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LLING AND PREPARATION OF REUSABLE, IG RANGE, HORIZONTAL BORE HOLES IN ROCK AND IN GOUGE

Vol. I. State-of-the-Art Assessment

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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 assesses the horizontal penetration capabilities of available drilling equipment. The drilling of horizontal holes to a maximum length of 5000 ft. (1524m) is found to be technically feasible and to offer an order of magnitude cost reduction over pilot tunneling. Limitations of present day equipment and techniques are identified and means to overcome these limitations are indicated.

This is the first of three volumes. Volume II is published as FHWA-RD-75-96, subtitle: Estimating Manual for Time and Cost Requirements. 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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1. Introduction

1.1 Background

Subsurface construction is the subject of increased interest in many sectors of our economy. Transportation planners would like to make greater use of the subsurface both to minimize the environmental impact of transportation systems and as a technique to reduce travel distances between points. Competition for space and noise considerations essentially demand that much needed urban-suburban mass transit systems be located underground. Large scale tunneling projects to overcome natural obstacles, such as the Seikan Railway Tunnel in Japan and the proposed tunnel under the English Channel ("Chunnel"), have contributed and will continue to contribute to the demand for improved subsurface construction techniques.

Utility industries are also under increased pressure to locate lines and facilities underground due to environmental considerations. Further, the disruption caused by cut and cover techniques has become unacceptable in some situations (river crossings and urban environments) creating a requirement for underground construction to be conducted by tunneling techniques.

The energy crisis has added to demands for underground construction and exploration techniques. In the coal mining industry, horizontal drilling is being used for methane drainage and relief of high pressure gas pockets. There is a strong push to use methane from coal beds to augment natural gas supplies. The Bureau of Mines estimates that, nationwide, coal seams less than 3,000 feet deep contain more pipeline quality gas than all of Alaska's present reserves.[1] Exploratory and production drilling in the petroleum field has been increasing as rapidly as the availability of equipment will allow. Underground facilities are being considered for insitu retorting of shale oil. In the atomic energy field, a shortage of underground radioactive waste storage facilities has caused the Atomic Energy Commission to require some atomic power plants to curtail electrical production. Leakage problems with existing storage facilities have lead to a program in which precision horizontal and angled drilling is being used in implanting underground monitors at the facilities.

At the present time, subsurface utilization in all areas is limited by high construction costs. A major element of these high costs is generated by the heavy financial and physical risks which derive from the uncertainty in predicting ground conditions at construction sites.

This study focuses on the particular problem of subsurface investigation along proposed tunnel alignments but clearly the solution to this problem will be of benefit in all areas requiring the application of underground exploration and construction techniques. Horizontal penetration is recognized as the only alternative available, under many conditions, for generating continuous data along a tunnel alignment. Typically, this penetration would be achieved by excavating a pilot tunnel along the proposed tunnel line. However, pilot tunnel costs have escalated to the point where they presently range from $225 per foot for "easy" conditions to $877 per foot for "difficult" conditions.[2] Horizontal, reuseable boreholes, explored with a combination of sensing techniques, have been suggested as an alternative method of horizontal penetration.

1.2 Purpose

The purpose of this report is to serve as a guide to the highway or transportation engineer in evaluating subsurface investigation techniques. In particular, this document provides the information needed to evaluate guided horizontal drilling as an alternative to pilot tunneling for achieving horizontal penetration.

In investigating the geology of a proposed tunnel site, the engineer will generally use the following techniques:

1.) Evaluate local knowledge of the geology based on nearby mines, tunnels, and other previous subsurface construction.

2.) Examine geological maps, aerial photographs, and possibly, radar or infrared scanning imagery.

3.) Extrapolate conditions on the basis of an examination of the surface geology.

4.) Drill vertical and inclined core holes.

If the tunnel alignment is close to the ground surface and the surface is accessible, discontinuous, direct penetration data may be obtained by widely-spaced, vertical or inclined core holes. If the tunnel is located under a high mountain or if access to the ground surface is difficult or impossible, horizontal penetration may be considered as a means of obtaining continuous data along the tunnel alignment. This horizontal penetration can be achieved by excavating a pilot tunnel or by horizontal boring techniques.

Pilot tunnels have shortcomings which suggest that more attention should be paid to alternative horizontal penetration techniques. A few of these shortcomings include:

1.) High Cost

2.) Long excavation time.

3.) Danger to the personnel involved.

A subsurface investigation system employing horizontal drilling and a combination of sensing techniques is one alternative to pilot tunneling. The purpose of this document is to provide the information necessary to evaluate horizontal drilling as a technique for horizontal penetration. No indirect sensing techniques are considered. However, an FHWA contract now in progress is developing a sensing system to be used in horizontal boreholes for pre-excavation investigation of tunnel sites.[3] The sensing device developed from this program will constitute one of the components of an information gathering system using horizontal drilling as a penetration technique.

1.3 Summary of Results

The results of this study indicate that there are four candidate techniques for drilling long-range horizontal boreholes in rock and gouge. These include:

(1) Diamond wireline core drilling.
(2) Rotary drilling.
(3) Down-hole motor drilling.
(4) Down-hole percussive drilling.

The estimated penetration capabilities and costs of these techniques are listed in Table 1.1. Diamond wireline core drilling is far and away the most developed horizontal rock drilling technique. With this technique, the prospective horizontal drilling customer has the choice of purchasing the equipment himself to perform the work or hiring a contractor. There are no contractors who make a practice of horizontal drilling in rock with the other listed techniques. Of these techniques, down-hole motor drilling would probably require the least amount of development effort in a horizontal drilling program and down-hole percussive drilling the most.

With available drill guidance techniques, hole deviation can be controlled to about ± 11 ft (3.3 m) per 1000 ft (305 m) drilled, "best case", and about ± 44 ft (13.4 m) deviation per 1000 ft (305 m), "worst case". Performance will vary within this range, depending more upon the care employed in using the available equipment, than the equipment itself.

TABLE 1.1 LONG HORIZONTAL DRILLING TIME AND COST ESTIMATES FOR AVERAGE GEOLOGY*

Technique	Hole Length, feet (m)	Hole Diameter, inches (mm)	Cost Per Foot (Meter) at Maximum Length
Diamond Wireline Core Drilling	5000 (1524) 4000 (1220)	2.36 (60) 2.98 (76)	$ 61 (200)
Rotary Drilling	5000 (1524) 0	6.75 (171) 12 (305)	$ 86 (282)
Down-Hole Percussive Drilling	1000 (305)	4-6 (102-152)	$ 48 (157)
Down-Hole Motor Drilling	4000 (1220) 2000 (610)	6.75 (171) 3 (76)	$ 89 (292)

*Assumes 11% soft rock, 59% medium rock, 30% hard rock.

Within the penetration and guidance limitations noted above, horizontal drilling offers a substantial cost saving over pilot tunneling as a means of achieving horizontal penetration. Furthermore, there is a considerable potential for extending the penetration capabilities of horizontal drilling and reducing hole deviation. These improvements are possible at a reduction in the time and cost required to drill a given distance.

1.4 Report Format

In evaluating horizontal penetration as a subsurface investigation technique, the following steps are involved:

(1) An assessment of the capabilities and economics of available penetration techniques.

(2) A value analysis of the information gathering potential of penetration techniques and associated sensing techniques.

(3) Selection of the most cost effective information gathering system.

(4) Detailed planning of the proposed horizontal penetration.

This document is written as an aid in tasks 1 and 4 of the decision-making process. To this end, the report is divided into three distinct sections. Chapters 2-4 of Volume I constitute an Executive Summary of the state-of-the-art of long horizontal drilling. This section provides a comprehensive but succinct assessment of available horizontal drilling techniques. Chapters on Planning Considerations and Management Considerations are included to outline the qualitative factors which should be considered in evaluating horizontal drilling.

The remainder of the document serves as a reference for the detailed planning of a long horizontal drilling program. Chapters 5 - 8 comprise the Technical Discussion section of the report. These chapters include detailed discussion of all aspects of horizontal drilling. Volume II, the third section of the report, presents a mathematical model which can be used to estimate time and cost requirements for horizontal drilling.

Procedures for performing a value analysis of information gathering systems are presented in a previous FHWA report on Subsurface Investigation Planning.[4] This document is an essential reference in any decision involving subsurface investigation techniques.

2. State-of-the-Art Horizontal Drilling Capability

The state-of-the-art of horizontal drilling is defined in terms of the capabilities of available production hardware and techniques which have been proven in horizontal drilling applications. Custom equipment, experimental equipment and the procedures associated with its use, and production equipment which has not been applied to horizontal drilling are not considered state-of-the-art. However, custom, experimental, and conceptual equipment and procedures are considered in evaluating near term horizontal drilling potential as is the modification of available production equipment to horizontal drilling.

2.1 Horizontal Drilling History

A listing of representative horizontal drilling is provided in Table 2.1. The discussion which follows refers to that drilling which is of particular significance in terms of establishing state-of-the-art capabilities for drilling long horizontal holes in rock.

The longest horizontal hole which has been drilled appears to be a 5,300 ft (1615 m), 6-3/4 inch (172 mm) diameter hole which was drilled about 1971-1972 on the Seikan Tunnel Project in Japan. This hole was drilled with an FS-400 Horizontal Boring Machine manufactured by Koken Boring Machine Co., Ltd. of Tokyo, Japan. A three cone rotary bit was used for drilling, a Dyna-Drill was used for hole direction changes, and a Sperry-Sun magnetic multishot survey instrument was used to survey the hole.

Diamond coring procedures have been utilized in all other horizontal drilling work beyond 2,000 ft. (610 m) in length. Longyear Company of Minneapolis, Minnesota and Longyear subsidiaries in Canada

TABLE 2.1 REPRESENTATIVE HORIZONTAL DRILLING

Distance/Diameter Feet (Meters)/Inches (Millimeters)	Material	Method/Equipment	Guidance	Goals	Contractor/Client	Date	Location
(1) 5,300 (1615)/6.75 (171)	Soft	Rotary/Koken FS400	Sperry-Sun/ Dyna-Drill	Rotary 6600 (2000) Downhole 16,400 (5,000)	-	1971-72	Seikan Tunnel, Japan
(2) 4,000 (1,220)/2.36 (60)	Medium-Hard	Diamond Coring/ Longyear 44	Wedging	5,000 (1,520)	Boart Drilling Ltd. (Longyear Subsidiary)	To Present	South Africa
(3) 4,000 (1,220)/2.36 (60)	Medium-Hard	Diamond Coring/ Longyear	Wedging	-	Canadian Longyear Ltd. /Brayhorn Mines Ltd.	≈ 1964	Central British Columbia
(4) 3,690 (1,125)/3 (76)	Very Soft	Diamond Coring/ Longyear 44	Wedging	-	Reynolds Electrical & Engineering/AEC	Nov. 72 - Present	Mercury, Nevada
(5) 3,000 (914)/2.36 (60)	Medium-Hard	Diamond Coring/ Longyear	Eastman/ Wedging	-	Boyles Brothers Drilling Co.	-	-
(6) 2,630 (802)/ -	Soft	Diamond Coring (?)/ Tone TEL-2C	-	-	-	1972-74	Seikan Tunnel, Japan
(7) 2,540 (774)/2 (51)	Coal	Rotary/Fletcher	-	3,000 (914)	Kerr-McGee	To Present	-
(8) 1,980 (604)/3 (76)	Medium-Hard	Diamond Coring/ Sprague & Henwood	Tro Pari Compass	-	Sprague & Henwood/ Penn. Turnpike Authority	1954	Lehigh Tunnel, Penn. Tpk.
(9) *1,700 (518)/3 (76)	Soft-Coal	Downhole, Diamond Bit/Dyna-Drill, Joy 22 Surface Rig	Sperry-Sun/ Dyna-Drill	-	Calvert Western, Fenix & Scisson/ Bureau of Mines	1973-74	-
(10) **≈1,600 (488)	Soil	Dyna-Drill	-	-	Titan Drilling	To Present	-
(11) 1,468 (447)/3.4 (87)	Soft	Double Tube Reverse Circulation (Continuous Coring/ Tone Surface Rig	-	-	Taisei Corp.	-	Seikan Tunnel, Japan

*Started 18° from vertical, drilled 1300 ft. to coal seam (at a depth of 700 ft) and 400 ft more horizontally in coal seam.
**Curved holes.

NOTE: All units are expressed in English units accompanied by metric equivalent units in parenthesis.

TABLE 2.1 REPRESENTATIVE HORIZONTAL DRILLING (Continued)

Distance/Diameter Feet (Meters)/Inches (Millimeters)	Material	Method/Equipment	Guidance	Goals	Contractor/Client	Date	Location
(12) 1,340 (408)/7.625 (194)	Soft	Rotary/Koken FS400	Sperry-Sun/ Dyna-Drill	-	-	-	Seikan Tunnel, Japan
(13) 1,257 (383)/2.36 (60)	Medium-Hard	Diamond Coring/ Canadian Mine Services	-	2,000 (610)	Canadian Mine Services	To Present	-
(14) ≈1,200 (366)/3-4 (76-102)	Soils	Rotary Drag Bit/ Aardvark, Tigre Tierra, Inc.	-	5,000 (1,524) with Wireline Coring	Soil Sampling Services	To Present	-
(15) 1,102 (336)/3.5 (89)	Coal	Rotary/Specially Built Longyear	Sperry-Sun/ Drilling Parameters, Dyna-Drill	-	Fenix & Scisson/ Bureau of Mines	1972	Ohio
(16) 1,180 (359)/3 (76)	Medium-Hard	Diamond Coring/ Longyear	Modified Eastman Wedging	-	Charles S. Robinson & Assoc.,	1970	Wheeler Junction, Colorado
(17) 1,034 (315)/3.5 (89)	Soft-Coal	Rotary, Roller Bit/ Specially Built Longyear Rig	Cableless Telemetry System by Telcom, Inc./ Drilling Parameters, Dyna-Drill	-	Fenix & Scisson, Telcom/Bureau of Mines	1972	Ohio
(18) 864 (263)/4 (102)	Medium-Hard	Downhole Percussive/ Ingersoll-Rand	None	1,000 (305)	Jacobs Assoc./ ARPA	1972	-
(19) 800 (244)/3-6 (76-152)	Soft-Coal	Rotary, with & without Down Hole Thruster, Roller Bit	On Board Survey Package/ Down-Hole Hydraulic Steering Shoe	-	By and For Continental Oil Co.	-	-

and South Africa have drilled holes out to about 4,000 ft. (1219 m) using diamond wireline coring techniques. This work has been performed in medium and hard rocks. The South African subsidiary of Longyear (Boart Drilling, Ltd.) anticipates that they will eventually drill horizontal holes to 5,000 feet (1524 m) on work in progress as of May 1975. Hole diameter on this work is 2.36 inches (60 mm) (BQ size).

