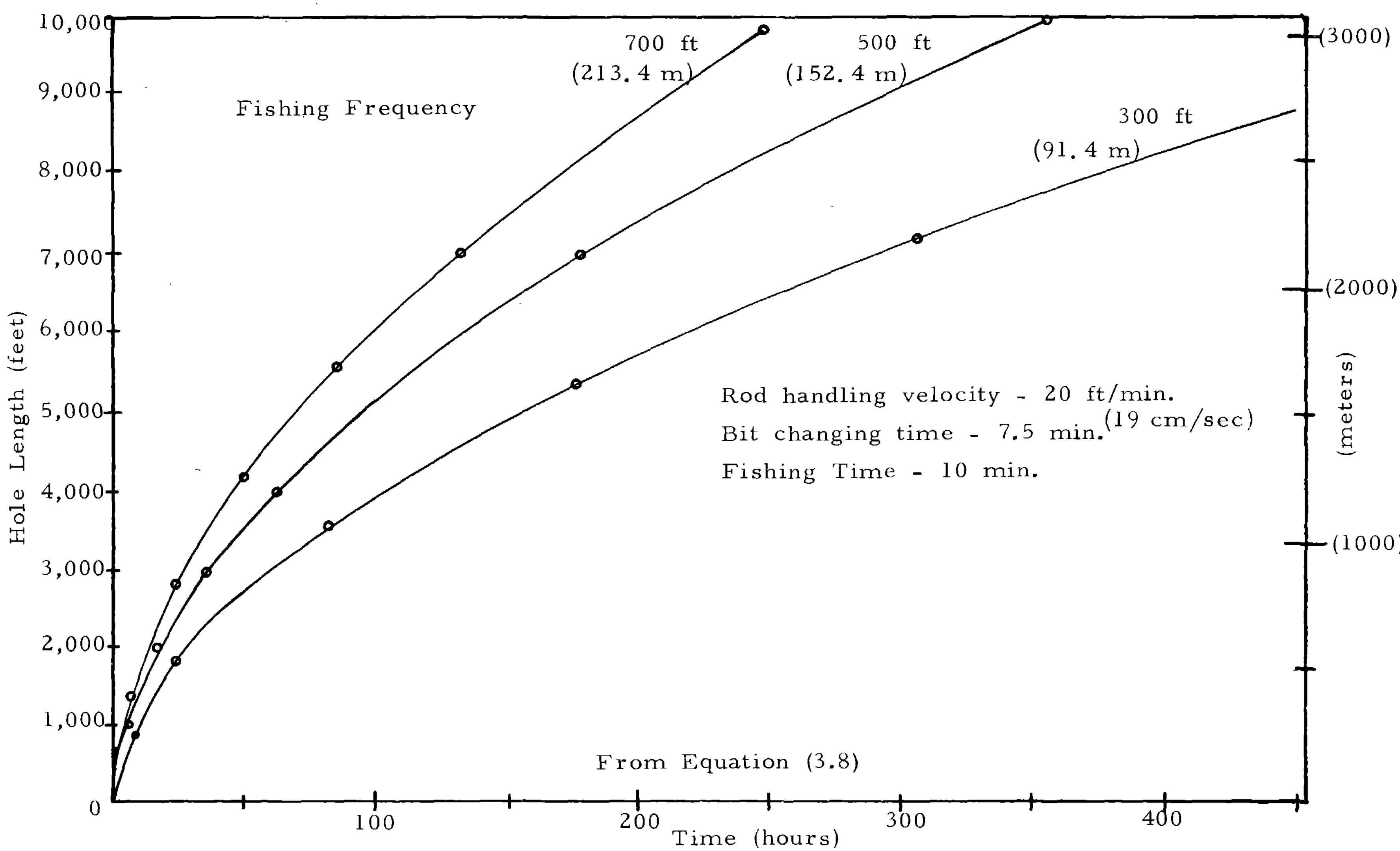

Figure 3.11 - Fishing Time

3.9 Hole Stabilization

Only grouting and cementing are considered here as means for hole stabilization. The time equation is:

$$t_9 = Rt_g + \frac{L_g}{P_{f,g}} + \frac{G_h L_g}{P_g} + \left[\frac{F_r(L - L_g)}{2 P_g} + \frac{L}{V_r}\right] (R + 1) \qquad (3.9)$$

From left to right, the terms of this equation represent the following items: the time required for the grout to set, the time required to drill through the grouted sections, the time required to pump the grout into the hole, and the time required for one round trip of the drill rod. Only one round trip is included because the second round trip would occur while the grout is setting. The number of grouting activities, R, and the total length of hole requiring grouting, L_g, must be estimated. Table 3.2 provides guidelines for estimating these parameters.

Other variables in this equation are the grout curing time, t_g, the grout pump capacity, P_g, the average drilling penetration rate through the grouted section, $P_{f,g}$, the volume of drilling fluid per foot of drill rod, F_r, and the volume of grout required for every foot of grouted length, G_h. The volume of drilling fluid per foot of drill rod, F_r, is equal to the internal volume of the drill rod per foot of length.

For illustration purposes, Figure 3.12 presents hole stabilization time requirements versus hole length with grouting frequency as a parameter. This figure assumes the "average" rock profile, a grout pump capacity, P_g, of 4 ft^3/min (113.3 ℓ/min), NX size drill rod, and the values from Table 3.3 for t_g, $P_{f,g}$, G_h, and V_r.

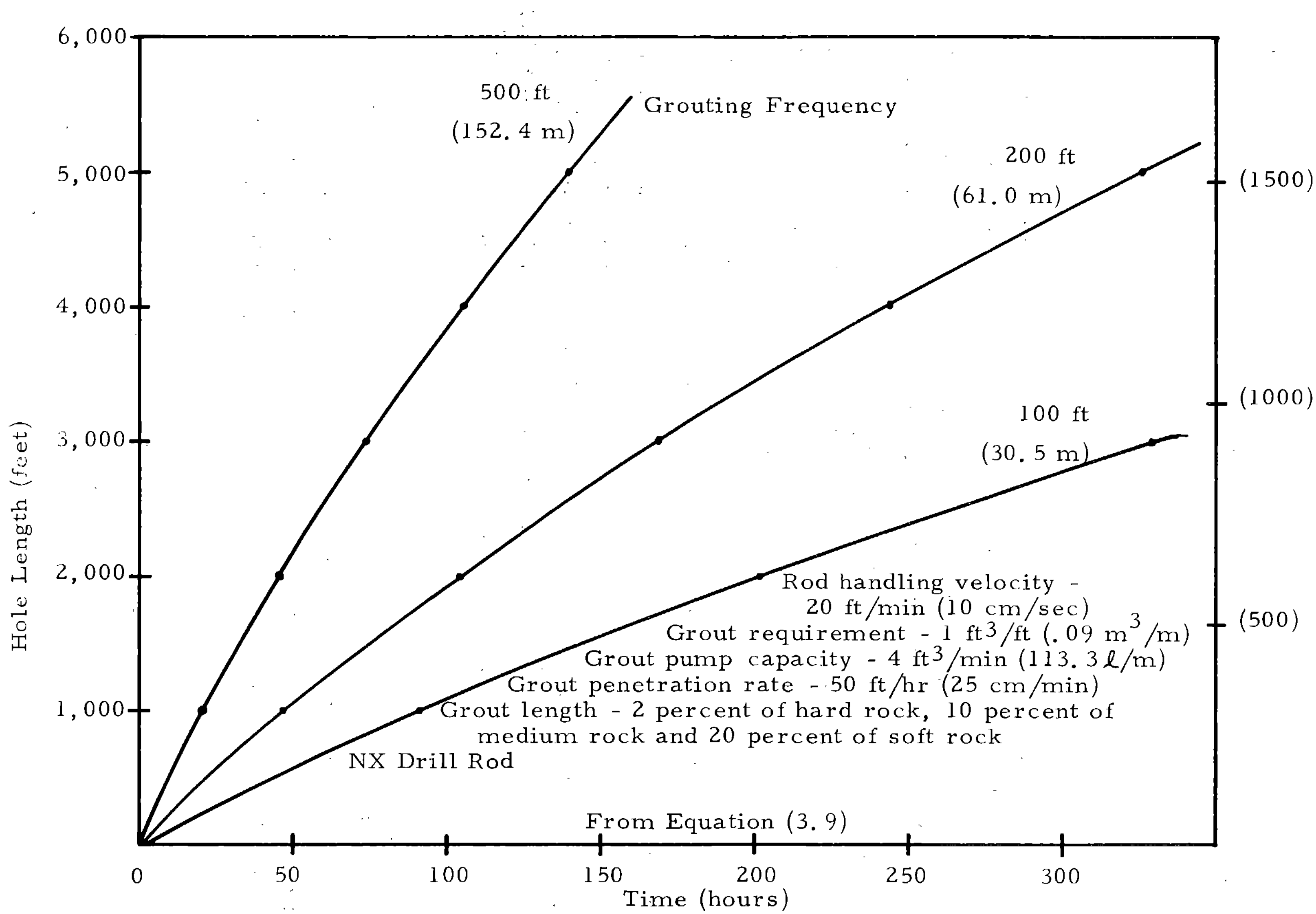

Figure 3.12 - Hole Stabilization Time

4. Job Efficiency, Indirect Costs, Profit, and Inflation

This section presents a general discussion of the following elements of the drilling cost estimate:

(1) Job efficiency and maintenance,

(2) Mobilization and set-up costs,

(3) Overhead,

(4) Profit, and

(5) Inflation escalation.