Boyles Brothers Drilling Co. of Salt Lake City, Utah has used similar equipment to drill horizontal holes to 3,000 feet (914 m) in length in medium and hard rock.

Again using similar equipment, the Atomic Energy Commission (AEC) has drilled horizontal holes as long as 2,690 feet (1125 m) in continuing work at the AEC test site near Mercury, Nevada. These holes are about 3 inches (76 mm) in diameter and are being drilled in very soft materials. The contractor on this work is Reynolds Electrical and Engineering Co. of Las Vegas, Nevada.

Sprague and Henwood, Inc. of Scranton, Pennsylvania drilled a 3 inch (76 mm) (NX size), 1,980 foot (604 m) horizontal hole in 1954 using diamond coring techniques. This work was performed for the Pennsylvania Turnpike Commission and the material drilled was medium and hard rock.

Jacobs Associates of San Francisco, California developed a technique for drilling horizontal holes using a pneumatic downhole percussion drill in 1972. This technique was used to drill 4 inch (102 mm) holes in medium and hard rock. The longest hole drilled was 864 feet (263 m). The Jacobs work also included the development of drill rod handling equipment which enabled 1,000 ft (305 m) sections of drill pipe to be inserted and withdrawn at up to 200 feet (61 m) per minute.

2.2 Assessment of State-of-the-Art Horizontal Drilling Capability

If we define the state-of-the-art of long horizontal drilling in terms of the capabilities of available production hardware and techniques which have been proven in horizontal drilling applications, the state-of-the-art can be diagramed as in Figure 2.1. There would be some overlap and the numbers have been rounded off but this figure represents a realistic graphic summary.

In terms of accuracy, the range of hole deviation which can be expected is about $\pm$ 11 - 44 ft (3.3 - 13.4 m) horizontally per 1000 ft (305 m) of length and $\pm$ 8 - 19 ft (2.4 - 5.8 m) vertically per 1000 ft (305 m) of length.

Grouting has been proven capable of handling most hole stabilization problems given that one is willing to spend the time and effort. One 2,600 foot (792 m) hole drilled for the Seikan Tunnel job was grouted 61 times, with the number of grouting shifts being twice the number of drilling shifts.[5] However, the material drilled in this work was soft and broken. In diamond coring work performed in medium and hard rocks, hole stability has not been noted as a significant problem.

The cost model of Volume II presents the following techniques as state-of-the-art candidates for horizontal drilling:

(1) Diamond wireline core drilling.
(2) Rotary drilling.
(3) Down-hole motor drilling.
(4) Down-hole percussive drilling.

The cost model has been used to project costs for all four techniques out to 5,000 feet (1524 m). However, diamond wireline core drilling and rotary drilling are the only techniques which can be considered to meet the definition of state-of-the-art for the longer distances.

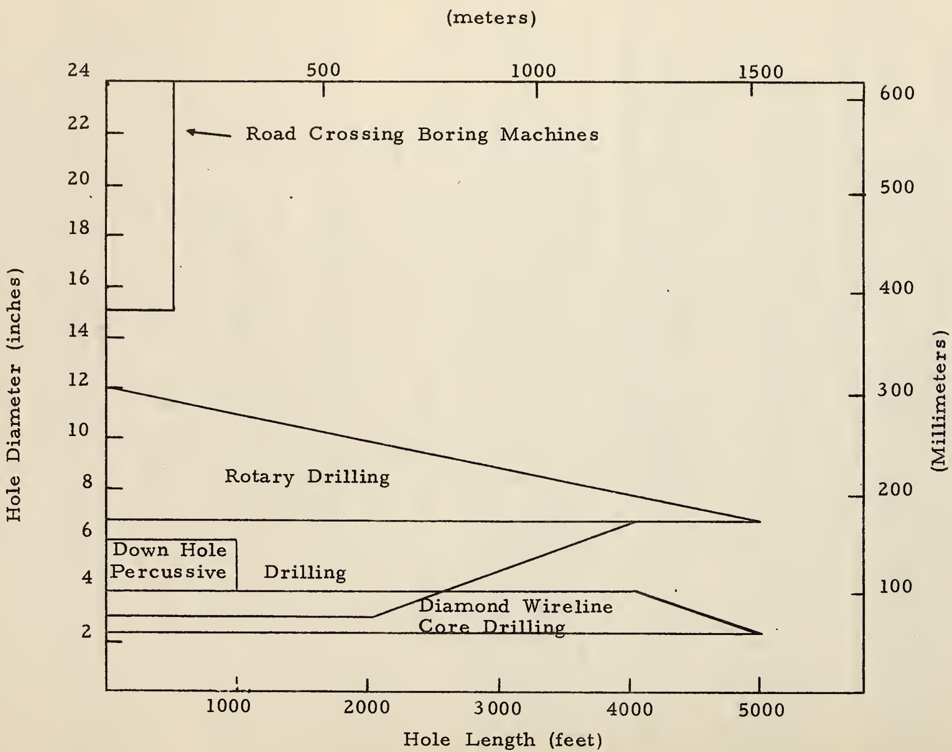


Figure 2.1 - State-of-the-Art Horizontal Penetration Capability

Of these, diamond wireline core drilling is far and away the most developed technique. Information on the cost and performance capabilities of the Koken FS-400 horizontal rotary drilling machine has been limited. It has been assumed that this machine would cost $100,000 for the purpose of exercising the rotary drilling cost model. Table 2.2 presents cost and time figures for the candidate drilling techniques for an "average" geological model. (11% soft rock, 59% medium rock, 30% hard rock.) For the non-coring techniques, a sample core is taken at 60 ft. (18.3 m) intervals.

Contractor estimates for a 5,000 foot (1524 m) hole drilled with diamond wireline coring equipment (the only technique for which contractor estimates are available) ranged from $50 to $100 per foot ($164 - $329 per meter). However, the concensus of contractors' opinions was that they would only undertake long horizontal drilling under a "time and materials" contractual arrangement.

It is clear that horizontal drilling is a substantially cheaper method of achieving penetrations along tunnel alignments than pilot tunneling. However, the state-of-the-art penetration capability of horizontal drilling is realistically about 5,000 feet (1524 m). Maximum hole diameter is limited to less than 11 inches (279 mm) for distances greater than 1000 feet (305 m).

2.3 Limiting Factors in Horizontal Drilling

In the broad sense, the most significant factor limiting the state-of-the-art of long horizontal drilling has been a lack of demand. It is frequently stated that long horizontal drilling is little used because it is expensive. It is much more accurate to conclude that horizontal drilling is expensive because the demand for it has not been sufficient to support the development of effective, economical techniques. In all probability, less than 10 horizontal holes have been drilled to 4000 ft (1219 m) and beyond. Contrast this with the petroleum drilling industry where an

TABLE 2.2 LONG HORIZONTAL DRILLING TIME AND COST ESTIMATES FOR AVERAGE GEOLOGY

Drilling Technique	Hole Diam. in (mm)	Coring Interval ft (m)	Distance, feet (meters) Time, Hours; Cost, \$/ft (\$/meter)				
			1000 (305)	2000 (710)	3000 (915)	4000 (1220)	5000 (1525)
Diamond Wireline	3 (76)	100%	275 32 (125)	712 38 (125)	1346 45 (148)	2161 53 (174)	3144 61 (200)
Rotary	6.75 (172)	60 (18)	224 55 (180)	554 60 (197)	1038 68 (223)	1708 77 (253)	2502 86 (282)
Down-Hole Motor	6.75 (172)	60 (18)	252 70 (230)	599 74 (243)	1106 80 (263)	1800 89 (292)	-
Down-Hole Percussive	6 (152)	60 (18)	217 48 (157)	-	-	-	-

estimated 3.4 billion dollars were spent in 1974 to drill 30,000 wells averaging 5,133 feet (1565 m) in depth.[6] Any technique as little used as horizontal drilling is likely to be expensive, even if the procedures involved are quite trivial.

However, the assumption is made that the demand for long horizontal drilling will increase substantially. Some of the factors which support this assumption are discussed in Section 1. 1.

In a more specific vein, the factors which limit the application of horizontal drilling can be broken down in terms of:

1.) Penetration capability.
2.) Hole guidance accuracy.
3.) Economics.

Factors which fall into the first category include the torque and thrust capabilities of existing surface equipment and the ability to transmit thrust and torque to the drilling bit. Only one piece of equipment has been designed to perform long horizontal rotary drilling and it is questionable whether this piece of equipment (Koken FS-400) is available in this country. The efficiency with which thrust and torque can be transmitted to the drilling bit are limited by drill pipe friction, a problem which is exacerbated by the buckling of the drill pipe. Downhole motors have not yet proven to be an economical solution to this problem in horizontal drilling.

Hole guidance accuracy is limited by the capabilities of <u>available</u> survey equipment and steering tools. At the present time there are no survey tools available which can stay with the drill bit while drilling horizontal holes and there are no devices available which allow the drill to be steered remotely from the surface.

Among the many factors which affect the economics of horizontal drilling are the excessive time required for guidance operations, drill rod handling, and, in core drilling, core retrieval operations.

There are, of course, other factors which limit horizontal drilling applications, but the above factors are particularly significant. Fortunately, equipment will soon be available to eliminate or reduce the effect of some factors. In some cases, equipment now used in other applications can be adapted for horizontal drilling or, if the demand is sufficient, experimental equipment can be made commercially available. Finally, and again if demand is sufficient, new equipment may be designed.

2.4 Extending Horizontal Drilling Capabilities

Raise boring machines have thrust and torque specifications which make them well suited for horizontal rotary drilling. With some modifications, these machines could function as effective horizontal rotary drilling machines.

Blast hole drilling rigs can be repackaged to function as horizontal drilling rigs. Schramm, Inc. of West Chester, Pa. has packaged standard blast hole drilling components into a configuration suitable for horizontal drilling. This approach could be followed with the equipment available from most blast hole drill manufacturers.

Drill pipe stabilizers which remain stationary while allowing the drill pipe to turn are used in petroleum drilling. This type of stabilizer could be adapted to rotary drilling as a means of controlling drill rod buckling while acting as a bearing between the drill pipe and hole. Stabilizers can be designed with an axial degree of freedom to reduce the effect of friction on thrust transmission.

Several manufacturers are pursuing programs to develop survey tools which can remain with the drill bit while drilling. Among the companies known to be financing development in this area are Shell Oil Co., Exxon, Ramond Precision (TELECO), and Gearhart Owen. Telcom, Inc. of McLean, Virginia has developed a cableless telemetry system which has been employed for horizontal drilling in coal. Sperry-Sun and Scientific Drilling Controls, Inc. have real time, wireline survey tools which are used in directional drilling. These devices could be made available for horizontal drilling if demand were sufficient.

Gyro tools are available to survey holes within ± 1 foot (.31 m) per 1,000 feet (305 m) drilled. At the present time, these devices are better suited to surveying completed holes than to serving as a reference device in guided drilling. However, with some modification, they might be adapted to the latter function.

A variable angle, remotely actuated steering tool is available for vertical drilling. (Dyna-Flex, Dyna-Drill Division of Smith International, Inc.) This tool might be adapted to horizontal drilling. At least one other remote steering tool has been designed and successfully operated on a proprietary horizontal drilling operation.

Rod handling machines, such as the experimental device developed by Jacobs Associates, are readily adaptable to horizontal drilling procedures and should result in substantial time and cost savings.

Double tube, reverse circulation, continuous coring methods have been used for horizontal drilling on the Seikan Tunnel Project. (1,470 feet (448 m).) This technique is particularly promising as a means of speeding up core drilling.

There is substantial potential for extending horizontal drilling capabilities in terms of increasing penetration capability and minimizing the deviation of the hole from the desired trajectory.

3. Planning Considerations

3.1 Background

Geological investigation of proposed tunnel locations is generally conducted in three phases. The initial phase is a geological reconnaissance using available maps, aerial photography, and, on occasion, radar or infrared scanning imagery. The purpose of this reconnaissance is to obtain a gross indication of geologic conditions as a guide in subsequent investigations. The second phase of investigation is directed toward determining the feasibility of a particular location. During this phase alternative tunnel alignments are evaluated based on a comparison of geologic conditions in the area of the proposed tunnel. Procedures may include core drilling and/or geophysical studies, and collection and laboratory examination of rock samples. Once a tunnel site has been selected, the investigation enters the third phase. Studies conducted in this stage are intended to assist in the final design and estimation of the costs of the tunnel. It is assumed that the employment of long horizontal penetration procedures would commonly be confined to the third phase of the investigation. This assumption is based primarily on economic considerations. Long horizontal penetration would undoubtedly be the most costly element of the investigation and would therefore be employed where the information gained would be of maximum benefit i.e. along the actual tunnel alignment.

3.2 Site Selection

Since long horizontal drilling would typically be employed after the tunnel route has been selected, the options available in selecting the drilling site will be limited. When there is a degree of flexibility in site selection, a primary consideration is to provide ample clearance behind the surface equipment so that drill rods can be handled in the maximum practical section length. The Jacobs Associates horizontal drilling program (item 18, Table 2.1) employed techniques to handle drill rod in 1,000 foot (305 m) sections, substantially decreasing the time required for drill rod handling. A second consideration in site selection is a ready supply of water for hole flushing.

3.3 Selection of a Drilling Method

The options available in selecting a state-of-the-art technique for horizontal drilling are limited. Long horizontal drilling is not a common procedure. In all probability less than 10 horizontal holes have been drilled beyond 4,000 ft. (1,219 m) in length. The drilling techniques which are defined as state-of-the-art include:

1.) Diamond wireline core drilling.
2.) Rotary drilling.
3.) Down-hole motor drilling.
4.) Down-hole percussive drilling.

However, the level of development of these techniques for horizontal drilling applications varies markedly.

Diamond wireline core drilling techniques have been employed most often in horizontal drilling. None the less, long horizontal drilling would represent an unusual job for any diamond drilling contractor. In terms of equipment capabilities, off-the-shelf diamond drilling rigs can be used for horizontal drilling, but the ratio of torque to thrust output for the rigs is not optimal for horizontal applications.

Long horizontal rotary drilling with rolling cutter bits has been confined to the Seikan Tunnel work (items 1 and 12, Table 2.1) and degasification holes in coal seams. (items 7, 15, and 17, Table 2.1) If rotary drilling is employed for a horizontal drilling project, a custom made surface rig will probably have to be employed.

Application of the down-hole motor to long horizontal drilling has commonly been limited to drilling direction changes.

In this application the utility of the down-hole motor is severely compromised by the lack of a "real time" survey tool for horizontal drilling. The use of the down-hole motor as the primary tool for advancing a horizontal hole is limited by a pricing strategy which is geared to an intermittent duty cycle. This pricing strategy is designed for the requirements of directional drilling in the petroleum field and its application to a straight hole drilling case causes the economics of down-hole motor drilling to become unattractive.

The Jacobs Associates horizontal drilling project has been the only attempt to apply down-hole percussive drilling to long horizontal drilling. (item 18, Table 2.1) This project did not address the problem of hole guidance. It is assumed that a down-hole motor could be employed to control the direction of a hole drilled with a down-hole percussive drill.

Any long horizontal drilling project will involve some degree of the development effort. In general, the amount of development effort necessary will be at a minimum for a project employing diamond wireline core drilling and at a maximum when down-hole percussive drilling is employed. The development necessary when employing either of the other two drilling techniques will fall somewhere between these extremes.

The above discussion of drilling method selection addresses the general problem of horizontal drilling in rock and gouge. For the specific case of horizontal drilling to investigate the geology along a proposed tunnel alignment, it is unlikely that any drilling technique, other than that of diamond wireline core drilling, will prove cost effective.

3.4 Drilling Costs

The economics of various drilling techniques in specific horizontal applications can be evaluated using the model presented in

Volume II of this report. Table 2.2 gives nominal estimates for planning purposes.

3.5 Site Preparation

In addition to the specific procedures described for the various drilling techniques elsewhere in this report, a concrete pad will be required to ensure that the surface rig employed is properly anchored. A second consideration is that the surface rig be aligned accurately in azimuth and elevation with the intended hole trajectory.

4. Management Considerations

In theory, the prospective horizontal drilling customer has two choices in conducting a horizontal drilling program. He can purchase the required equipment, and hire the personnel required to perform the job or, he can utilize a contractor to perform the job.

For any but the largest of horizontal drilling programs, the economics of the situation will favor contracting the work. The capital cost of the equipment, the scarcity of skilled personnel, and high utilization requirements are the major factors influencing the economics in favor of contracting.

There are several contractors with some experience in long horizontal drilling with diamond core drilling equipment. (See Appendix A) However, it should be noted that horizontal drilling jobs are the exception and they do not represent a substantial percentage of the contractors' work. Horizontal drilling by techniques other than diamond core drilling will probably still be contracted, but the customer will probably have to pay the capital cost for that equipment which is peculiar to the horizontal drilling job. As the overall demand for horizontal drilling increases, one would expect to see more contractors entering the field, and, with increased competition and higher equipment utilization, the economic factors should shift even more in favor of contracting the work. An increase in demand should also result in a greater willingness on the part of equipment manufacturers to invest time and money into development of new equipment and techniques.

4.1 Contracting Arrangements

If a decision is made to contract a horizontal drilling program, there are three basic formats which the contract may assume. The advantages and disadvantages of each type of contract are discussed briefly in the following paragraphs.

4.1.1 Lump Sum Contracts

The lumped sum contract calls for the completion of the hole at a fixed price or fixed price per foot. The specified price is to include all services and the contractor assumes all risks.

Typically, this will be the most expensive type of contract. Due to a general lack of detailed knowledge about the conditions which will be encountered while drilling, the contractor will need to base his estimated costs on the worst possible situation. As the quantity and quality of information about hole conditions increases, the risk factor will decrease and this type of contract should become less expensive. However, since the purpose of the hole is to aid in assessing ground conditions, this type of contract will probably remain the most expensive. The exception to this might be in the case of multiple, closely spaced horizontal holes.

The lump sum contract is seldom encountered in horizontal drilling.

4.1.2 Mutual Risk Contract

The mutual risk type of contract takes a form similar to the lump sum contract except that it provides certain escape clauses for the contractor. If no problems are encountered, the hole would be completed at a fixed cost or cost per foot. When problems arise, however, the escape clauses come into effect and the fixed cost per foot is supplemented by differing amounts depending on the problems encountered. Difficulties which might be covered by escape clauses could be exceptionally hard formations, unstable ground, excessive ground water, etc.

This type of contract tends to be less expensive than the lump sum type and requires less accurate data about ground conditions for realistic bidding. Mutual risk contracts are rare in horizontal drilling.

4.1.3 Time and Materials Contracts

In time and materials contracts, the contractor supplies all equipment, supplies, and manpower to perform the job, but assumes none of the risk. The total cost of the hole will depend heavily on exactly what difficulties, if any, are encountered.

This type of contract tends to be the least expensive of the three types and is preferred by most contractors.

4.2 Contract Drilling Costs

The cost of drilling horizontal holes is composed of four elements:

1.) Fixed costs,
2.) Variable costs,
3.) Indirect costs, and
4.) Risk factor.

Each of these factors contributes to the total cost and the elements of each are discussed below.

4.2.1 Fixed Costs

Fixed costs include all expenses which will be incurred regardless of the progress of the operation. These costs would be composed of such items as depreciation, payroll, supplies, insurance, etc. These costs will normally be lumped together as a daily cost for rig operation.

4.2.2 Variable Costs

Variable costs include those items which depend on the hole and drilling progress. Such items as drill rod, drilling fluid, grout, drill bits, etc. would be included under variable costs.

The better the information about hole and drilling conditions, the better the estimate of variable costs will be.

4.2.3 Indirect Costs

Indirect costs are unique to the contractor. These costs will include the overhead and general and administrative costs and are generally expressed as a percentage of the direct costs.

4.2.4 Risk Factor

The risk factor used by a contractor is based on a number of considerations. Among these are such things as experience on comparable jobs, knowledge of the drilling conditions at the site, risks to be assumed, and the competitive situation. In a lump sum contract, the risk factor may comprise the largest single expense.

5. Systems Analysis of Horizontal Drilling

The goal of Part II of this report is to describe and evaluate procedures to (1) drill a horizontal hole which will meet specified requirements and (2) to gather information on the material being drilled, In the following sections, the specifications for the candidate procedures are detailed, a functional analysis of the problem is conducted, and candidate methods are selected.

5.1 Hole Specifications

The horizontal drilling procedures described in this study should be capable of creating holes within the following specifications:

(a) Hole Dimensions - Hole diameters of 2-24 inches (51-610 mm) are to be considered. The maximum hole lengths obtainable with available techniques are evaluated within this range of diameters.

(b) Accuracy - Guidance procedures are to be employed to minimize deviation of the hole from the desired trajectory. Deviation must be limited to $\pm$ 30 ft (9.1 m) to ensure that the hole remains within the "area of interest" for investigation of the tunnel alignment.

(c) Material Drilled - Candidate drilling methods must be capable of penetrating soft, medium, and hard rock and gouge. For the purpose of this study, rock hardness is defined in terms of the unconstrained uniaxial compressive strength of the rock in the following manner:

Soft	$< 8{,}000$ psi (55.2×10^6 N/m^2)
Medium	8,000 - 22,000 psi
Hard	$> 22{,}000$ psi (151.7×10^6 N/m^2)

Gouge is made up of thoroughly crushed and comminuted rock formed by the grinding action which occurs through the movement of the adjacent walls of a fault. Gouge formed in the presence of water generally includes clay minerals and clay-size particles of other rock minerals. Gouge is found in large faults and minor subsidiary fractures. Normally gouge will deform plastically and under pressure it may squeeze into underground openings. For a more detailed discussion of gouge materials, see reference 7.

(d) <u>Hole Life</u> - The holes created by the prescribed procedures are required to remain open for up to one year. Metallic casing cannot be used to maintain the hole opening since it would interfere with some of the survey techniques which are being contemplated for the completed hole.

Procedures are evaluated for the following data gathering functions:

(a) Core drilling and retrieval.

(b) Undisturbed sampling and retraction from gouge.

(c) In situ measurement of water permeability and pressure.

5.2 Functional Description

5.2.1 Drilling the Hole

Any drilling system must perform certain functions to accomplish the task of drilling a hole. These functions are required whether the hole is to be vertical, angled, or horizontal. While hole orientation does not alter the list of functions which make up the drilling task, it does change the variables which must be dealt with in performing the function.

Drilling a hole along a specified trajectory involves four major functions:

1. Material disengagement

2. Transporting the disengaged material from the hole face (Chip removal)

3. Ensuring that the hole remains open after the material disengagement device has passed. (Hole stabilization)

4. Guiding the material disengagement device along the desired trajectory. (Guidance)

In the following sections these functions are defined in more detail.

5.2.1.1 Material Disengagement

Drilling systems are normally characterized in terms of the material disengagement technique which they employ (i. e., diamond drilling, percussive drilling, etc.). Material disengagement is the process of breaking down the material being penetrated. In conventional drilling techniques this involves breaking the material into a number of small pieces or chips.

Regardless of the technique employed, material disengagement requires the expenditure of energy at the tool rock interface. The efficiency of drilling techniques is evaluated on the basis of the amount of energy expended relative to the volume of material removed. The energy expended by conventional techniques is a function of the strength of the material drilled and the size of the chips produced. Once a chip is created, it must be removed from the tool/rock interface or it will be further divided or ground. This regrinding wastes energy and reduces penetration rates. Therefore, the second major function required in a drilling operation is chip removal.

5.2.1.2 Chip Removal

Chip removal normally involves two steps, (1) flushing the chips from the tool/rock interface and (2) transporting the chips out of the hole. This function is common to all conventional rock drilling techniques.

5.2.1.3 Hole Stabilization

Hole stabilization involves keeping the hole open during the drilling operation and for a period of time after drilling is completed.

5.2.1.4 Guidance

Guidance involves two distinct functions, defined as (1) survey and (2) steering. Survey procedures are used to establish the trajectory of an existing length of hole. Steering is in turn broken down into two functions, (a) maintaining the drilling assembly on the desired hole trajectory and (b) directing the drilling assembly to the desired trajectory when survey results indicate that a direction change is required. Drill string stabilizing procedures (not to be confused with hole stabilization procedures) are used to maintain a straight hole trajectory, deflection procedures are applied to make a discrete direction change, and variations of both procedures are used to drill a curved trajectory.

5.2.2 Information Gathering

Some geological information can be gathered by monitoring the drilling operation. Procedures for this are discussed in Section 5.3. Descriptions of the specific information gathering methodologies prescribed in Section 5.1 are presented in Section 6.

5.3 Procedures

5.3.1 Drilling the Hole

Figure 5.1 presents a flow diagram of a generalized procedure which applies to all conventional methods of drilling a horizontal hole. As indicated in the diagram, hole size, hole length, and the anticipated geology of the area to be drilled are primary considerations in selecting a drilling method.

Having selected a drilling method and obtained the necessary equipment, the drilling operation begins with the setting up of the equipment. (Mobilization) An initial length of hole is drilled and cased to provide a stable reference for subsequent drilling.

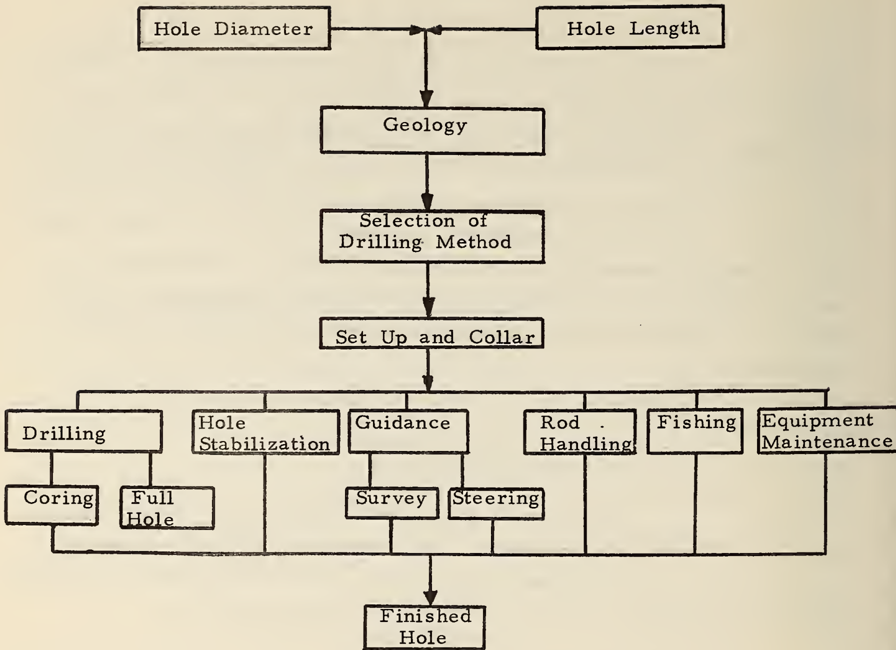


Figure 5.1 - Generalized Horizontal Drilling Procedure

The drilling operation is broken down in terms of the activities involved. Drilling includes the functions of material disengagement and chip removal. These functions, along with hole stabilization and guidance, have been described in Section 5.2.1. Rod handling includes adding sections to the drill string as the hole advances and removing and reinserting the entire drill string to (1) change worn drilling bits, (2) change from a coring mode to a full hole mode, and vice versa, (3) correct hole stability problems, (4) change the drilling assembly as a part of steering operations, and (5) perform fishing activities.

Fishing activities are required when a system failure occurs. Examples of such failures include, breaking the drill string ("twist off" etc.) and "sticking" the drill string. (An inability to turn the drill string or move it in or out of the hole.)

Equipment maintenance includes the preventative and corrective maintenance required for the equipment being employed.

5.3.2 Information Gathering

In Section 1.3 the type of geological information available prior to undertaking a horizontal penetration program is discussed. Geological mapping and surface investigations can determine rock types (relative percentages) and rock structure. Rock structure information can include attitude of beds in sedimentary formations, attitude of folds, attitude and dimension of faults, and attitude and frequency of fracture systems. This information base will be modified and added to by carefully monitoring the drilling operation.

A qualitative evaluation of the strength of the formation being drilled can be obtained by monitoring the relationship between the energy being applied to the drilling system (torque, thrust, etc.) and the resultant penetration rate.

The chips generated in the drilling operation can be retrieved and examined to determine what minerals the formation is made up of and to what degree, if any, alteration of the minerals has taken place.

The coring mode of drilling accomplishes the dual program objectives of creating a hole and gathering information simultaneously.

A loss of circulation of the fluid being used to flush rock debris from the hole gives an indication of formation porosity.

Hole stability problems or a lack of hole stability problems give an indication of the existence of formation weathering, fault zones, gouge zones, and a general indication of the competence of the formation. (Competent formations will support an opening without artificial support.)

The dip of the formation bedding planes and the presence of fault zones and other formation anolmalies can be inferred from their effect on hole trajectory.

Ground water conditions can also be determined during drilling operations by observing water outflow from the hole.