4.1 Job Efficiency

In addition to the time required to complete the applicable drilling operations, it is necessary to make an allowance for lost time, equipment maintenance, and other delays which will probably occur. Such an allowance can be considered as 'job efficiency' and expressed as a percentage of total operating time. Although this factor could vary significantly depending on job conditions and crew experience, for the purposes of this model a job efficiency allowance of 20% is used. Thus, if drilling operations required 500 hours to complete, the total job time would be 600 hours.

4.2 Indirect Costs

For a typical horizontal drilling project, the indirect cost is made up of two items - mobilization and set-up expenses and overhead.

4.2.1 Mobilization and Set-Up Cost

Mobilization and set-up costs are those expenses which are incurred in starting and finishing a drilling project. They would normally include such items as site preparation, equipment and facility transportation, assembly, and disassembly. Such items as access roads or other major expenditures which may be required would be included in this category. Site location and terrain has a large effect on the size of these expenses.

The exact mobilization and set-up cost has to be estimated for each specific job. For the purposes of the example estimates in Appendix A, arbitrary costs of between $3,000 and $5,000 have been assumed.

4.2.2 Overhead

Overhead includes those expenses which are required for the general supervision and administration of the drilling project. Items which might be included in overhead are payroll services, job transportation, headquarters operation, performance bonds, etc. Overhead is usually expressed as a fixed percentage of the costs directly attributable to the project, i.e. the sum of direct costs and mobilization and set-up costs.

Each contractor will have his own overhead rate and the exact percentage will vary. For typical horizontal drilling applications, the overhead rate is about 15% and that is the rate used in the example estimates in Appendix A.

4.3 Profit

Profit is expressed as a percentage of the total costs including overhead. Each contractor will have his own profit factor which may vary depending on the prevailing business situation and outlook, and on the contractor's desire to obtain a certain contract.

For the purposes of the example estimates in Appendix A, a profit factor of 15% has been assumed.

4.4 Inflation Escalation

In all probability the cost figures presented in this manual will have to be adjusted for inflation in future applications.

The inflation escalation procedures which follow are based on available published indices. These indices may be found in the following references:

1. Labor - "Construction Review," Department of Commerce;

2. Equipment - "Engineering News Record," Bureau of Labor;

3. Materials - "Construction Review," Department of Commerce"

The procedure used in correcting for inflation is as follows:

1. Obtain the most recent value of the appropriate index.

2. Divide this index by the appropriate base index. The indices which correspond to the prices in the manual are given below.

3. Multiply the cost from this manual by the number obtained in step (2). The resulting product in the cost figure which should be used for the estimate.

The values of the various indices which correspond to the prices in this document are:

(1) Labor - 161

(2) Equipment - 157

(3) Materials - 161

These indices are based on 1967 prices (i. e. the 1967 indices = 100).

As an example of the use of this procedure, consider the determination of the labor hourly cost at some time in the future when the labor index is 243.

$$(\text{Labor Cost/hr}) = \left(\frac{\text{Current Index}}{\text{Base Index}}\right) \times (\text{Base Labor Cost/hr})$$

$$= \left(\frac{243}{161}\right) \times (\$36.00)$$

$$= (1.51) \times (\$36.00)$$

$$= \$54.34$$

Thus the appropriate labor hourly rate would be \$54.34/hr. Equipment and material costs would be adjusted in a similar fashion.

5. Direct Costs

The direct costs of a horizontal drilling project are labor, equipment, and materials. Once the total time required for the job is known, the direct costs may be evaluated provided that the labor, equipment, and materials hourly rates are known.

The following paragraphs provide a basis for determining these hourly rates. Representative hourly rates in 1974 dollars are provided as well as guidelines for making more exact estimates.

5.1 Labor Cost

The labor cost for a horizontal drilling project may be expressed as the product of the total time and the labor hourly rate.

For horizontal drilling projects, a crew normally consists of one driller and two helpers and operates on a three shift per day basis. In addition, the owner usually provides one man to record and interpret drilling and survey data. The labor hourly rate should include the base wages, fringe benefits, and applicable payroll insurance and taxes for the three man drilling crew. This hourly cost will vary depending on the location of the project and whether union or non-union labor is employed.

For the purposes of the example estimates in Appendix A, a representative labor hourly rate of $36.00 has been used. This is 1974 dollars and must be corrected for inflation escalation.

5.2 Equipment Cost

The equipment cost for a horizontal drilling project may generally be expressed as the product of the total time and the equipment hourly rate. At the current time, however, the Dyna-Drill is an exception to this rule and its pricing policy is discussed separately from the equipment hourly rate. When a Dyna-Drill is employed, the equipment cost is obtained as the sum of the cost of the equipment which may be priced by an hourly rate and the cost of the Dyna-Drill.

5.2.1 Equipment Hourly Rate

The equipment hourly rate includes both the ownership or rental costs and the operating and maintenance expenses. Equipment is considered to include all items which, once a horizontal drilling project is finished, are available for use on the next project. It includes such items as drill rigs, drill rod, core barrels, survey instruments, wirelines, pumps, mud tanks, mud mixers, etc.

Each drilling situation - drilling technique, hole length, and hole diameter - may, and probably will, require different types, sizes, and quantities of the various items of equipment. Two different tacks are available to determine equipment hourly rate depending on the detail which is desired. The first and simplest approach is to determine an "average" equipment cost based on some "average" hole specifications and equipment requirements. The other approach is to list in detail the equipment required for a specific horizontal drilling project. The equipment hourly rate would then be based on this equipment list.

Table 5.1 is the result of the first approach and gives a range of equipment hourly rates for each of the drilling techniques. These rates are in 1974 dollars and will need to be corrected for inflation. The ownership costs are based on three shifts per day and allow for all drilling and auxiliary equipment. The operating and maintenance costs include fuel, power, lubrication, repairs, parts, etc. These rates were determined from discussions with horizontal drilling contractors and by averaging data from equipment manufacturers.

Table 5.1

Equipment Ownership and Operation Costs

Drilling Method	Ownership Cost ($/hr)	Operating Cost ($/hr)	Total Cost ($/hr)
Diamond Wireline Core	10-14	4-6	14-20
Rotary	24-28	8-10	32-38
Down-Hole Motor	32-36	5-8	37-44
Down-Hole Percussion	20-24	9-12	29-36

The second approach to obtaining the equipment hourly rate is more accurate and more involved. Examples of this approach are included in the sample estimates in Appendix A.

The starting point for the second approach is a detailed equipment list. This equipment list might be obtained from a horizontal drilling contractor or might be drawn up on the basis of the information in Volume I of this report.

Once the required equipment is known, ownership or rental costs plus operating and maintenance costs are needed. There are several sources for this cost information. Rental rates and operating and maintenance costs for some of the more standard items of equipment such as pumps, compressors, etc. may be obtained from:

(1) Rental Rate Blue Book for Construction Equipment or,

(2) AGC Equipment Rental Book.

It is more difficult to obtain costs for the less common items of equipment such as drill rigs, drill rod, etc. Some equipment manufacturers or horizontal drilling contractors may be willing to lease these items, hence supplying rental costs. On items that are not available for lease, the following rule-of-thumb may be used. The ownership costs for one month of 5 day weeks, 3 shift days will be on the order of 10% of the purchase price of the item, i.e.

$$\begin{pmatrix}\text{Ownership}\\\text{cost per hour}\end{pmatrix} = \frac{(0.10)\ (\text{Purchase Price})}{\left(4\frac{1}{3}\ \frac{\text{weeks}}{\text{month}}\right)\left(\frac{5\ \text{days}}{\text{week}}\right)\left(\frac{3\ \text{shifts}}{\text{day}}\right)\left(\frac{8\ \text{hours}}{\text{shift}}\right)}$$

For example, the ownership costs of a $10,400 piece of equipment will be approximately $2.00 per hour. This rule-of-thumb is used in the construction industry but should be used only in situations where rental or ownership costs have not been available from other sources.

Operating and maintenance expenses for the less common items of equipment may be obtainable from equipment manufacturers or horizontal drilling contractors. If not available from these sources, they will have to be estimated.

5.2.2 Dyna-Drill Costs

At the current time, the cost of a Dyna-Drill which is feasible for horizontal drilling (i.e., 5" (12.7 cm) and larger) is not adequately represented by an hourly rate. A Dyna-Drill is leased on the following basis and the various charges depend on size and type.

(1) There is a standby charge per day.

(2) There is a fixed fee for the first eight hours of drilling or part thereof plus an hourly charge for time over the eight hours. Only actual drilling time counts and the unit costs nothing when it is being run into or out of the hole. However, any time the hole is lengthened by some means other than the Dyna-Drill, a new eight hour fixed fee is initiated.

To illustrate this pricing policy consider the following sequence of drilling operations.

(a) Dyna-Drill is run into the hole, drills for two hours, and is pulled out.