In summary, a great deal of geological information can be obtained by monitoring the drilling operation. Specific methodologies for the data gathering activities listed in Section 5.1 are described in Section 6.

5.4 Drilling Methods

5.4.1 Prior State-of-the-Art Studies

There have been four reviews and evaluations of the state-of-the-art of horizontal since 1968. However, only one of these studies considered the use of horizontal drilling as a geological investigation tool in planning and estimating tunnel construction.

Horizontal Boring Technology: A State-of-the-Art Study is a report on the state-of-the-art of horizontal boring technology for underground power transmission installations prepared by the Bureau of Mines at the request of the Department of the Interior.[8] This report has sections on rock penetrating methods and equipment and on borehole survey and guidance. Brief descriptions of capabilities, procedure, and available equipment are included. Figure 5.2 is from this report. This figure presents a graphical evaluation of the horizontal rock penetration capabilities of various drilling methods. The report is dated September 1968.

In 1972 Jacobs Associates of San Francisco conducted a program under the sponsorship of the Advanced Research Projects Agency on "Research In Long Hole Exploratory Drilling For Rapid Excavation Underground." The objective of this program was to develop a drilling technique to sample from a horizontal hole up to 1,000 ft. (305 m) in depth. It was anticipated that the "sample borer" would be employed in conjunction with a tunnel-boring machine during operation. This requirement dictated a drilling technique with a rapid penetration rate. It was further stipulated that only "moderately strong rock" and "high strength rock" were to be considered. The report defined rocks in this range as having uniaxial compressive strengths from 10,000 to 30,000 psi. (6.9×10^7 to 20.7×10^7 N/m^2) A Phase I report was issued in April of 1972 which was in essence an evaluation of techniques to determine which drilling methods should be employed

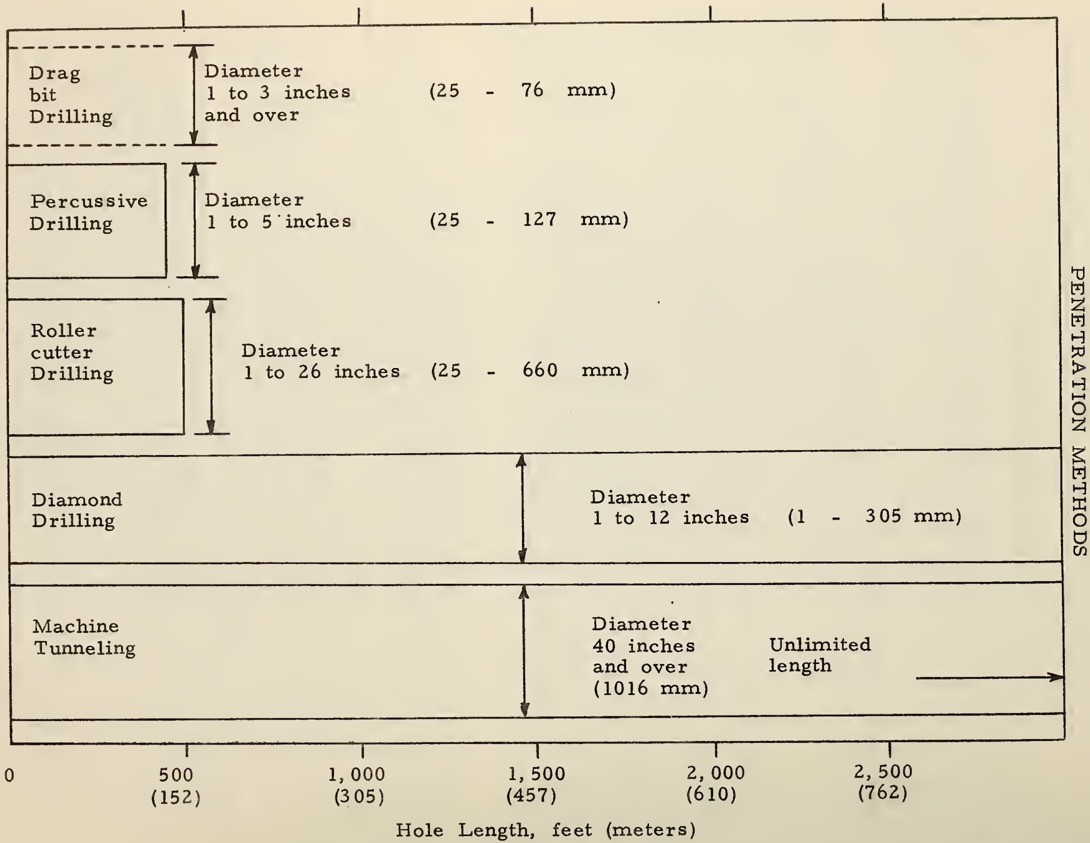


Figure 5.2 - Horizontal Rock Penetration from Horizontal Boring Technology; A State-of-the-Art Study, Paone, et. al., September 1968 [5]

in a subsequent field test program.[9] Rolling cutter bits, diamond wireling coring, and down-hole percussive drilling were recommended for the test program. The test results were presented in a Phase II report dated October 1972. A down-hole percussive technique with intermittent diamond coring was selected as the drilling method which came closest to meeting the program requirements. The longest hole drilled was 864 ft. (263 m) long and 4 inches (102 mm) in diameter. The results of this test are referenced elsewhere in this report with regard to the particular methodologies employed. Of particular interest is a novel method of handling 1,000 ft. (305 m) of drill rod at up to 200 fpm (1.01 m/sec) which was developed and tested during the program.

In March 1973 Fennix and Scisson, Inc. of Tulsa, Oklahoma reported on a Bureau of Mines contract on Advanced Techniques for Drilling 1,000 ft. Small Diameter Horizontal Holes in a Coal Seam.[11] The goal of this contract was to "demonstrate in the field the control devices and techniques applicable to drilling 3-inch diameter, horizontal holes with enough accuracy to stay within a coal seam and come within 30 ft. of a designated point at a depth of 1,000 ft."[11] There was no requirement for geological sampling. This report included a state-of-the-art review of drilling long horizontal holes, including discussions on equipment and methods. The longest hole drilled for this contract was a 1,102 ft. (336 m) long, 3.5 inch (89 mm) hole drilled with a rolling cutter bit and a custom built drilling rig. The results of the Fennis and Scisson work are referenced elsewhere in this report where they apply to particular methodologies.

The Bureau of Mines has continued research on horizontal drilling for coal degasification. The Bureau has now drilled horiztonal holes up to 2,126 ft. (648 m) in length. (As of Sept. 1975) A Bureau of Mines Report of Investigation titled, Rotary Drilling of Holes in Coal Beds for Degasification by Cervik, Fields, and Aul is expected to be published in October, 1975. This document is intended to serve as a detailed horizontal drilling handbook for rotary drilling in coal.

In a May 1974 report, Fennix and Scisson, Inc. presented the results of a study titled, Improved Subsurface Investigation for Highway Tunnel Design and Construction. Volume I. Subsurface Investigation System Planning.[4] This report has a section on Horizontal Long Hole Drilling which (1) reviews the state-of-the-art of long horizontal drilling, (2) compares horizontal penetration techniques, and (3) discusses the feasibility of drilling long horizontal holes. This report makes the following selection of "best potential systems:"

"The following are examples of rotary drilling assemblies that have been or could be used to drill long horizontal holes in soil and rock. To date, only assemblies A & B have been used to successfully directionally drill a straight horizontal hole longer than 3,000 feet and only assembly A has been used to drill a horizontal hole one mile long.

I. Existing Equipment and Technology Developed

A. Standard rotary non-coring assembly

1. Rotary bit designed for type and hardness of material to be penetrated.
2. Stabilization designed for maximum horizontal and vertical directional control.
3. Non-magnetic survey assembly.
4. Rigid drill pipe to surface.

B. Standard rotary wireline diamond coring assembly

1. Rotary diamond coring bit.
2. Wireline coring assembly.
3. Reaming shells and stabilizers designed for maximum vertical and horizontal directional control.
4. Non-magnetic survey assembly.
5. Rigid drill pipe to surface.

C. Continuous coring assembly

1. Rotary diamond coring bit.
2. Reaming shells and stabilizers designed for maximum vertical and horizontal directional control.
3. Non-magnetic survey assembly.
4. Rigid dual wall pipe to surface for continuous ejected core.

D. In-Hole Motor

1. Rotary bit designed for hardness of material to be penetrated.
2. In-hole, positive displacement mud motor with or without bent sub or bent housing.
3. Optional stabilization.
4. Non-magnetic survey assembly.
5. Rigid drill pipe to surface."[4]

5.4.2 State-of-the-Art Horizontal Drilling Methods

Specific criteria for evaluating candidate horizontal drilling methods are presented in Section 5.1. The general criterion of state-of-the-art is defined in the discussion which follows. Since the term state-of-the-art implies techniques which are available and proven, state-of-the-art horizontal drilling methodology is defined in terms of available production hardware and procedures which have been proven in horizontal drilling applications. Custom equipment, proprietary or government sponsored experimental equipment and the procedures associated with its use, and production equipment which has not been applied to horizontal drilling are not considered state-of-the-art. However, custom, experimental, and conceptual equipment and procedures, as well as the modification of available production equipment to function in horizontal drilling, will be discussed in relation to "next generation" drilling capabilities.

On the basis of the above criteria, the following techniques are considered state-of-the-art horizontal drilling methods:

(1) Diamond wireline core drilling.

(2) Rotary drilling (with rolling cutter bits)

(3) Down-hole motor drilling.

(4) Down-hole percussive drilling.

This list does not include several of the horizontal penetration techniques which have been proposed in prior studies. The reasons for this are as follows. Rotary drilling with drag bits, discussed in reference 8 (See Figure 5.2), is eliminated from consideration because drag bits are limited to applications in soils and soft rock. Machine tunneling, which is also evaluated in reference 8 (See Figure 5.2), is, of course, not a drilling technique and produces holes of far greater diameter than the sizes considered in this study. The continuous coring technique, suggested in the May 1974 Fennis and Scisson report, is not considered state-of-the-art because, as noted in that report, "so far as is known, this technique has not as yet been adapted to drilling horizontal holes."[4] Evidence of one such application has in fact been obtained (See Item 11, Table 2.1) but the details available on this work are too sketchy to support consideration of the technique as state-of-the-art horizontal drilling method. This technique is discussed in detail in Section 6 as a promising next generation drilling and information gathering method.

The four candidate drilling methods all fit the generalized flow diagram of Figure 5.1. However, only diamond wireline core drilling is able to create a hole and gather cores simultaneously. If one of the other three techniques is to be employed, and core samples are needed, the drilling assembly must be replaced by a coring assembly when cores are taken. This increases the amount of drill rod handling required for these techniques.

In the following section, horizontal drilling methodology is described in detail and the capabilities of the state-of-the-art of horizontal drilling are assessed.

6. Horizontal Drilling Methodology

6.1 Drilling Methods

6.1.1 Diamond Wireline Core Drilling

Diamond core drilling is an attritive material disengagement in which rock is ground away by abrasive action. The drill bit is made up of diamonds set in a matrix material. The bit cuts an annulus in the rock, leaving a central core which is collected in a core barrel as the bit advances. The core barrel is retrieved when it becomes full. The procedure is depicted in Figure 6.1 and Figures 6.2 thru 6.5 illustrate wireline drilling equipment.

There are in fact two methods of diamond core drilling. In conventional core drilling the core barrel is attached to the end of the drill string, requiring that the entire drill string be withdrawn from the hole to recover the core and install an empty core barrel. In wireline core drilling, the core barrels are pumped down the center of the drill string and retrieved on a wireline when they are full. Since wireline core drilling does not require that the drill string be pulled from the hole when cores are recovered it is clearly the preferred method for drilling long holes.

As noted previously, diamond core drilling is the only candidate drilling method which creates a hole and provides core samples simultaneously. There are full hole diamond bits, however, the full hole bits give lower penetration rates and higher bit costs than core bits of the same outside diameter.[9]

Diamond wireline core drilling is employed in both the mining and petroleum drilling fields. Wireline core drilling in the mining field involves complete drilling systems from surface rigs to bits.

In the petroleum industry, wireline core drilling is employed as a technique for obtaining intermittent core samples, from a hole which is being drilled primarily by rolling cutter bits. Wireline equipment for petroleum drilling includes bits and core barrels rather than complete drilling systems, and is made for much larger hole diameters than wireline equipment for mining applications. Generally, the two fields involve an entirely different list of equipment manufacturers and contractors. Christensen Diamond Products Co. of Salt Lake City, Utah is one of the few companies involved in both fields.

The discussion which follows applies to diamond wireline core drilling with what is generally termed mining or exploration equipment. Procedures applied to petroleum drilling are discussed in Section 6.6.

6.1.1.1 Operating Procedures

Diamond wireline core drilling procedures are illustrated schematically in Figure 6.1. The general procedural diagram of Figure 5.1 applies to wireline core drilling and all other conventional techniques. The drill must be aligned with a level or transit and firmly anchored in place. A concrete pad should be constructed to support the surface rig. An initial length of hole is drilled and cased to bedrock to provide a secure and accurate starting point and a stuffing box is attached to the casing to control the flow of the drilling fluid.

As the bit advances, the material disengaged by the bit is flushed from the hole. Water and drilling muds have been used for chip removal in horizontal wireline core drilling. The drilling fluid is pumped down the center of the drill string to the bit, where it washes the hole face and carries the rock debris out of the hole through the annular space between the hole wall and the outside of the drill rods. New sections of drill rod are added as the hole advances. When the hole has advanced far enough to fill the core barrel, a device called an over shot is pumped down the drill string where it latches on to the core barrel. The core barrel is then retrieved on a wireline attached to the overshot, and an empty core barrel is run down the drill string.