(b) Diamond core bit run into the hole, drills a 5 foot (1.52 m) core sample, and is pulled out.

(c) Dyna-Drill is run back into the hole, and drills for ten hours.

The Dyna-Drill costs for this sequence will be two fixed fees plus two hours plus standby charges.

The same basic pricing policy applies even if the other means used to lengthen the hole is a different type of Dyna-Drill. The following sequence of drilling operations illustrates this policy.

(a) Straight-housing Dyna-Drill is run into the hole, drills for two hours, and is pulled out.

(b) Bent housing Dyna-Drill is run into the hole, drills for 20 minutes, and is pulled out.

(c) Straight housing Dyna-Drill is run back into the hole, drills for ten hours, and is pulled out.

The Dyna-Drill costs for this sequence will be two fixed fees plus two hours for the straight housing Dyna-Drill plus one fixed fee for the bent housing Dyna-Drill plus standby charges on both Dyna-Drills.

This pricing policy has arisen due to the character of the oil field use of the Dyna-Drill i.e. very infrequently and primarily for drilling direction changes. At the current time, the smaller Dyna-Drills (1-3/4 in. (4.45 cm) and 3-3/4 in. (9.53 cm)) are available for lease on a monthly basis in the mining industry. It is anticipated that similar arrangements would result if horizontal drilling becomes a reasonable volume of business.

The specific charges for the different sizes and types of Dyna-Drill as well as the current pricing policy are available from the Dyna-Drill Co.

5.3 Materials Cost

The material cost for a horizontal drilling project may be expressed as the sum of two costs: the product of the total time and the material hourly rate plus the product of the hole length and the footage rate (cost per foot).

The material cost is taken to include all items which are not considered to be reuseable on another drilling project and includes such items as drill bits, drilling mud, grout, etc.

As with equipment cost, there are two approaches which may be taken in estimating the materials hourly and footage rates.

Table 5.2 presents ranges for the hourly and footage rates for the different drilling techniques. These rates are for an "average" hole, are in 1974 dollars, and should be corrected for inflation.

More detailed material lists and cost rates are included in the example estimates in Appendix A. The primary source of these rates are the material suppliers.

Table 5.2

Job Supply and Material Costs

Drilling Method	Cost per Hour ($)	Cost per Lineal Foot ($)
Diamond Wireline Core	15-19	2-4
Rotary	18-22	1-4
Down-Hole Motor	18-22	1-4
Down-Hole Percussion	10-14	2-4

6. General Comments

Making realistic estimates of the time and cost of completing any construction activity requires an extensive background in both the technical and practical aspects of the work. This, plus the fact that no two projects are the same, makes it very difficult to establish a standard estimating procedure or format. Although the guidelines and graphs presented in this study provide a basis for making reasonable estimates for a variety of situations, it is apparent that there would be many variations in both physical and technical aspects which must be properly evaluated before using the model.

Drill bits have a tendency to drill perpendicular to the strata dip which in some formations could create severe directional control problems and directional changes may be required every 10 or 20 feet (3.05 or 6.1 m) to maintain the required accuracy. High water flows may cause washouts and hole collapse. These and other unknown conditions could greatly increase the cost of drilling a horizontal hole.

Considering the above points, an estimate for drilling a long horizontal hole should be treated cautiously and the model in this report should only be used as a guide.

Selection of a drilling method should also be approached with caution. Percussive in-hole drilling has not been accomplished beyond 1,000 feet (305 m) and because of the gravitational effects on the heavy in-hole drill, severe directional control problems may be encountered. Diamond core drilling has been done to 4,000 feet (1220 m) horizontally and with present equipment it appears quite feasible to drill to 5,000 feet (1524 m) with 1% accuracy.

A.1 Introduction

This Appendix estimates the cost of drilling a sample long horizontal hole by each of the four drilling techniques. By using the same job requirements for each drilling technique, it is possible to obtain an idea of how the costs of the different techniques might compare.

Section A.2 details the specific requirements for the hole and Section A.3 describes the assumptions which must be made. The actual estimates of the cost of drilling this hole by each of the four techniques are carried out in Sections A.4, A.5, A.6, and A.7. Section A.8 presents a summary of all four estimates.

A.2 Job Requirements

The job requirements for these example estimates are as follows:

(a) a 5,000 foot (1524 m) long horizontal hole,

(b) BX (approximately 2.36 inches (6.0 cm) diameter) minimum size,

(c) Maintain the hole within a ± 1% deviation, and

(d) A 5 foot (1.52 m) core sample is required at least every 60 feet (18.3 m).

A.3 Assumptions

Various assumptions must be made as to what operations and drilling requirements will be necessary to meet the job criteria. The assumptions which apply to all four drilling techniques are:

(a) It is assumed that no geological information is available. Consequently the average rock profile is used giving the following sections for the 5,000 foot (1524 m) hole.

Soft Rock	-	11%	-	550 feet (168 m)
Medium Rock	-	59%	-	2,950 feet (899 m)
Hard Rock	-	30%	-	1,500 feet (457 m)

(b) A direction change will be required every 90 feet (27.4 m) to maintain alignment.

(c) A hole survey will be conducted every 30 feet (9.1 m) and three additional hole surveys will be required every 90 feet (27.4 m) for the direction changes.

(d) An average of one fishing activity will be required every 300 feet (91.4 m).

(e) Hole stabilization will be required once every 200 feet (61.0 m). The length of hole requiring stabilization is based on the type of rock. From Table 3.2 and the geology assumed for this problem, 17.4 feet (5.3 m) of hole will require stabilization for each activity.

(f) An average drill rod extraction and return velocity of 20 feet per minute (10 cm/sec) will be assumed.

(g) A job efficiency factor of 0.20 will be used.

A.4 Diamond Wireline Core Drilling Estimate

In addition to the assumptions made in Section A.2, it is assumed that the hole will be drilled using an NX diamond core bit and a 10 foot (3.05 m) long NX core barrel.

A.4.1 Time Estimates

Table A.1 shows the times estimated for the diamond wireline core drilling and where these estimates were obtained.

Table A.1

Time Estimates for Diamond Wireline Core Drilling of Sample Hole

Item	Obtained from	Time (hr)
Wireline core drilling	Figure 3.1	960
Hole survey 1 every 30 feet (9.1 m)	Figure 3.7	90
3 every 90 feet (27.4 m)	Figure 3.7	94
Direction changes	Figure 3.9	970
Fishing	Figure 3.11	158
Hole stabilization	Figure 3.12	326
Subtotal		2,598
Job efficiency and maintenance	0.2 (Subtotal)	520
Total time		3,118

As shown in the table, the total time required, excluding mobilization and set-up is 3,118 hours resulting in an average production rate of 1.6 feet/hour (0.8 cm/min).

A.4.2 Cost Estimates

Detailed equipment and material cost estimates are drawn up in Tables A.2 and A.3. Where possible these costs were obtained from equipment manufacturers and contractors.

Crew costs are estimated to be $36.00 per hour and mobilization and set-up costs have been taken to be $4,400.

Since all these costs are in 1974 dollars, no inflation escalation factors are needed.

A.4.3 Total Cost

The time and cost estimates are combined in Table A.4. The total cost of the hole is estimated to be $302,938 or $60.59 per foot ($198.78/m).

A.5 Rotary Drilling Estimate

In addition to the assumptions of Section A.2, the following additional assumptions are made:

(a) The hole will be drilled using 6-3/4 inch (17.2 cm) rolling cutter bits.

(b) Direction changes will be made by a Dyna-Drill with a bent housing.

(c) An NX diamond core bit and a 5 foot (1.52 m) core barrel will be used for intermittent core samples.

Table A.2

Equipment Cost for Diamond Wireline Core Drilling Estimate

	Item Description	Quantity	Cost ($)	Ownership Cost/hr (5 day - 3 Shift) ($/hr)	Operating and Maintenance Cost/hr ($/hr)	Total Cost/hr ($/hr)
a)	Drill	1	24,000	4.80	2.30	7.10
b)	Circulating Pump	1	6,000	1.20	0.50	1.80
c)	Supply Pump	1	4,000	0.80	0.40	1.20
d)	Hydraulic Ram	1	10,000	2.00	0.50	2.50
e)	Generator and Lights	2	9,000	1.30	0.86	2.16
f)	Mud Tanks	2	200	0.04	-	0.04
g)	Mud Mixer	1	236	0.05	0.02	0.07
				Total Cost/hr		$ 14.87

Table A.3

Job Supply and Material Costs for Diamond Wireline Core Drilling Estimate

	Item Description	Quantity	Cost ($)	Cost/hr (5 day - 3 Shift) ($/hr)	Maintenance Cost/hr ($/hr)	Total Cost/hr ($/hr)	Cost/ft ($/ft)
a)	Core Barrel Assembly - 10 ft long	2	1,439	0.29	0.07	0.36	-
b)	Overshot Assembly	2	725	0.14	0.03	0.17	-
c)	Wireline	6000 ft	1,200	0.24	-	0.24	-
d)	Drill rod	5000 ft	29,275	5.85	-	5.85	-
e)	Outer core barrel tube	10	749	-	-	-	0.15
f)	Inner core barrel tube	20	983	-	-	-	0.20
g)	Survey Instrument	1		2.08	-	2.08	-
h)	Miscellaneous		5,000	1.00	0.30	1.30	-
i)	Diamond core bits and reaming shells			-	-	-	1.99
j)	Drilling mud	10 sacks/ shift	5.50/ sack	6.87	-	6.87	-
k)	Grout			-	-	-	0.35
				Total Cost		$ 16.87/hr	$2.69/ft ($8.83/m)

Table A.4

Estimated Cost for Diamond Wireline Core Drilling

Item	Calculated from		Cost ($)
Labor Cost	(Total time) x (Cost/hr) (3118) x (36.00)	=	112,248
Equipment Cost	(Total time) x (Cost/hr) (3118) x (14.87)	=	46,365
Materials Cost per hour	(Total time) x (Cost/hr) (3118) x (16.87)	=	52,601
per foot	(Hole length) x (Cost/ft) (5000) x (2.69)	=	13,450
Mobilization and Set-Up Cost			4,400
	Subtotal 1		229,064
Overhead	(0.15) x (Subtotal 1)		34,360
	Subtotal 2		263,424
Profit	(0.15) x (Subtotal 2)		39,514
	Total Cost		$ 302,938
	Average Cost		$60.59/ft ($198.78/m)

(d) Direction changes will be combined with the core sampling, i.e., every 60 feet (18.3 m), instead of every 90 feet (27.4 m). This saves time.

A.5.1 Time Estimates

Table A.5 shows the times estimated for rotary drilling and the figure from which they were obtained.

As can be seen, the total time required excluding mobilization and set-up is 2,476 hours resulting in an average production rate of 2.0 ft/hr (1.0 cm/min).

A.5.2 Cost Estimates

Detailed equipment and material costs are drawn up in Tables A.6 and A.7. Where possible, these costs were obtained from equipment manufacturers and contractors.

Crew costs were estimated in the text to be $36.00 per hour and mobilization and set-up costs were taken to be $4,400.

Since all these costs are in 1974 dollars, no inflation escalation factors are necessary.

A.5.3 Total Cost

Time estimates and cost estimates are combined in Table A.8 to yield the total cost of the job.

As shown in the table, the total cost of the hole is estimated to be $427,486 or $85.50 per foot ($280.50/m).

Table A.5

Time Estimates for Rotary Drilling of Sample Hole

Item	Obtained from	Time (hr)
Full hole drilling	Figure 3.2	195
Hole Survey 1 every 30 feet (9.1 m)	Figure 3.7	90
3 every 60 feet (27.4 m)	Figure 3.7	144
Intermittent coring and direction change combined	Figure 3.10	1,150
Fishing	Figure 3.11	158
Hole stabilization	Figure 3.12	326
Subtotal		2,063
Job efficiency and maintenance	0.2 (Subtotal)	413
Total Time		2,476

Table A.6

Equipment Cost for Rotary Drilling Estimate

	Item Description	Quantity	Cost ($)	Ownership Cost/hr (5 day - 3 Shift) ($/hr)	Operating and Maintenance Cost/hr ($/hr)	Total Cost/hr ($/hr)
a)	Drill	1	100,000	19.23	6.30	25.54
b)	Survey Collars	2		-	-	2.66
c)	Circulating Pump	1	6,000	1.20	0.60	1.80
d)	Supply Pump	1	4,000	0.80	0.40	1.20
e)	Hydraulic Ram	1	10,000	2.00	0.50	2.50
f)	Generator and Lights	2	9,000	1.30	0.86	2.16
g)	Mud Tanks	2	200	0.04	-	0.04
h)	Mud Mixer	1	236	0.05	0.02	0.07
				Total Cost/hr		$ 35.97

Bent Housing Dyna-Drill Cost

Operation: $1010/8 hrs of drilling* plus $120/hr over 8 hours

Standby: $25/day

*A new 8 hour shift is begun any time the hole is lengthened by any other means.

Table A.7

Job Supply and Material Costs for Rotary Drilling Estimate

	Item Description	Quantity	Cost ($)	Cost/hr (5 day - 3 Shift) ($/hr)	Maintenance Cost/hr ($/hr)	Total Cost/hr ($/hr)	Cost/ft ($/ft)
a)	Core barrel assembly - 5 ft long	1	170	0.03	0.01	0.04	-
b)	Drill rod	5000 ft	34,000	6.53	-	6.53	-
c)	Survey Instrument	1		2.08	-	2.08	-
d)	Outer core barrel tube	2	220	-	-	-	0.04
e)	Miscellaneous		5,000	1.00	0.30	1.30	-
f)	Rolling cutter bits			-	-	-	0.21
g)	Diamond core bits			-	-	-	0.18
h)	Drilling mud	12 sacks/ shift	5.50/ sack	8.25	-	8.25	-
i)	Grout			-	-	-	1.40
				Total Cost		$ 18.20/hr	$1.83/ft ($6.00/m)

Table A.8

Estimated Cost for Rotary Drilling

Item	Calculated From		Cost ($)
Labor Cost	(Total time) x (cost/hr) (2476) x (36.00)	=	89,136
Equipment Cost hourly	(Total time) x (cost/hr) (2476) x (35.97)	=	89,062
Dyna-Drill operation	(Number of direction changes) x (cost/8 hrs) (83) x (1010)	=	83,830
standby	(Number of days) x (cost/day) (104) x (25)	=	2,600
Materials Cost per hour	(Total time) x (cost/hr) (2476) x (18.20)	=	45,063
per foot	(Hole length) x (cost/ft) (5000) x (1.83)	=	9,150
Mobilization and Set-Up Cost			4,400
	Subtotal 1		323,241
Overhead	(0.15) x (Subtotal 1)		48,486
	Subtotal 2		371,727
Profit	(0.15) x (Subtotal 2)		55,759
	Total Cost		$ 427,486
	Average Cost		$85.50/ft ($280.50/m)

A.6 Down-Hole Motor Drilling Estimate

The assumptions which must be made in addition to those made in Section A.2 are:

(a) The hole will be drilled using 6-3/4 inch (17.2 cm) rolling cutter bits on a 5" (12.7 cm) Dyna-Drill.

(b) Direction changes will be made by means of a Dyna-Drill with a bent housing.

(c) An NX diamond core bit and a 5 foot (1.52 m) core barrel will be used for intermittent core samples.

(d) Direction changes will be combined with the core sampling, i.e., every 60 feet (18.3 m) instead of every 90 feet (27.4 m). This saves time.

A.6.1 Time Estimates

Table A.9 shows the times estimated for the down-hole motor drilling and the figure from which they were obtained.

As can be seen, the total time required, excluding mobilization and set-up, is 2,590 hours resulting in an average production rate of 1.9 feet/hour (0.95 cm/min).

A.6.2 Cost Estimates

Detailed equipment and material cost estimates are drawn up in Tables A.10 and A.11. Where possible, these costs were obtained from equipment manufacturers and contractors.

Crew costs are estimated to be $36.00 per hour and mobilization and set-up costs are taken to be $4,400.

Table A.9

Time Estimates for Down-Hole Motor Drilling of Sample Hole

Item	Obtained from	Time (hr)
Full hole drilling	Figure 3.3	290
Hole survey 1 every 30 feet (9.1 m)	Figure 3.7	90
3 every 60 feet (27.4 m)	Figure 3.7	144
Intermittent coring and direction change combined	Figure 3.10	1,150
Fishing	Figure 3.11	158
Hole stabilization	Figure 3.12	326
Subtotal		2,158
Job efficiency and maintenance	(0.2 subtotal)	432
Total Time		2,590

Table A.10

Equipment Cost for Down-Hole Motor Drilling Estimate

	Item Description	Quantity	Cost ($)	Ownership Cost/hr (5 day-3 Shift) ($/hr)	Operating and Maintenance Cost/hr ($/hr)	Total Cost/hr ($/hr)
a)	Drill	1	24,000	4.80	2.30	7.10
b)	Survey Collars	2		-	-	2.66
c)	Circulating Pump	1	18,000	3.46	1.70	5.16
d)	Supply Pump	1	4,000	0.80	0.40	1.20
e)	Hydraulic Ram	1	10,000	2.00	0.50	2.50
f)	Generator and Lights	2	9,000	1.30	0.86	2.16
g)	Mud Tanks	2	200	0.04	-	0.04
h)	Mud Mixer	1	236	0.05	0.02	0.07
				Total Cost/hr		$ 20.89

Straight Housing Dyna-Drill Cost

Operation: $750/8 hrs of drilling* plus $75/hr over 8 hours

Standby: $25/day

Bent Housing Dyna-Drill Cost

Operation: $1010/8 hrs of drilling* plus $120/hr over 8 hours

Standby: $25/day

*A new 8 hour shift is begun any time the hole is lengthened by any other means.