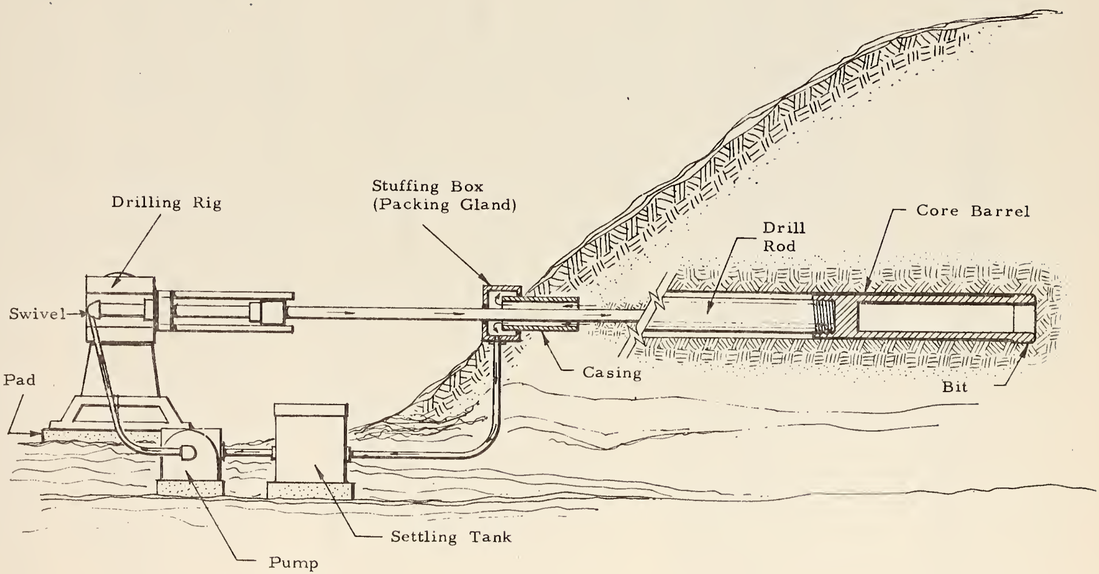


Figure 6.1 - Horizontal Diamond Wireline Core Drilling

The drill string is pulled from the hole to replace the bit when it becomes worn.

6.1.1.2 Equipment

A general equipment and materials list for diamond wireline core drilling is presented in Table 6.1. The following discussion describes the primary elements of the drilling system, namely, (1) the drill rig, (2) drill rod, (3) overshot and core barrel assemblies, and (4) bits. (Figures 6.2 thru 6.5)

Typical diamond core drilling rigs may be powered by gasoline or diesel engines, compressed air, or electric motors. The swivel head rotates 360^{o} and has either a manual or hydraulic (automatic) chuck. The drill rods pass thru the chuck and a water swivel is attached to the outboard end of the rod. This swivel is removed and reinstalled when drill rod sections are added. The drill string is gripped by the chuck, the chuck is driven forward by a pair of hydraulic cylinders, the chuck disengages from the rod and is retracted by the cylinders, and the cycle is repeated. A diamond drilling rig is illustrated in Figure 6.2.

A letter code designation is used to indicate compatible systems of down-hole wireline equipment. The first letter of the codes refers to the outside diameter of the hole produced by a given series. A table of hole outside diameters corresponding to the letter designation codes is presented in Table 6.2. The equipment discussion which follows will refer to equipment sizes by these letter designations.

Wireline drill rods are available in the A to P sizes and in 5, 10, and 20 foot (1.5, 3.1, 6.1 m) lengths. The newer designs used cold drawn seamless steel tubing for the rod body with alloy steel sections added at each end for the male (pin) and female (box) thread connections.

Table 6.1 - General Equipment and Materials List for Diamond Wireline Core Drilling

	Item Description
(a)	Drill
(b)	Circulating Pump
(c)	Supply pump
(d)	Hydraulic Ram
(e)	Generator and Lights
(f)	Mud Tanks
(g)	Mud Mixer
(h)	Core barrel assembly
(i)	Overshot assembly
(j)	Wireline
(k)	Drill rod
(l)	Outer core barrel tube
(m)	Inner core barrel tube
(n)	Survey instrument
(o)	Diamond core bits and reaming shells
(p)	Drilling mud
(q)	Grout

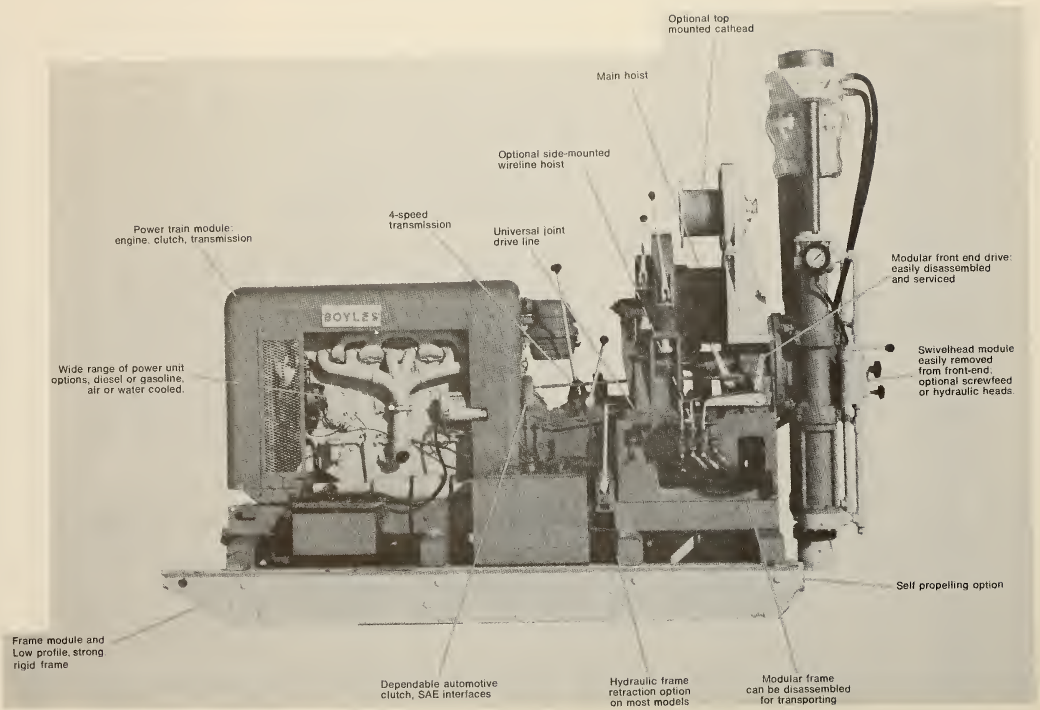


Figure 6.2 - Diamond Drilling Rig
(Courtesy, Boyles Diamond Drilling Equipment)

Table 6.2 - Diamond Core Drilling Hole Dimensions

Size	Hole Diameter	
	Inches	mm
R	1.175	29.8
E	1.485	37.7
A	1.890	48.0
B	2.360	60.0
N	2.980	75.7
H	3.782-3.907	96.0-99.2
P	4.827	122.6

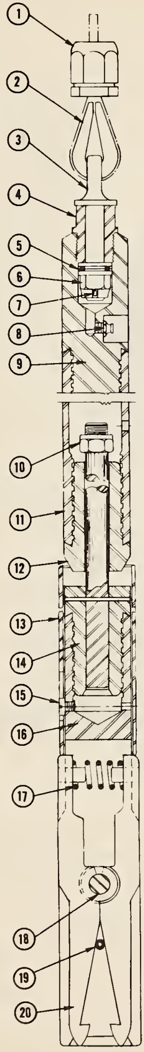
Wireline core barrels and overshots are available in the A thru P sizes. The core barrels come in 5, 10, 15, and 20 foot (1.5, 3.1, 4.6, 6.1 m) lengths. An N size overshot and core barrel are illustrated in Figures 6.3 and 6.4 respectively.

A diamond coring bit is illustrated in Figure 6.5. Most exploratory drilling and all long horizontal drilling has been done with bits in the A to N sizes. However, wireline bits up to P size are available. As noted previously, the bits used in petroleum applications are much larger, running to 12.25 inches (311 mm) outside diameter.

Diamond wireline drilling equipment manufacturers and drilling contractors are listed in Appendix A. Among the major U.S. equipment manufacturers are Acker Drill Company, Inc. and Sprague and Henwood Inc., both of Scranton, Pennsylvania, Boyles Operations of Ontario, Canada, Christensen Diamond Products of Salt Lake City, Utah, Joy Manufacturing Co. of Claremont, New Hampshire, and Longyear Company of Minneapolis, Minnesota. Among the contractors, Longyear Co., Boyles Bros. Drilling Co. of Salt Lake City, Utah, Reynolds Electrical and Engineering Co. of Las Vegas, Nevada, and Sprague and Henwood have experience in long horizontal core drilling.

6.1.1.3 Capabilities

Ideally, the horizontal penetration capability of diamond wireline core drilling could be determined by comparing bit thrust and torque requirements with surface rig thrust and torque outputs on the basis of the efficiency with which energy is transmitted from the rig to the bit. Unfortunately, data is not available on energy transmission efficiency in horizontal drilling and procedures have not been developed to calculate such data. Therefore, energy transmission efficiency must be inferred from case histories and educated guesses.



NQ Overshot Assembly

Item	Part Number	Name of Part	No. Req'd	Unit Wt. Lbs.	KG.
01-20	28033	Complete Overshot Assy		33.5	15.1
01	25987	Cable Clamp	1	*	*
02	25988	Wire Rope Thimble	1	*	*
03	25991	Eye Bolt	1	*	*
04	25990	Cable Swivel Collar	1	*	*
05	25986	Needle Thrust Bearing	1	*	*
06	25985	Castle Nut	1	*	*
07	Coml	Cotter Pin 3/32" X 3/4"	1	*	*
08	17447	Grease Fitting	1	*	*
09	27477	Body	1	2.1	.9
10	22917	Hex Stop Nut 1/2-13 Unc	1	*	*
11	20013	Jar Tube	1	17.7	8.0
12	14653	Jar Head	1	*	*
13	15965	Locking Sleeve	1	3.5	1.6
14	14654	Jar Staff Assy	1	2.5	1.1
	15371	For Spare Or Replacement Shear Pins	-	*	*
15	27747	Machine Screw 1/4-20 Unc 3/8 Lg	1	*	*
16	26608	Overshot Head	1	4.2	1.9
17	15373	Lifting Dog Spring	1	*	*
18	25980	Pivot Pin Lifting Dog	1	*	*
19	24307	Spring Pin 1/4" Dia X 2 In Lg	1	*	*
20	14651	Lifting Dog	2	1.0	.5

NQ-U Conversion Kit

* Weighs less than one pound (.45 kg)

** Use locking sleeve for lowering in dry holes only. It must be removed when hoisting inner tube.

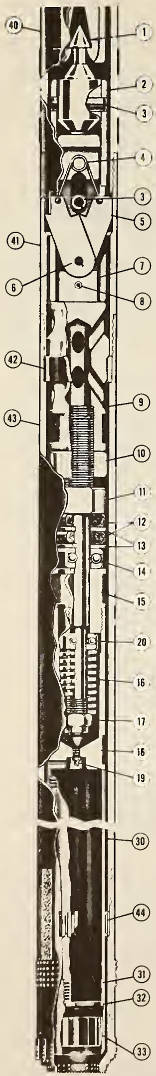
The NQ Core Barrel can be easily converted to an NQ-U Core Barrel by means of an NQ-U Conversion Kit. The Kit comes assembled, ready for installation. Only the ball check spring, ball, locking coupling and drive coupling come as separate components. Order kit part number:

*•26108 NQ-U Conversion Kit 24.8 11.3

* Note: NQ-U overshot must also be ordered for use with above kit. See page 16 Section I-A.

• Not generally carried in stock.

Figure 6.3 - NQ Overshot Assembly
(Courtesy, Acker Drill Company, Inc.)



NQ Wire Line

Item	Part Number	Name of Part	No. Req'd	Unit Wt. Lbs.	KG.
01-45	24907	Core Barrel Assy 5-Ft		95	43.0
01-45	24876	Core Barrel Assy 10-Ft		139	62.9
01-45	24911	Core Barrel Assy 15-Ft		183	82.9
01-33	24908	Inner Tube Assy 5-Ft		38	17.1
01-33	24877	Inner Tube Assy 10-Ft		47	21.4
01-33	24912	Inner Tube Assy 15-Ft		56	25.4
01-20	24878	Head Assy		21	9.5
01	24879	Spearhead	1	1.2	.6
02	24880	Case Latch Retracting	1	3.5	1.6
03	24305	Pin Spring 1/2 In Dia X 2 In Lg	2	*	*
04	24881	Spring	1	*	*
05	24882	Latch	2	*	*
06	24548	Pin Spring 1/2 In Dia X 1 1/2 In Lg	1	*	*
07	24883	Support Latch	1	*	*
08	22646	Pin Spring 1/4 In Dia X 1 1/2 In Lg	1	*	*
09	24884	Body Latch	1	6.1	2.8
10	24885	Nut Lock	1	*	*
11	24886	Spindle Assy	1	3.1	1.4
12	24887	Valve Shut-Off	2	*	*
13	24888	Washer Valve-Adjusting	2	*	*
14	24312	Bearing Ball Thrust	1	*	*
15	24889	Bearing Spindle	1	1.6	.7
16	24313	Spring Compression	1	*	*
17	24314	Nut Self-Locking	1	*	*
18	24890	Cap Inner Tube	1	3.2	1.5
19	17447	Grease Fitting Hydraulic	1	*	*
20	18298	Bearing Hanger	1	*	*
30	24909	Tube Inner 5-Ft	1	12.3	5.6
30	24891	Tube Inner 10-Ft	1	24.5	11.1
30	24913	Tube Inner 15-Ft	1	36.8	16.7
31	24892	Case Core Lifter	1	*	*
32	24893	Ring Stop	1	*	*
33	24894	Lifter Core	1	*	*
40	24895	Coupling Locking	1	5.8	2.6
41	24896	Coupling Adapter	1	3.6	1.6
42	24897	Ring Landing	1	*	*
43	24910	Tube Outer 5-Ft	1	44	20.0
43	24898	Tube Outer 10-Ft	1	79	35.9
43	24914	Tube Outer 15-Ft	1	114	51.8
44	24899	Stabilizer Inner Tube	1	*	*
45	24900	Protector Thread	1	4.0	1.8

OPTIONAL ACCESSORY EQUIPMENT AND TOOLS (not shown)

24315	Wrench 2 In Open-End	2	3.0	1.4
24901	Blank Reaming Shell NQ			

* Weighs less than one pound (.45 kg)

CHROME PLATING. Hardness is 9 Moh's scale. To order, add "CP" to Core Barrel part number and specify "chrome plated" with:

21372 OUTER TUBE. 18" (.46 m) an outer surface at both ends, 1/16" (1.6 mm) from each end, .004" (.1 mm) thick.

21833 INNER TUBE. Entire inner surface, .002" - .004" (.05-.1 mm) thick.

NQ-U Conversion Kit (See Reverse Side)

Figure 6.4 - NQ Wireline Core Barrel (Courtesy, Acker Drill Company, Inc.)