Table A.11

Job Supply and Material Costs for Down-Hole Motor Drilling Estimate

	Item Description	Quantity	Cost ($)	Cost/hr (5 day - 3 Shift) ($/hr)	Maintenance Cost/hr ($/hr)	Total Cost/hr ($/hr)	Cost/ft ($/ft)
a)	Core barrel assembly - 5 ft long	1	170	0.30	0.01	0.04	-
b)	Drill rod	5000 ft	34,000	6.53	-	6.53	-
c)	Survey Instrument	1		2.08	-	2.08	-
d)	Outer core barrel tube	2	220	-	-	-	0.04
e)	Miscellaneous		5,000	1.00	0.30	1.30	-
f)	Rolling cutter bits			-	-	-	0.21
g)	Diamond core bits			-	-	-	0.18
h)	Drilling mud	12 sacks/shift	5.50/sack	8.25	-	8.25	-
i)	Grout			-	-	-	1.40
				Total Cost		$ 18.20/hr	$1.83/ft ($6.00/m)

Since all these costs are in 1974 dollars, no inflation escalation factors are necessary.

A.6.3 Total Cost

Time and cost estimates are combined in Table A.12 to yield the total cost of the job. The total cost of the hole is estimated to be $476,447 or $95.29 per foot ($312.63/m).

A.7 Down-Hole Percussion Drilling Estimate

In addition to the assumptions in Section A.2, the following additional assumptions are made:

(a) A 4 inch (10.2 cm) diameter hole will be drilled.

(b) Direction changes will be made using a Dyna-Drill.

(c) An NX diamond core bit and a 5 foot (1.52 m) core barrel will be used for intermittent core samples.

(d) Direction changes will be combined with the core sampling and performed every 60 feet (18.3 m) instead of every 90 feet (27.4 m). This saves time.

A.7.1 Time Estimates

Table A.13 shows the times estimated for the down-hole percussive drilling and where these times were obtained.

From the table, the total time required, excluding mobilization and set-up, is 2,585 hours resulting in an average production rate of 1.9 feet/hour (0.95 cm/min).

Table A.12

Estimated Cost for Down-Hole Motor Drilling

Item	Calculated from		Cost ($)
Labor Cost	(Total time) x (Cost/hr) (2590) x (36.00)	=	93,240
Equipment Cost Hourly	(Total time) x (Cost/hr) (2590) x (20.89)	=	54,105
Straight Housing Dyna-Drill operation	(Number of direction changes plug 1) x Cost/8 hrs) (84) x (750)	=	63,000
standby	(Number of days) x (Cost/day) (108) x (25)	=	2,700
Bent Housing Dyna-Drill operation	(Number of direction changes) x (Cost/8 hrs) (83) x (1010)	=	83,830
standby	(Number of days) x (Cost/day) (108) x (25)	=	2,700
Materials Cost per hour	(Total time) x (Cost/hr) (2590) x (18.20)	=	47,138
per foot	(Hole length) x (Cost/ft) (5000) x (1.83)	=	9,150
Mobilization and Set-Up Cost		=	4,400
	Subtotal 1		360,263
Overhead	(0.15) x (Subtotal 1)		54,039
	Subtotal 2		414,302
Profit	(0.15) x (Subtotal 2)		62,145
	Total Cost		$ 476,447
	Average Cost		$95.29/ft ($312.63/m)

Table A.13

Time Estimates for Down-Hole Percussion Drilling of Sample Hole

Item	Obtained from	Time (hr)
Full hole drilling	Figure 3.4	164
Cycling drilling fluid	Figure 3.6	122
Hole survey 1 every 30 feet (9.1 m)	Figure 3.7	90
3 every 60 feet (27.4 m)	Figure 3.7	144
Intermittent coring and direction change combined	Figure 3.10	1,150
Fishing	Figure 3.11	158
Hole stabilization	Figure 3.12	326
Subtotal		2,154
Job efficiency and maintenance	(0.2 subtotal)	431
Total time		2,585

A.7.2 Cost Estimates

Detailed equipment and material cost estimates are presented in Tables A.14 and A.15. Where possible, these costs were obtained from equipment manufacturers and contractors.

Crew costs are estimated to be $36.00 per hour and mobilization and set-up costs have been taken to be $4,400.

Since all costs are in 1974 dollars, no inflation escalation factors are needed.

A.7.3 Total Cost

Time and cost estimates are combined in Table A.16 to obtain the total cost of the hole. The total cost is estimated to be $406,131 or $81.23 per foot ($266.49/m).

A.8 Summary

Sample cost estimates have been drawn up for drilling a 5,000 foot (1524 m) horizontal hole by each of the four drilling techniques. These estimates are presented in detail in Sections A.4, A.5, A.6, and A.7.

In addition to these estimates for a 5,000 foot hole (1524 m), estimates were made for similar holes of 1,000, 2,000, 3,000 and 4,000 feet (305, 610, 914, and 1219 m). The estimated times and costs of all five sample holes are presented in Tables A.17 through A.24. Figure A. 1 plots the resulting total costs as a function of hole length.

Table A.14

Equipment Cost for Down-Hole Percussive Drilling Estimate

	Item Description	Quantity	Cost ($)	Ownership Cost/hr (5 day-3 Shift) ($/hr)	Operating and Maintenance Cost/hr ($/hr)	Total Cost/hr ($/hr)
a)	Drill	1	40,000	8.00	3.30	11.30
b)	Survey Collars	2		-	-	2.66
c)	Circulating Pump	1	6,000	1.20	0.60	1.80
d)	Supply Pump	1	4,000	0.80	0.40	1.20
e)	Hydraulic Ram	1	10,000	2.00	0.50	2.50
f)	Generator and Lights	2	9,000	1.30	0.86	2.16
g)	Mud Tanks	1	100	0.02	-	0.02
h)	Mud Mixer	1	236	0.05	0.02	0.07
i)	Percussive Drill	1	7,200	1.40	0.25	1.65
j)	Air Compressor	1		6.55	2.65	9.20
				Total Cost/hr		$ 32.56

Bent Housing Dyna-Drill Cost

Operation: $1010/8 hrs of drilling* plus $120/hr over 8 hours

Standby: $25/day

*A new 8 hour shift is begun any time the hole is lengthened by any other means.

Table A.15

Job Supply and Material Costs for Down-Hole Percussive Drilling Estimate

	Item Description	Quantity	Cost ($)	Cost/hr (5 day - 3 Shift) ($/hr)	Maintenance Cost/hr ($/hr)	Total Cost/hr ($/hr)	Cost/ft ($/ft)
a)	Core barrel assembly - 5 ft long	1	170	0.03	0.01	0.04	-
b)	Drill rod	5000 ft	38,000	7.29	-	7.29	-
c)	Survey Instrument	1		2.08	-	2.08	-
d)	Outer core barrel tube	2	220	-	-	-	0.04
e)	Miscellaneous		5,000	1.00	0.30	1.30	-
f)	Percussive button bits			-	-	-	0.19
g)	Diamond core bits			-	-	-	0.18
h)	Drilling mud	400 sacks	5.50/ sack	-	-	-	0.44
i)	Grout			-	-	-	1.40
				Total Cost		$ 10.71/hr	$2.25/ft ($7.38/m)

Table A.16

Estimated Cost for Down-Hole Percussive Drilling

Item	Calculated from		Cost ($)
Labor Cost	(Total time) x (Cost/hr) (2585) x (36.00)	=	93,060
Equipment Cost Hourly	(Total time) x (Cost/hr) (2585) x (32.56)	=	84,168
Bent Housing Dyna-Drill operation	(Number of direction changes) x (Cost/8 hrs) (83) x (1010)	=	83,830
standby	(Number of days) x (Cost/day) (108) x (25)	=	2,700
Materials Cost per hour	(Total time) x (Cost/hr) (2585) x (10.71)	=	27,685
per foot	(Hole length) x (Cost/ft) (5000) x (2.25)	=	11,250
Mobilization and Set-Up Cost			4,400
	Subtotal 1		307,093
Overhead	(0.15) x (Subtotal 1)		46,064
	Subtotal 2		353,157
Profit	(0.15) x (Subtotal 2)		52,974
	Total Cost		$ 406,131
	Average Cost		$81.23/ft ($266.49/m)

Table A.17

Estimated Times for Diamond Wireline Core Drilling of 1000, 2000, 3000, 4000, and 5000 Foot Holes

Operation	Length of Hole (Feet)				
	1000	2000	3000	4000	5000
Wireline core drilling	108	247	447	690	960
Hole survey					
1 every 30 ft (9.1 m)	9	21	40	64	90
3 every 90 ft (27.4 m)	7	20	36	60	94
Direction change	49	170	364	630	970
Fishing	9	28	59	100	158
Hole Stabilization	47	104	169	243	326
Subtotal	229	590	1115	1787	2598
Job efficiency and maintenance	46	118	223	357	520
Total Time (hours)	275	708	1338	2144	3118
Production Rate (ft/hr)	3.6	2.8	2.2	1.9	1.6
(cm/min)	(1.8)	(1.4)	(1.1)	(0.95)	(0.8)

Table A.18

Estimated Costs for Diamond Wireline Core Drilling of 1000, 2000, 3000, 4000, and 5000 Foot Holes