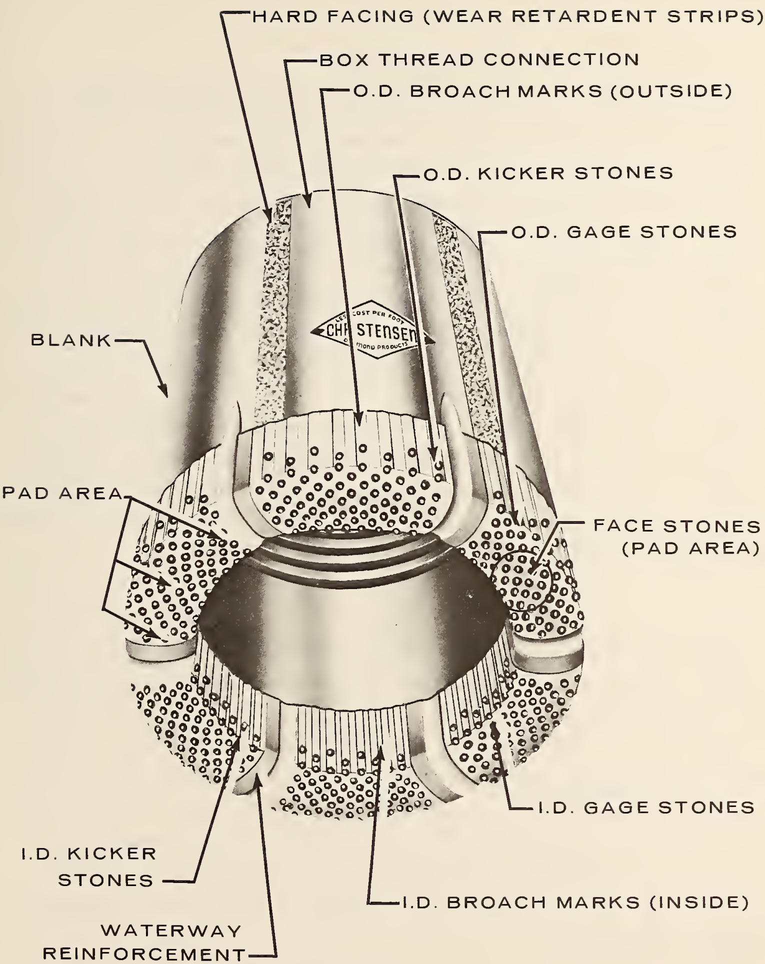


Figure 6.5 - Diamond Core Bit
(Courtesy, Christensen Diamond Products)

Nominal thrust requirements for diamond coring bits can be obtained from manufacturers' data[13] and corresponding torque requirements can be derived from analytical or empirical relationships. This has been done and the results are plotted as a function of bit size in Figures 6.6 and 6.7. Representative drill rig specifications have been obtained from manufacturers and are given in Table 6.3. Drill rig manufacturers are not consistant in terms of the specifications which they provide so some omissions are evident in this Table. Most of the listed rigs are available with a variety of power plant options so the table lists the maximum horsepower unit quoted in the company literature. The manufacturers do not list torque specifications for the rigs, therefore the figure in the table is derived from the maximum power plant output. This procedure can be expected to substantially overrate torque output. Torque is listed for 400 rpm which is a nominal recommended bit speed for N size bits.

The horizontal drilling being carried on by the AEC at the Mercury, Nevada test site (item 4, Table 2.1) is the only sustained, well documented program of horizontal diamond wireline core drilling which has been conducted. This work is being performed in very soft (1,500 - 2,000 psi compressive strength) formations. Horizontal wireline drilling in harder materials (items 2, 3, and 5; Table 2.1) has been privately funded and the data on this work is very limited. The Longyear 44 drill has been used to drill 4,000 foot horizontal holes (items 2 and 3, Table 2.1) and Longyear Co. personnel are of the opinion that the unit is capable of drilling to 5,000 feet horizontally in competent materials.[14]

The thrust necessary to move the drill string is proportional to f x w where:

f = effective coefficient of friction

w = effective drill string weight.

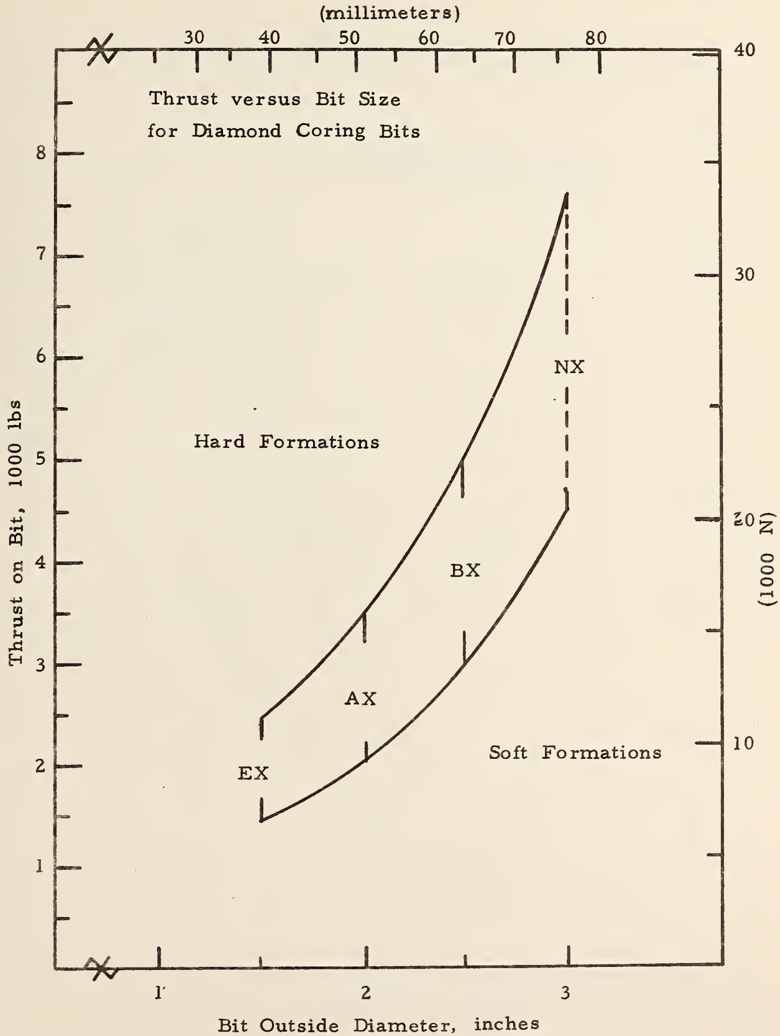


Figure 6.6 - Coring Bit Thrust Requirements

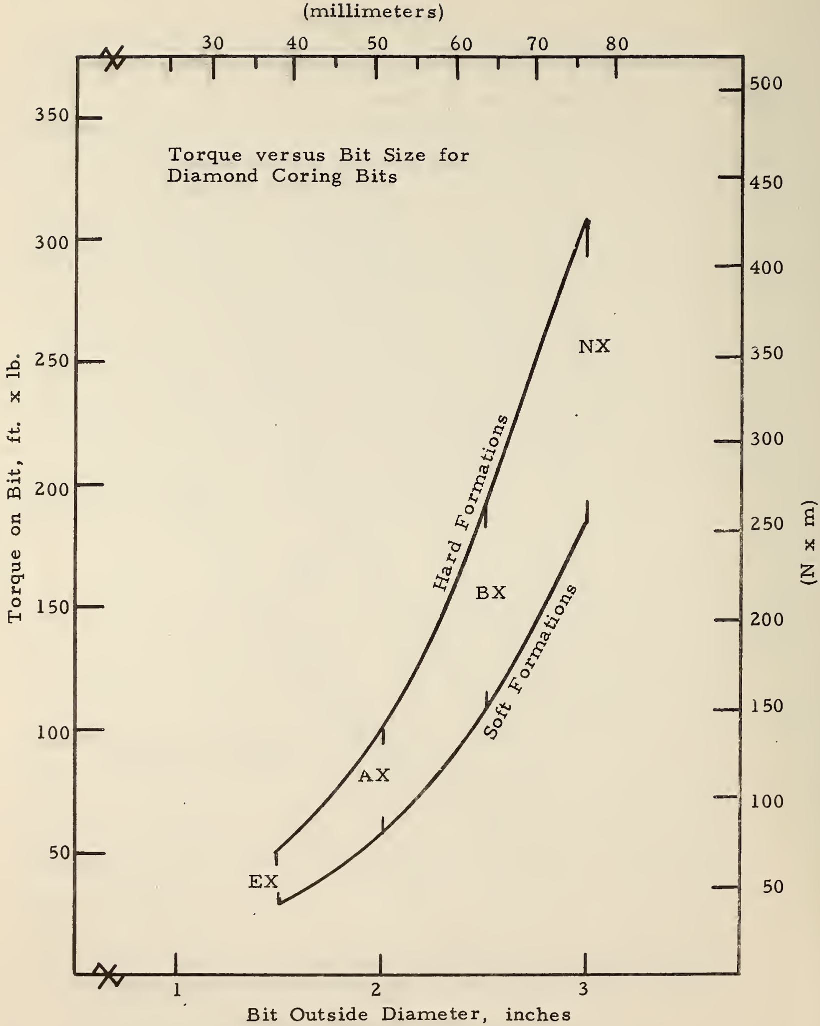


Figure 6.7 - Coring Bit Torque Requirements

Table 6.3 - Diamond Drilling Rig Specifications

Manufacturer	Acker	Boyles Operations	Joy	Longyear	Sprague & Henwood	Tigre Tierra	Tone
Model	Mark III Hillbilly	BBS-56	22-SHD	44	40 CL	Aardvark 125	TEL 2C
Power Unit	52.7 H.P. Gasoline	110 H.P. Gasoline	35 H.P. Gasoline	60 H.P. Diesel	33 H.P. Gasoline	121 H.P. Diesel	29 H.P. Electric
Thrust at 1,000 psi, lb (N)	15,700 (69,834)	-	16,780 (74,637)	≈22,000 (97,856)	16,800 (74,726)	5,000 (22,240)	-
Torque at 400 RPM, ft. lb. (N · m)	692 (938)	1,326 (1798)	565 (766)	788 (1069)	433 (587)	2,500 (3390)	387 (525)
Stroke, in. (mm)	24-36 (610-914)	24-40 (610-1016)	24, 30 (610, 762)	24 (610)	24 (610)	11 ft (3353)	-
Angle Range	360°	360°	360°	360°	360°	Horizontal	-
Dimensions:							
Length, in. (mm)	100 (2540)	-	140 (3556)	108 (2743)	104 (2642)	186 (4724)	-
Width	40 (1016)	-	54 (1372)	46 (1168)	46 (1168)	96 (2438)	-
Height	64 (1626)	-	-	66 (1676)	56 (1422)	72 (1829)	-
Weight, lb (N)	2,630 (11,698)	-	4,400 (19,571)	-	2,900 (12,899)	19,860 (88,471)	4,850 (21,573)
Mounting	Skid	Skid	Skid	Skid	Skid	Tracked	-

The torque required to turn the string is proportional to 0.5 D x f x w where D equals the hole diameter.

Figure 6.8 plots the ratio of thrust to torque output required to overcome drill string friction against hole size. The output ratios for the drill rigs listed in Table 6.3 are also included on the plot. This indicates that, for horizontal applications, available surface rigs are torque limited rather than thrust limited. If the rig torque outputs from Table 6.3 are compared with the drill rod data of Table 6.4, it is also clear that penetration capability is surface rig limited rather than drill string limited. This agrees with the assumptions of drilling contractors.[14]

If the manufacturer's assessment that the Longyear 44 machine is capable of drilling holes to 5,000 ft (1524 m) in the B size is accepted, then the capabilities of other machines can be inferred by comparing their output to the Longyear machine. This suggests that the Boyles BBS-56 machine is capable of drilling to 9,200 ft (2804 m). However, the total horizontal drilling task involves many more variables than surface rig torque output. Based upon available data and detailed interviews with drilling contractors and equipment manufacturers 5,000 ft (1,524 m) appears to be a reasonable assessment of the maximum penetration capability of state-of-the-art wireline core drilling equipment for a B size bit.

The lower limit on hole size is determined by the 1.75 inch (44.5 mm) outside diameter of available hole survey tools. These devices cannot be run in rods smaller than B size (1.8125 inch (46 mm) inside diameter). Diamond wireline drilling is not common in sizes above N, primarily due to cost considerations. Available equipment in the larger H and P sizes is limited and the equipment has not been applied to long horizontal drilling. Therefore, the N size should be considered the upper limit for diamond wireline core drilling.

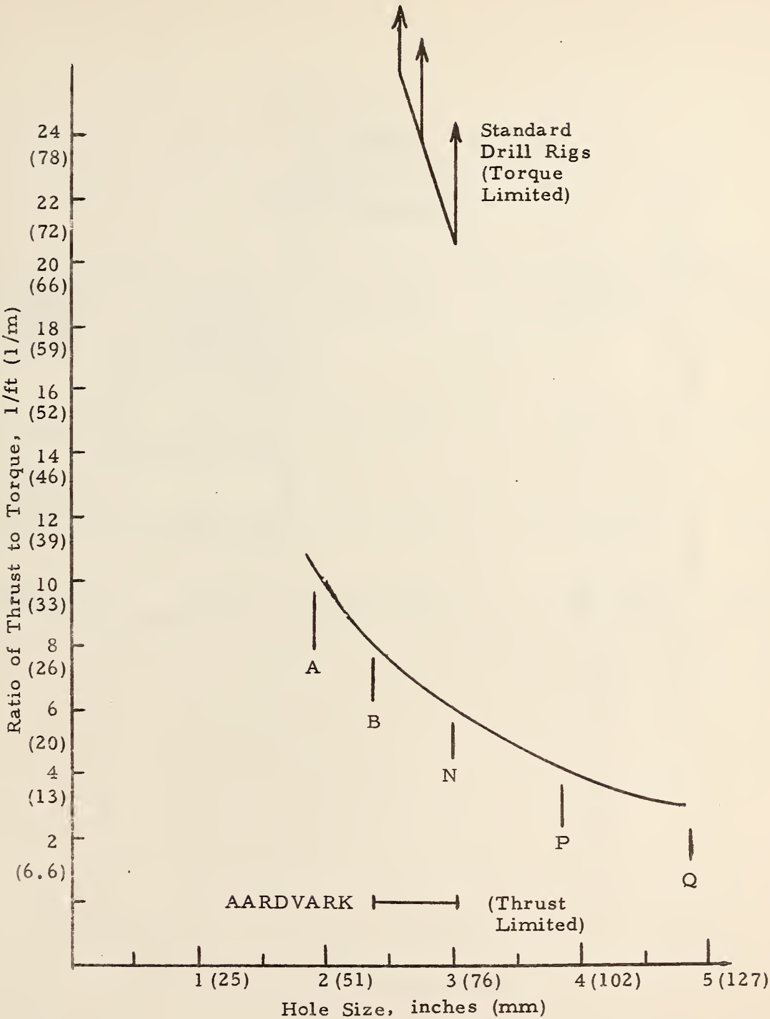


Figure 6.8 - Ratio of Thrust Friction to Torque Friction as a Function of Hole Size

TABLE 6.4

DRILL ROD DATA

Size	OD, in. (mm)	ID, in. (mm)	Minimum Yield Strength, psi (N/m^2)	Maximum Torque, Ft. lb. (N · m)
AQ	1.75 (44.5)	1.438 (36.5)	15,000 (103,425,000)	716 (971)
BQ	2.1875 (55.6)	1.875 (47.6)	15,000 (103,425,000)	1182 (1603)
NQ	2.75 (69.9)	2.4375 (61.9)	15,000 (103,425,000)	1954 (2650)

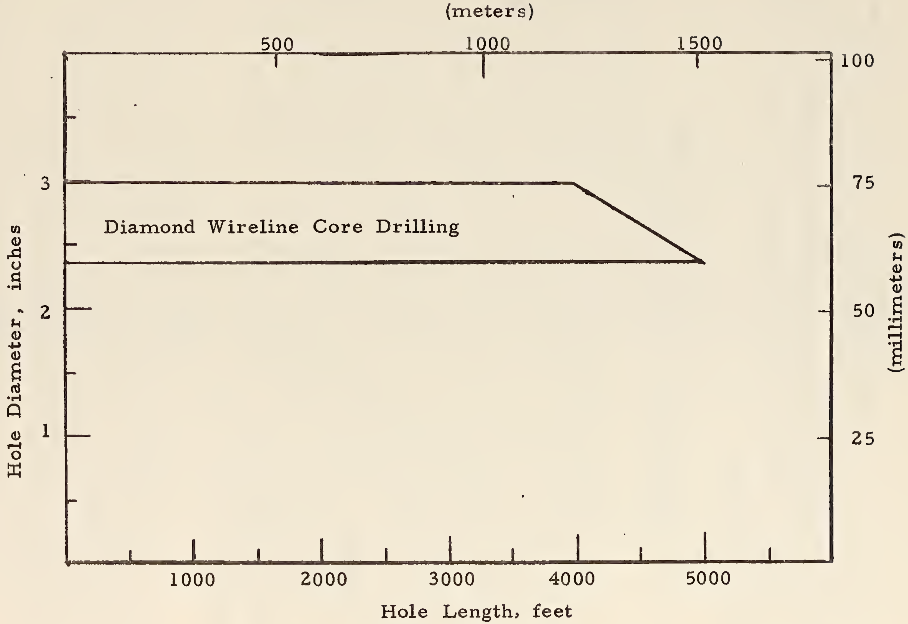


Figure 6.9 - Horizontal Diamond Wireline Coring Penetration Capability

State-of-the-art penetration capabilities are illustrated graphically in Figure 6.9. The penetration capability for the N size was determined from the simplified assumption energy transmission efficiency will be reduced in proportion to drill rod weight for a fixed drill rig output.

6.1.2 Rotary Drilling (Rolling Cutter Bits)

Rotary drilling techniques were developed primarily for drilling petroleum wells but they are now also widely used in blast-hole drilling. A typical rotary drilling setup for vertical drilling is illustrated in Figure 6.10. Note that the bit thrust is generated by the heavy collars which make up the drill string immediately above the bit. The drill collar weight exceeds bit thrust requirements so that the drill pipe portion of the drill string is always in tension. When rotary drilling techniques are applied to horizontal drilling two factors are immediately apparent. (See Figure 6.11.) First, the bit thrust must now be applied to the bit by the surface drilling unit and second, the entire drill string is now in compression. These two facts are the primary reasons that preclude "turning petroleum technology on its side", to drill long horizontal holes.

To apply rotary drilling techniques to horizontal drilling (1) drill rigs must be developed which have the capability of providing the necessary thrust forces to the drill string and (2) procedures and equipment must be developed to minimize drill string buckling. Very little work has been done in either area.

With rolling cutter bits, material disengagement is accomplished with a crushing action. Heavy thrust and continuous rotation are applied to the bit, causing the bit teeth to crush and fragment the rock. In similar materials, the thrust and torque

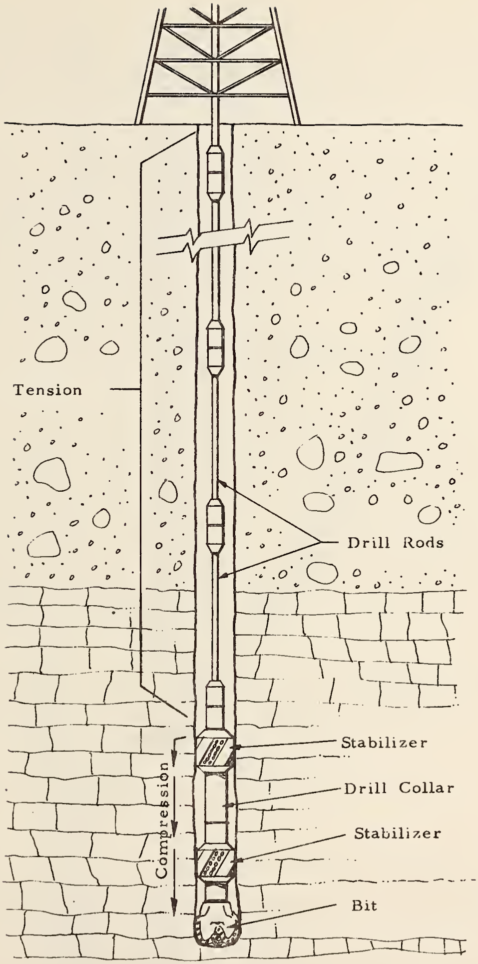


Figure 6.10 - Vertical Rotary Drilling

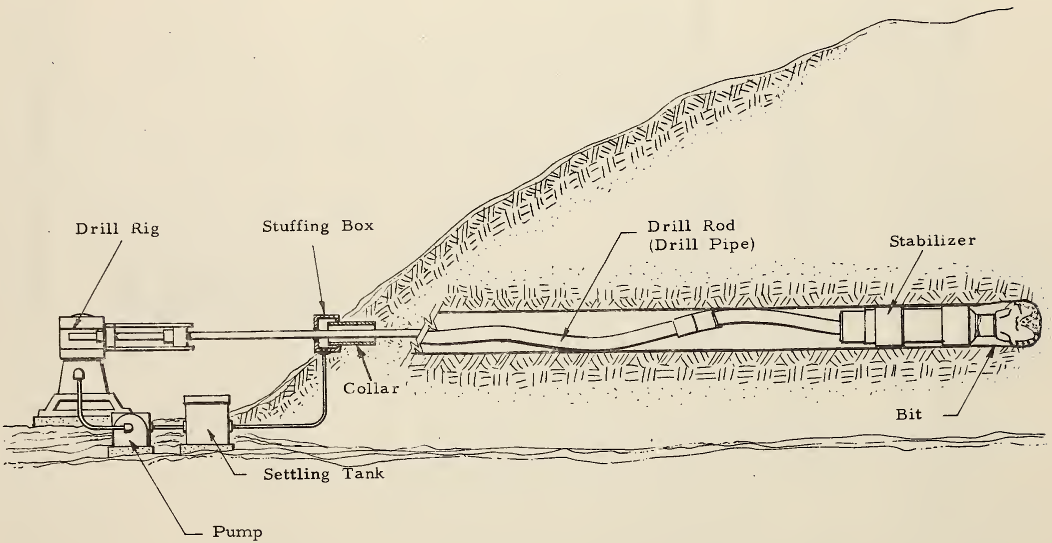


Figure 6.11 - Horizontal Rotary Drilling

required for rolling cutter bits far exceeds that required for diamond bits of the same diameter. Rolling cutter bits are available for materials ranging from very soft to very hard. (See Figures 6. 12 and 6. 13)

Rolling cutter bits are generally full hole bits. Some effort has been made to develop rolling cutter coring bits, but these efforts have been largely experimental and they have not been applied to horizontal drilling.[15] The use of rolling cutter bits for coring is discussed further in Section 6.6.

6.1.2.1 Operating Procedures

The procedures employed in horizontal rotary drilling are similar to the procedures employed in horizontal wireline core drilling. The only significant difference between the two techniques, in a procedural sense, is that rotary drilling does not include coring procedures. If coring is required in horizontal rotary drilling, diamond coring techniques must be employed for the length of hole where cores are needed.

Air, water, and drilling mud are used as chip removal fluids in vertical rotary drilling but water or drilling mud would be more likely in horizontal applications.

6.1.2.2 Equipment

An equipment and materials list for horizontal rotary drilling is presented in Table 6.5. The following discussion concerns drilling rigs and bits.

There is only one drilling rig made specifically for long horizontal rotary drilling. This unit is the Koken FS400 manufactured by Koken Boring Co., Ltd. of Tokyo, Japan.

Table 6.5 - General Equipment and Materials List for Horizontal Rotary Drilling

Item	Description
(a)	Drill
(b)	Survey collars
(c)	Circulating pump
(d)	Supply pump
(e)	Hydraulic Ram
(f)	Generator and Lights
(g)	Mud tanks
(h)	Mud mixer
(i)	Drill rod
(j)	Survey instrument
(k)	Rolling cutter bits
(l)	Drilling mud
(m)	Grout

Specifications for this unit are listed in Table 6.6. Two applications of the unit are listed in Table 2.1. (Items 1 and 12). Problems encountered in attempting to obtain detailed information on this rig suggest that it may not be readily available.

Horizontal rotary drilling in the United States has been limited to soft (coal) and very soft materials. (See Table 2.1.) Heavy duty diamond drilling rigs or custom made rigs have been used in most of this work. (Items 7, 15, and 17, Table 2.1.) None of these units have thrust and torque capabilities compatible with rotary drilling in harder materials.

Raise boring machines have been suggested as candidate drilling rigs for horizontal drilling rock.[16] Specifications for a Dresser Model 300 raise borer are included in Table 6.6. This unit is manufactured by the Mining Services and Equipment Division of Dresser Industries, Inc., Dallas, Texas. Other raise boring machine manufacturers are listed in Appendix I. Raise borers would require modification in order to be used as horizontal rotary drilling machines, and a development effort would be required in order to develop procedures for their use. However, they are strong candidates for "next generation" horizontal rotary drilling. Rotary blast hole drilling rigs can also be "repackaged" to perform as horizontal rotary drilling machines.

There is a class of equipment which has been developed for boring small utility tunnels beneath streets, highways, railways, and other structures where cut-and-cover techniques are not practical.[17] This equipment is used to bore in rock with boring heads which employ toothed rolling cutter bits. State-of-the-art efforts in this field have been limited to lengths under 500 ft (152 m) and diameters from 15 to 72 inches (381 - 1829 mm)[17] The equipment used in this field may also be adaptable for drilling long horizontal holes in smaller diameters.

Rolling cutter bits are available in diameters from 3.75 to 26 inches (95 - 660 mm).

Table 6.6 - Rotary Drilling Rig Specifications

Manufacturer	Koken Boring Machine	Dresser Industries
Model	FS-400	300
Power Unit	400 H. P. Electric	75 H. P. Electric
Thrust, lb (N)	88,000 (391,424)	90,000 (400,320)
Pull, lb (N)	110,000 (489,280)	180,000 (800,640)
Torque, ft-lb (N-m)	16,420 (22,266) 0-50 rpm	22,000 - 6565 (29,832 - 8902)
Stroke, ft (m)	18.4 (5.6)	0 RPM - 60 RPM
Angle Range	Horizontal	90° to 20° (90° ≡ Vertical)
Dimensions		
Height, ft (m)	6.2 (1.9)	9.4 (2.86)
Width	5.1 (1.6)	3.58 (1.09)
Length	35.9 (10.9)	9.83 (3.02)
Weight, lb (N)	28,600 (127,213)	15,300 (68,054)

Bits may be of the milled-tooth type (Figure 6.12) or the insert type (Figure 6.13) milled-tooth cutters are manufactured from heat-treated alloy steels in which rows of teeth have been cut from the outside of a cone. Milled-tooth cutters generally are limited to rocks in the soft to medium-hard range. The milled-tooth cutter is generally much cheaper than a comparable insert cutter.

Insert cutters consist of a series of tungsten carbide inserts pressed into a cutter cone. The greater operating life of the insert cutter can frequently give it an economic advantage over the milled tooth cutter, particularly in harder materials.

Rolling cutter bit manufacturers are listed in Appendix A. Listings of manufacturers supplying other rotary drilling supplies can be found by consulting the references noted in Appendix A.

6.1.2.3 Capabilities

In rotary drilling with rolling cutter bits, the requirement to be able to drill hard rock establishes a lower limit on hole size. The following observation was made concerning drilling hard rock with rolling cutter bits in the Jacobs Associates program:

"Drilling could not be accomplished in the hard rock at the Aromas site with the 4-1/4 in., three-cone steel tooth bit because it was impossible to apply sufficient thrust. The drill rig is limited to about 15,000 lb maximum thrust, as are most of the available small rotary rigs designed primarily for diamond drilling. There was no way to measure the net thrust achieved at the bit through the rather flexible drill rod. It is believed to have been less than half the minimum 20,000 lb required for this bit size in rotary drilling in hard rock. As a result of this it can be concluded that it will not be economical to design a drilling method using rolling cutter bits for

Figure 6.12 - Milled-Tooth Rolling Cutter Bit
(Courtesy, Hughes Tool Co.)