Item	Length of Hole (Feet)				
	1000	2000	3000	4000	5000
Labor Cost	9,900	25,488	48,168	77,184	112,248
Equipment Cost	4,089	10,528	19,896	31,881	46,365
Materials Cost					
Per hour	4,639	11,944	22,572	36,169	52,601
Per foot	2,690	5,380	8,070	10,760	13,450
Mobilization and Set-Up Cost	3,000	3,300	3,600	4,000	4,400
Subtotal 1	24,318	56,640	102,306	159,994	229,064
Overhead	3,648	8,496	15,346	23,999	34,360
Subtotal 2	27,966	65,136	117,652	183,993	263,424
Profit	4,195	9,770	17,648	27,599	39,514
Total Cost	$32,161	$74,906	$135,300	$211,592	$302,938
Average Cost ($/ft)	$32.16	$37.45	$45.10	$52.90	$60.59
($/m)	($105.52)	($122.88)	($147.97)	($173.55)	($198.78)

Table A.19

Estimated Times for Rotary Drilling of 1000, 2000, 3000, 4000, and 5000 Foot Holes

Operation	Length of Hole (Feet)				
	1000	2000	3000	4000	5000
Full hole drilling	37	73	100	153	195
Hole survey					
1 every 30 ft (9.1 m)	9	21	40	64	90
3 every 60 ft (27.4 m)	15	33	60	99	144
Intermittent coring and direction change combined	70	200	420	750	1150
Fishing	9	28	59	100	158
Hole Stabilization	47	104	169	243	326
Subtotal	187	459	858	1409	2063
Job Efficiency and Maintenance	37	92	172	282	413
Total Time (hours)	224	551	1030	1691	2476
Production Rate (ft/hr)	4.5	3.6	2.9	2.3	2.0
(cm/min)	(2.2)	(1.8)	(2.45)	(1.2	(1.0)

Table A.20

Estimated Costs for Rotary Drilling of 1000, 2000, 3000, 4000, and 5000 Foot Holes

Item	Length of Hole (Feet)				
	1000	2000	3000	4000	5000
Labor Cost	8,064	19,836	37,080	60,876	89,136
Equipment Cost					
Hourly	8,057	19,819	37,049	60,825	89,062
Bent Housing Dyna-Drill					
Operation	16,160	33,330	49,490	66,660	83,830
Standby	250	575	1,075	1,775	2,600
Materials Cost					
Per hour	4,077	10,028	18,746	30,776	45,063
Per foot	1,830	3,660	5,490	7,320	9,150
Mobilization and Set-Up Cost	3,000	3,300	3,600	4,000	4,400
Subtotal 1	41,438	90,548	152,530	232,222	323,241
Overhead	6,216	13,582	22,880	34,833	48,486
Subtotal 2	47,654	104,130	175,410	267,055	371,727
Profit	7,148	15,620	26,312	40,058	55,759
Total Cost	$54,802	$119,750	$201,722	$307,113	$427,486
Average Cost ($/ft)	$54.80	$59.88	$67.24	$76.78	$85.50
($/m)	($179.80)	($196.44)	($220.61)	($251.90)	($280.50)

Table A.21

Estimated Times for Down-Hole Motor Drilling of 1000, 2000, 3000, 4000, and 5000 Foot Holes

Operation	Length of Hole (Feet)				
	1000	2000	3000	4000	5000
Full hole drilling	55	110	162	230	290
Hole survey					
1 every 30 ft (9.1 m)	9	21	40	64	90
3 every 60 ft (27.4 m)	15	33	60	99	144
Intermittent coring and direction change combined	75	200	425	750	1150
Fishing	9	28	59	100	158
Hole Stabilization	47	104	169	243	326
Subtotal	210	496	915	1486	2158
Job Efficiency and Maintenance	42	99	183	297	432
Total Time (hours)	252	595	1098	1783	2590
Production Rate (ft/hr)	4.0	3.3	2.7	2.2	1.9
(cm/min)	(2.0)	(1.7)	(1.4)	(1.1)	(1.0)

Table A.22

Estimated Costs for Down-Hole Motor Drilling of 1000, 2000, 3000, 4000, and 5000 Foot Holes

Item	Length of Hole (Feet) 1000	2000	3000	4000	5000
Labor Cost	9,072	21,420	39,528	64,188	93,240
Equipment Cost					
Hourly	5,264	12,430	22,937	37,247	54,105
Straight Housing Dyna-Drill					
Operation	12,750	25,500	37,500	50,250	63,000
Standby	275	625	1,150	1,875	2,700
Bent Housing Dyna-Drill					
Operation	16,160	33,330	49,490	67,670	83,830
Standby	275	625	1,150	1,875	2,700
Materials Cost					
Per Hour	4,586	10,829	19,984	32,451	47,138
Per Foot	1,830	3,660	5,490	7,320	9,150
Mobilization and Set-Up Cost	3,000	3,300	3,600	4,000	4,400
Subtotal 1	53,212	111,720	180,829	266,876	360,263
Overhead	7,982	16,758	27,124	40,031	54,039
Subtotal 2	61,194	128,478	207,953	306,907	414,302
Profit	9,179	19,272	31,193	46,036	62,145
Total Cost	$70,373	$147,750	$239,146	$352,943	$476,447
Average Cost ($/ft)	$70.37	$73.88	$79.72	$88.24	$95.29
($/m)	($230.88)	($242.37)	($261.53)	($289.49)	($312.63)

Table A.23

Estimated Times for Down-Hole Percussive Drilling of 1000, 2000, 3000, 4000, and 5000 Foot Holes

Operation	Length of Hole (Feet)				
	1000	2000	3000	4000	5000
Full Hole Drilling	28	60	90	128	164
Cycling Drilling Fluid	5	19	44	78	122
Hole Survey					
1 every 30 ft (9.1 m)	9	21	40	64	90
3 every 60 ft (27.4 m)	15	33	60	99	144
Intermittent coring and direction change combined	70	200	420	750	1150
Fishing	9	28	59	100	158
Hole Stabilization	47	104	169	243	326
Subtotal	183	465	882	1462	2154
Job Efficiency and Maintenance	37	93	176	292	431
Total Time (Hours)	220	558	1058	1754	2585
Production Rate (ft/hr)	4.6	3.6	2.8	2.3	1.9
(cm/min)	(2.3)	(1.8)	(1.4)	(1.1)	(0.95)

Table A.24

Estimated Costs for Down-Hole Percussive Drilling of 1000, 2000, 3000, 4000, and 5000 Foot Holes

Item	Length of Hole (Feet)				
	1000	2000	3000	4000	5000
Labor Cost	7,920	20,088	38,088	63,144	93,060
Equipment Cost					
Hourly	7,163	18,168	34,448	57,110	84,168
Bent Housing Dyna-Drill					
Operation	16,160	33,330	49,490	66,660	83,830
Standby	250	600	1,125	1,850	2,700
Materials Cost					
Per Hour	2,356	5,976	11,331	18,785	27,685
Per Foot	2,250	4,500	6,750	9,000	11,250
Mobilization and Set-Up Cost	3,000	3,300	3,600	4,000	4,400
Subtotal 1	39,099	85,962	144,832	220,549	307,093
Overhead	5,865	12,894	21,725	33,082	46,064
Subtotal 2	44,964	98,856	166,557	253,631	353,157
Profit	6,745	14,828	24,984	38,045	52,974
Total Cost	$51,709	$113,684	$191,541	$291,676	$406,131
Average Cost ($/ft)	$51.71	$56.84	$63.85	$72.92	$81.23
($/m)	($169.65)	($186.49)	($209.47)	($239.24)	($266.49)

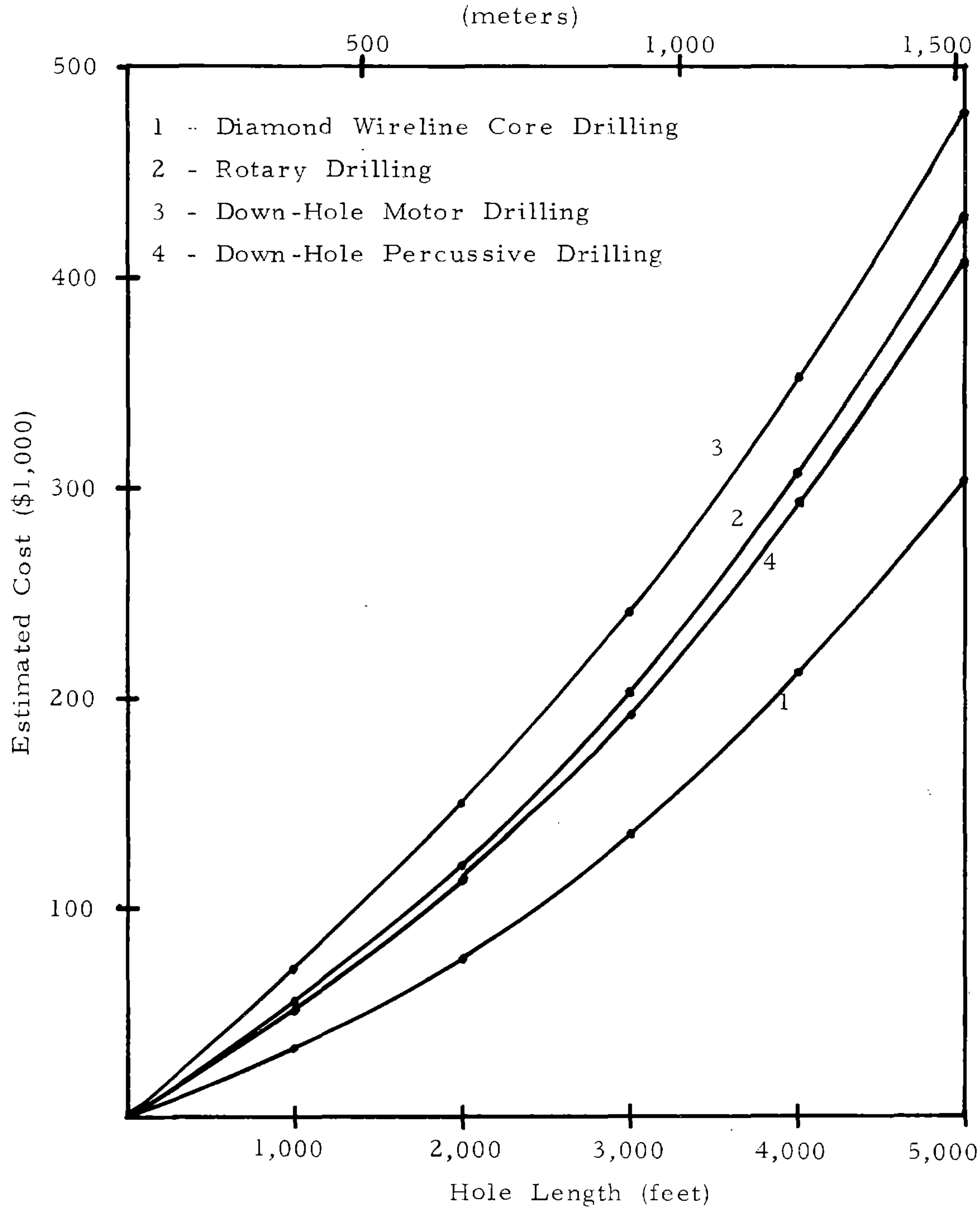

Figure A.1 - Summary of Cost Estimates

APPENDIX B

HANDLING OTHER GEOLOGIC CONDITIONS

All graphs presented in the body of this estimating volume assume an average geologic rock profile consisting of 11% soft rock, 59% medium rock, and 30% hard rock. Hence if it is known or expected that the actual rock type to be encountered will be significantly different from this average profile, the graphs will not apply and the specific time equations should be used.

Figures B.1, B.2, and B.3 present penetration rate as a function of rock compressive strength for rolling cutter bits, percussive button bits, and diamond core bits. Also presented on these plots are average bit life.

The use of these figures is best explained by example. Assume that a 6,000 ft (1829 m) horizontal hole is to be drilled using rotary techniques and a 6-3/4" (17.2 cm) rolling cutter bit. It is expected that one-third of the rock encountered will be hard, one-third medium, and one-third soft. The only time estimates which are affected are the wireline core drilling time from Eqn. (3.11) the full hole drilling time from Eqn. (3.2), and the hole stabilization time from Eqn. (3.9).

The full hole drilling time is given by equation (3.2):

$$t_2 = \sum_{n=1}^{N} \left(\frac{G_n}{P_{f,n}}\right) + B\, t_b + j\, \frac{L}{V_r}\, (B + 1) \qquad (3.2)$$

To evaluate this equation, it is necessary to determine the length of each geological section, the penetration rate in each section, and the average bit life in each section. The lengths are known: G_1 = 2,000 ft (610 m) (hard rock), G_2 = 2,000 ft (610 m) (medium rock), and G_3 = 2,000 ft (610 m) (soft rock). The penetration rates are obtained from

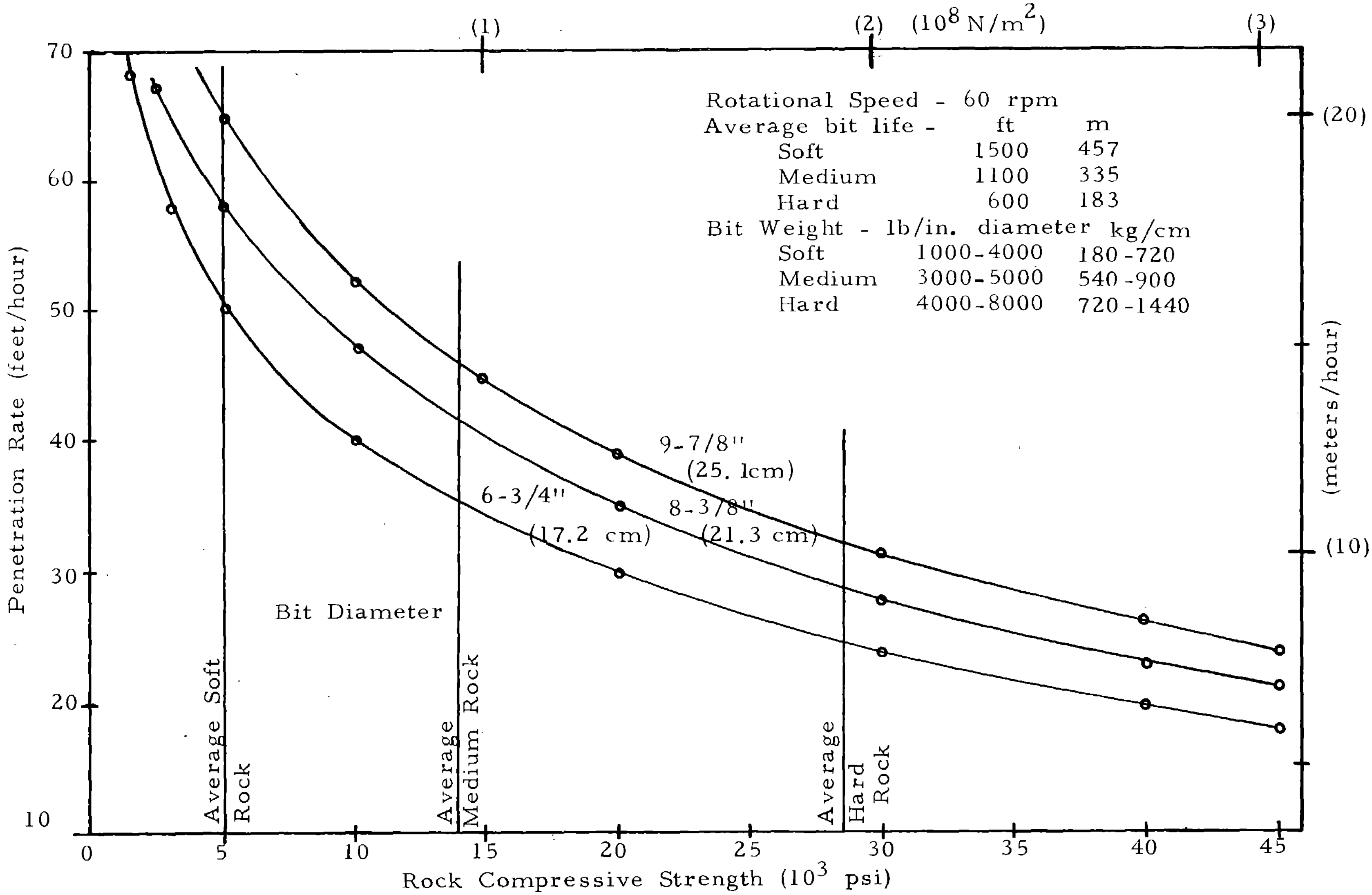

Figure B.1 - Penetration Rates for Rolling Cutter Bits

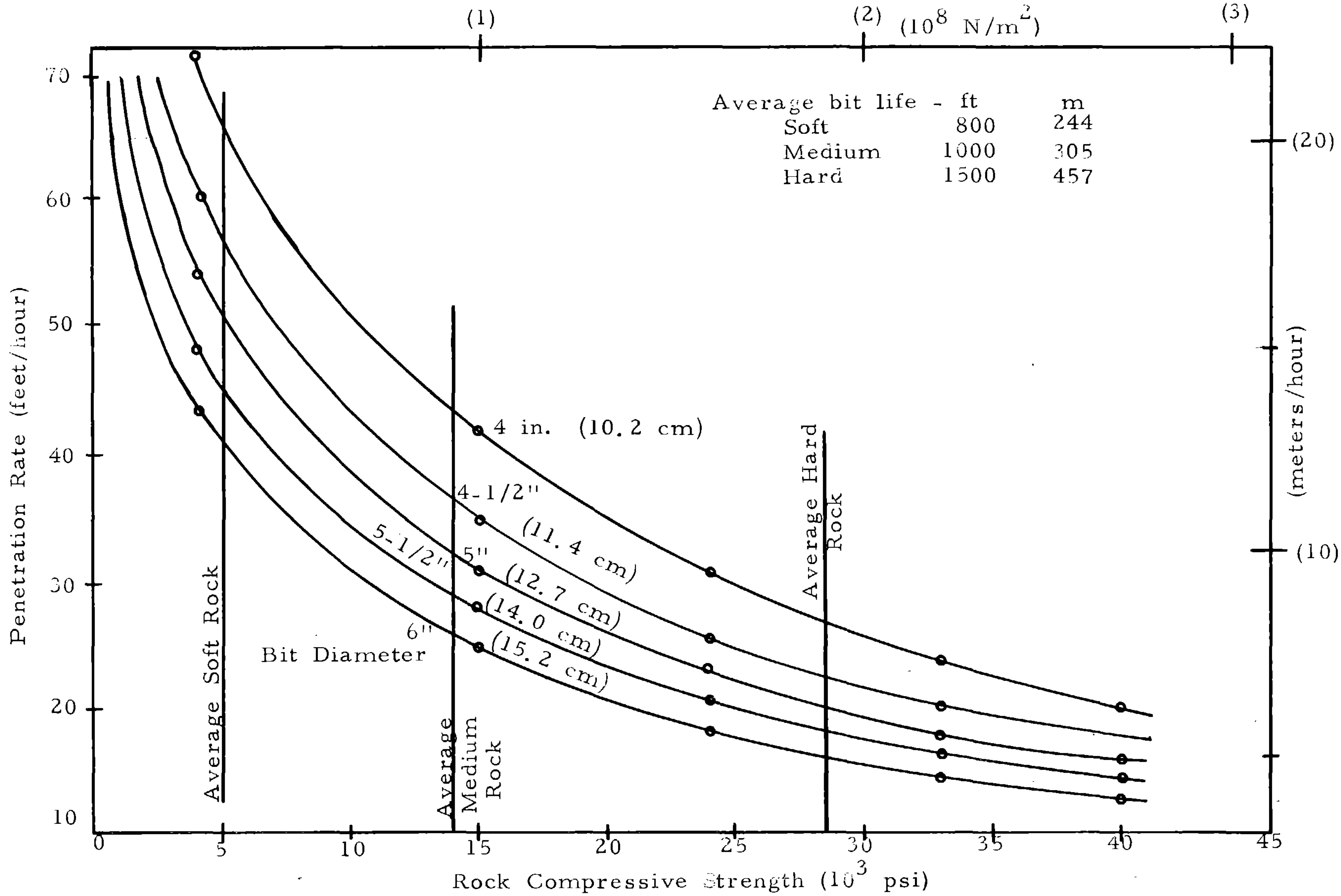

Figure B.2 - Penetration Rates for Percussion Bits

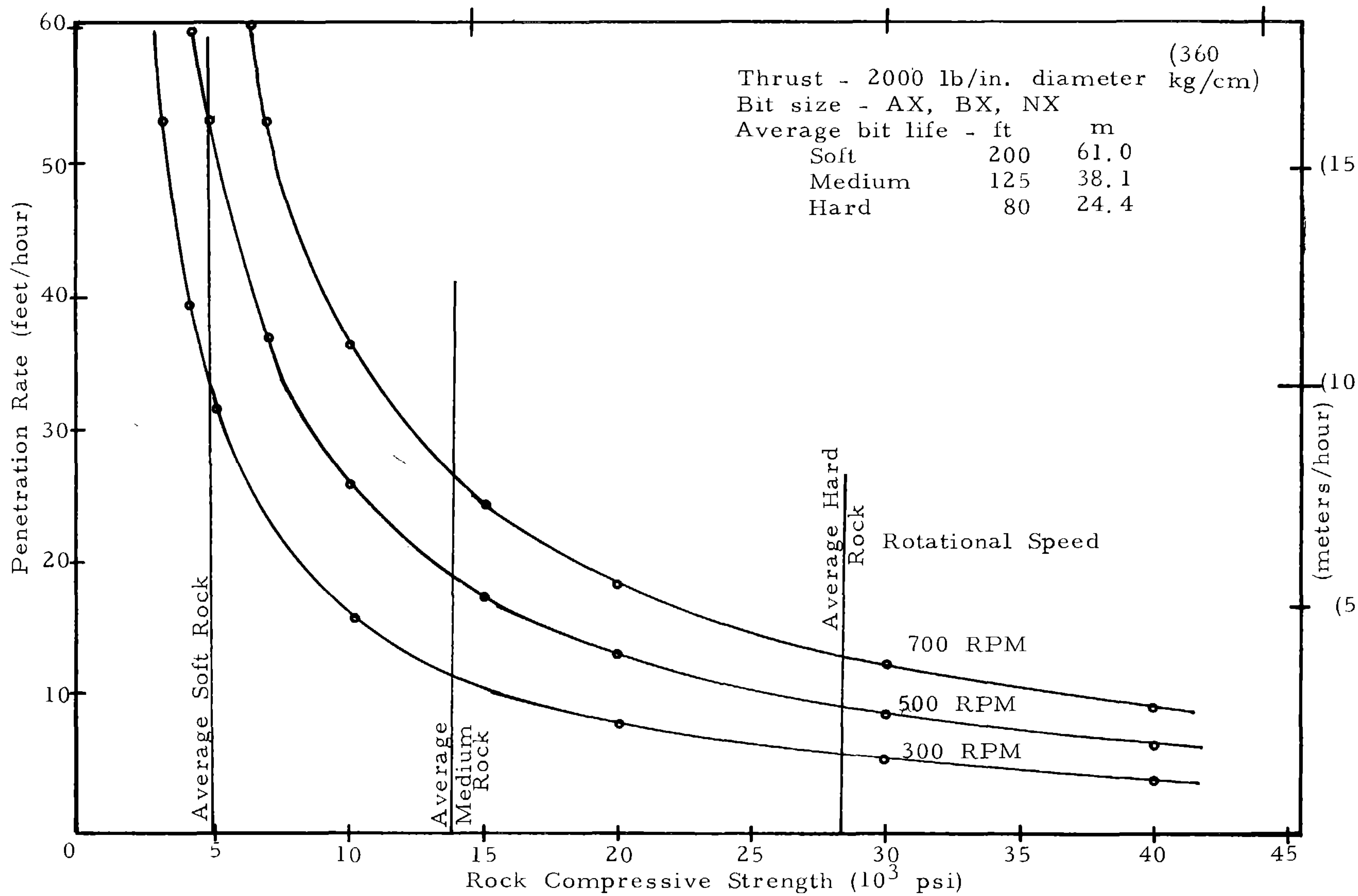

Figure B.3 - Penetration Rates for Diamond Coring Bits

Figure B.1 as: $P_{f,1}$ = 25 ft/hr (12.5 cm/min) (hard rock), $P_{f,2}$ = 35 ft/hr (17.5 cm/min) (medium rock), and $P_{f,3}$ = 50 ft/hr (25 cm/min) (soft rock). Average bit lives are also obtained from Figure B.1 as: 600 feet (183 m) in hard rock, 1,100 feet (335 m) in medium, and 1,500 feet (457 m) in soft.

The average bit life for the entire drilling is found as

$$B_{L,avg.} = \frac{L}{\frac{G_1}{B_{L,1}} + \frac{G_2}{B_{L,2}} + \frac{G_3}{B_{L,3}}} \qquad (B.1)$$

or

$$B_{L,avg.} = \frac{6000 \text{ ft}}{\left(\frac{2000}{600}\right) + \left(\frac{2000}{1100}\right) + \left(\frac{2000}{1500}\right)}$$

$$B_{L,avg.} \approx 925 \text{ ft}$$

and therefore the number of bits required will be given by

$$\frac{L}{B_{L,avg.}} = \frac{6000}{925} \approx 6.5$$

and the number of bit changes, B, will be taken as 6. The full hole drilling time may now be evaluated assuming t_b = 7.5 minutes and V_r = 20 ft/min (10 cm/sec) from Table 3:

$$t = \left[\frac{2000}{25} + \frac{2000}{35} + \frac{2000}{50}\right] + (6)\ \frac{(7.5)}{60} + \frac{(6000)}{(20)\ (60)}\ (7)$$

$$= 80 + 57 + 40 + 0.75 + 35$$

$$t = 212.75 \text{ hrs.}$$

The hole stabilization time is given by equation (3.9).

$$t_9 = Rt_g + \frac{L_g}{P_{f,g}} + \frac{G_h L_g}{P_g} + \left[\frac{F_r (L - L_g)}{2\ P_g} + \frac{L}{V_r}\right] (R + 1) \qquad (3.9)$$

The total length of hole to be grouted may be obtained from Table 3 as:

$$L_g = (0.02)(2000) + (0.10)(2000) + (0.15)(2000)$$

$$L_g = 540 \text{ ft } (166 \text{ m})$$

If grouting activities occur every 200 ft (61.0 m), R = 5000/200 = 25. From Table 3: t_g = 8 hrs, $P_{f,g}$ = 50 ft/hr (25 cm/min), V_r = 20 ft/min (10 cm/sec), and G_h = 1 ft^3/ft (0.09 m^3/m). The grout pump capacity is estimated to be 4 ft^3/min (113 ℓ/min) and the fluid requirements per foot of drill rod is calculated for 4-1/2" (11.4 cm) O.D. (3.64 in. (9.25 cm) I.D.) drill rod to be 0.0723 ft^3/ft (0.0065 m^3/m). From this information, the hole stabilization time is estimated to be:

$$t = (25)(8) + \frac{540}{54} + \left[\frac{(0.0723)(4460) + (1)(540)}{(4)(25)(60)} + \frac{2(5000)}{(60)(20)(25)}\right] \sum_{j=1}^{25} (j)$$

$$t = 365.85 \text{ hrs.}$$

Other geological conditions would be handled in similar fashion.