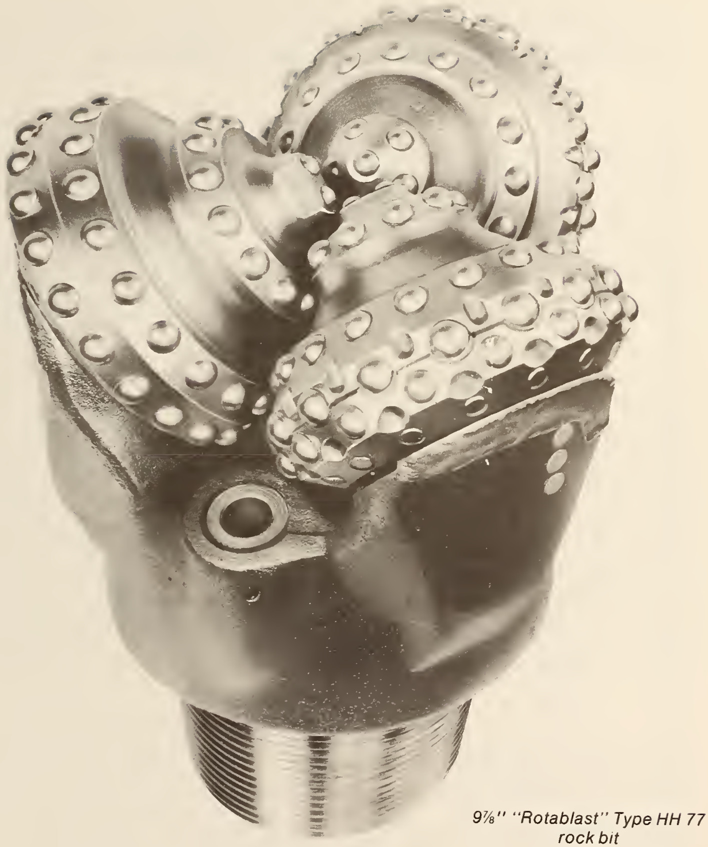


Figure 6.13 - Insert Rolling Cutter Bit
(Courtesy, Hughes Tool Co.)

horizontal holes more than 100 ft deep with a bit smaller than 7 in. Rods for smaller hole sizes will be too limber."[12]

In addition to the problem of drill rod stiffness noted above, the life of rolling cutter bits for hard rock is limited by the bearing capacity which can be built into the bits as size is decreased. Williamson reported a bit life of "several inches" in trying to drill hard abrasive rock with a 4.25 inch (108 mm) roller bit.[10] Typically, roller bits designed for hard rock are above 6 inches (152 mm) in diameter. For example, Hughes blast hole bit catalog does not list tungsten carbide bits below 6.75 inches (172 mm) in diameter.[18] The improvement in roller bit economy with size is evident in one reference which notes a 50 percent improvement in bit economy in going from a 6.25 inch (159 mm) diameter bit to a 9 inch (229 mm) diameter bit in blast hole applications.[9] In the petroleum industry the 7.875 (200 mm) and 8.5 inch (216 mm) diameter bit sizes are most common.[19] In this case the economies of smaller casing apparently outweigh the economies of larger bit sizes. In blast hole applications casing is not a requirement. In order to accommodate the range of rock strengths anticipated in drilling along tunnel alignments, a 6.75 inch (172 mm) diameter hole size is recommended as the minimum for horizontal rotary drilling.

The upper limit on hole size and the penetration capabilities of horizontal rotary drilling are limited by the available surface rigs. Nominal bit thrust and torque requirements for rolling cutter bits are presented in Figures 6.14 and 6.15. A comparison of the bit thrust requirements with the thrust output of the diamond drilling rigs listed in Table 6.3 indicates why diamond drilling rigs are not suitable as horizontal rotary drilling rigs for harder materials. In addition, the rotational speed and torque output of the diamond rigs are not suited to rolling cutter bits.

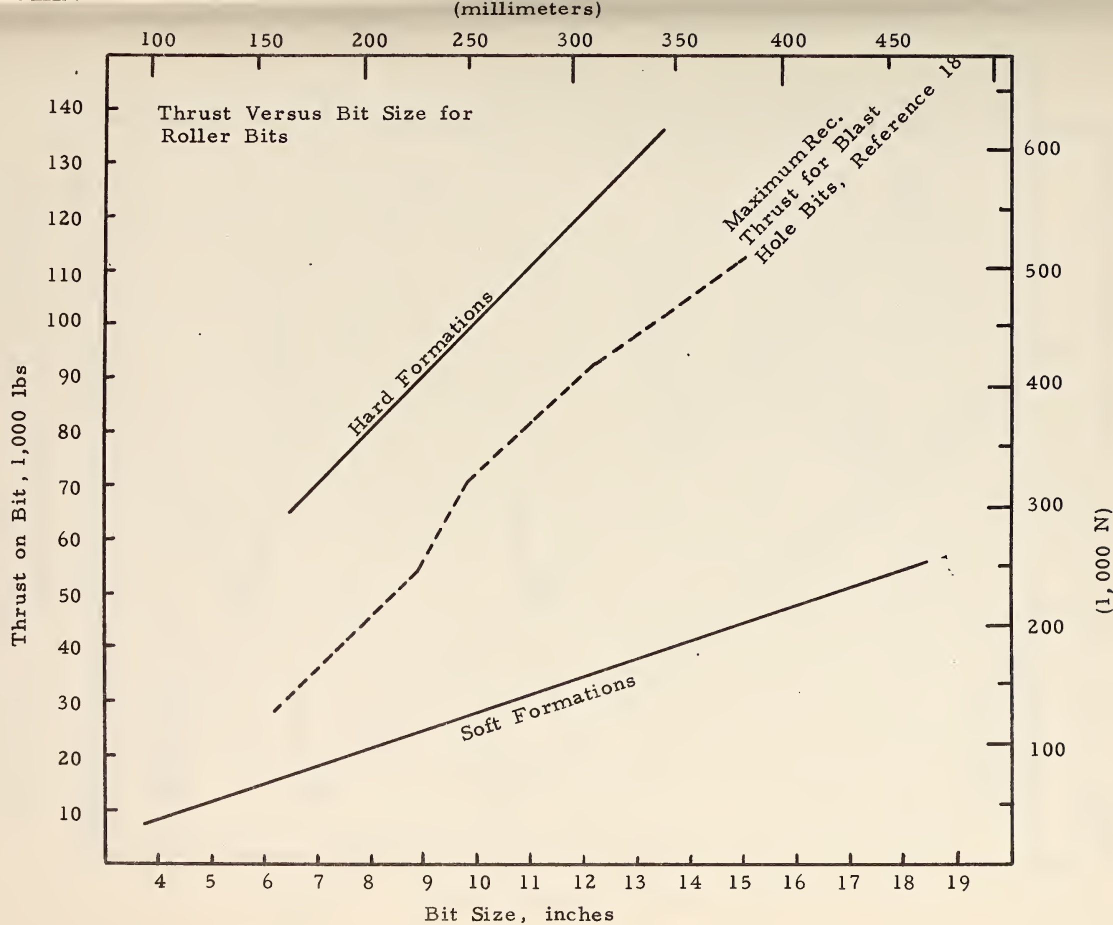


Figure 6.14 - Rolling Cutter Bit Thrust Requirements

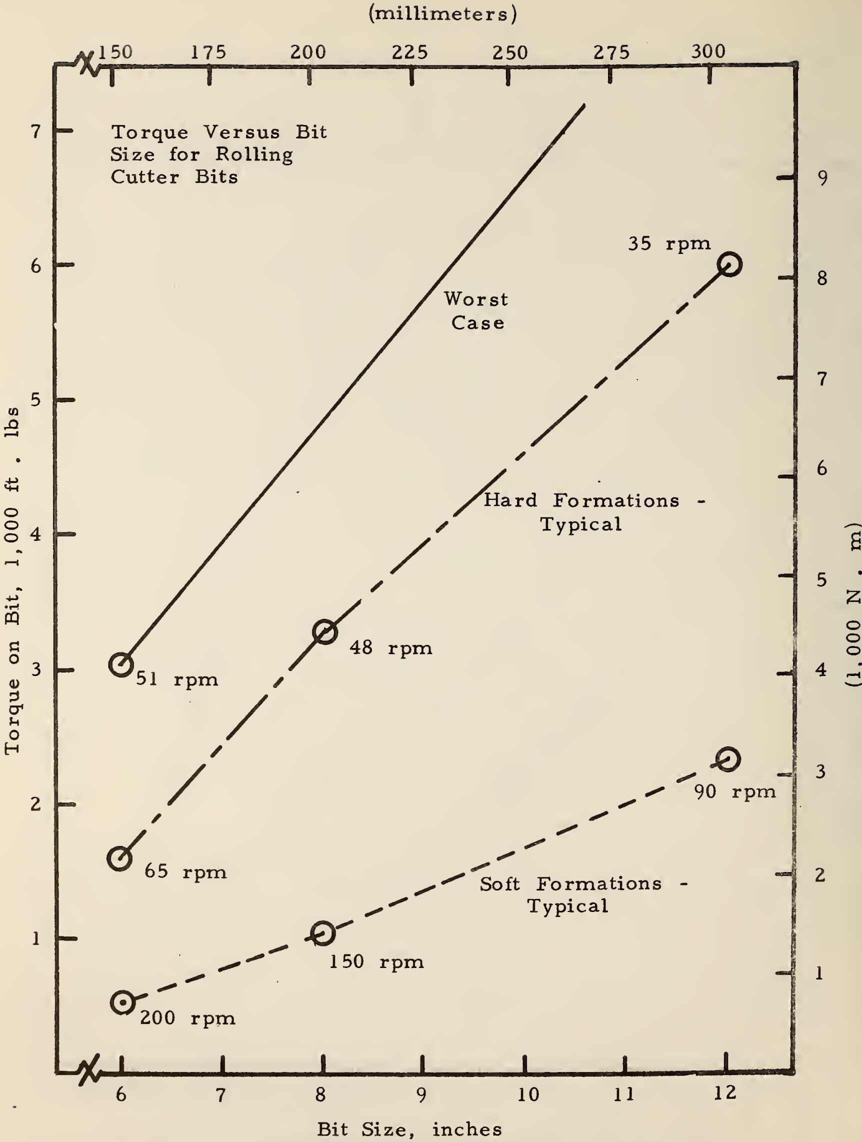


Figure 6.15 - Rolling Cutter Bit Torque Requirements

The performance parameters of the Koken rig (Table 6.6) are suited to the requirements of rolling cutter bits. However, as in the case of diamond core drilling, there is no data available on the efficiency at which the output of the drilling rig is transmitted to the drill bit in horizontal drilling. The Koken machine is rated by the manufacturer to have a horizontal penetration capability of 6,600 ft (2000 m) when applied to rotary drilling.[20] Available information indicates that the rig has been used to drill a 6.75 in. (171 mm) hole to 5,300 ft (1615 m) in soft materials.[4] The manufacturer's assessment of penetration capability appears quite optimistic for harder materials. For example, the Longyear 44 diamond drilling rig has a ratio of torque and thrust output to bit requirements of about 5:1 and 4:1 respectively, in hard materials and a proven horizontal penetration capability of 4,000 ft (1219 m). By contrast, the same ratios for the Koken machine with a 6.75 inch (172 mm) bit are about 3:1. On the other hand, since the stiffness of the drill string increases in proportion to the fourth power of the diameter, it could be possible that the larger diameter drill string used in rotary drilling is less subject to buckling and thus more efficient in transmitting energy to the bit. In any case, given the lack of solid data on the efficiency of energy transmission in horizontal drilling, an assessment of a 5,000 ft (1524 m) penetration capability for a 6.75 inch (172 mm) hole is made for the Koken machine. The maximum thrust output of the Koken machine corresponds to maximum nominal bit thrust requirement (dotted line, Figure 6.14) for a bit diameter of about 12 inches (305 mm). This is assumed to represent the zero penetration rate capability for the Koken machine. Penetration capability for rotary drilling in diameters above 6.75 inches (152 mm) is projected from this assumption.

The horizontal drilling capabilities of state-of-the-art rotary drilling equipment and procedures are presented graphically in Figure 6.16 along with the state-of-the-art capabilities of road crossing boring machines.

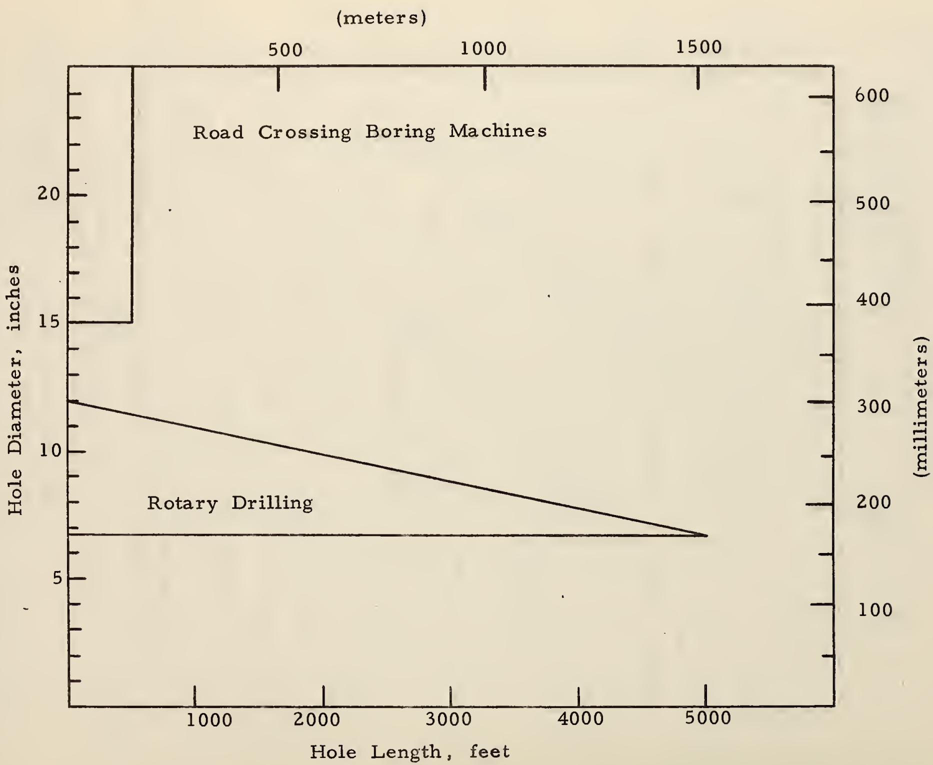


Figure 6.16 - Horizontal Rotary Drilling Penetration Capability

6.1.3 Down-Hole Percussive Drilling

In percussive drilling rock is fragmented by repetitive impaction. The impacts are provided by an air-driven piston or "hammer". Drills are designed to index the bit between impacts so that a fresh rock surface is struck with each blow.

Percussive drills are divided into two broad classes, drills for which the hammer remains at the surface and drills for which the hammer goes in the hole immediately behind the bit. Surface units lose effectiveness with hole length as the hammer impacts are attenuated by the drill string. This technique begins to lose effectiveness in holes beyond 100 feet (30.5 m) in length and would be essentially useless beyond 200 feet (61 m). The down-hole percussive drill is effective at longer distances and has been applied to horizontal drilling in a program conducted by Jacobs Associates of San Francisco, California.[10]

Percussive drills can drill soft, medium, and hard rocks, but they are most effective, relative to alternative techniques, in medium and hard rock. Air is blown down the center of the drill string to carry the rock debris from the hole through the annulus between the drill rods and the hole wall. A water and air mist is sometimes used for debris removal when drilling in sticky material. However, the effectiveness of percussive techniques is severely limited by the presence of ground water.

6.1.3.1 Operating Procedures

Procedures for horizontal drilling with down-hole percussive drills were developed and documented in the Jacobs Associates program referred to in the previous section. Figure 6.17, taken from the Jacobs report, indicates the equipment and procedures involved.

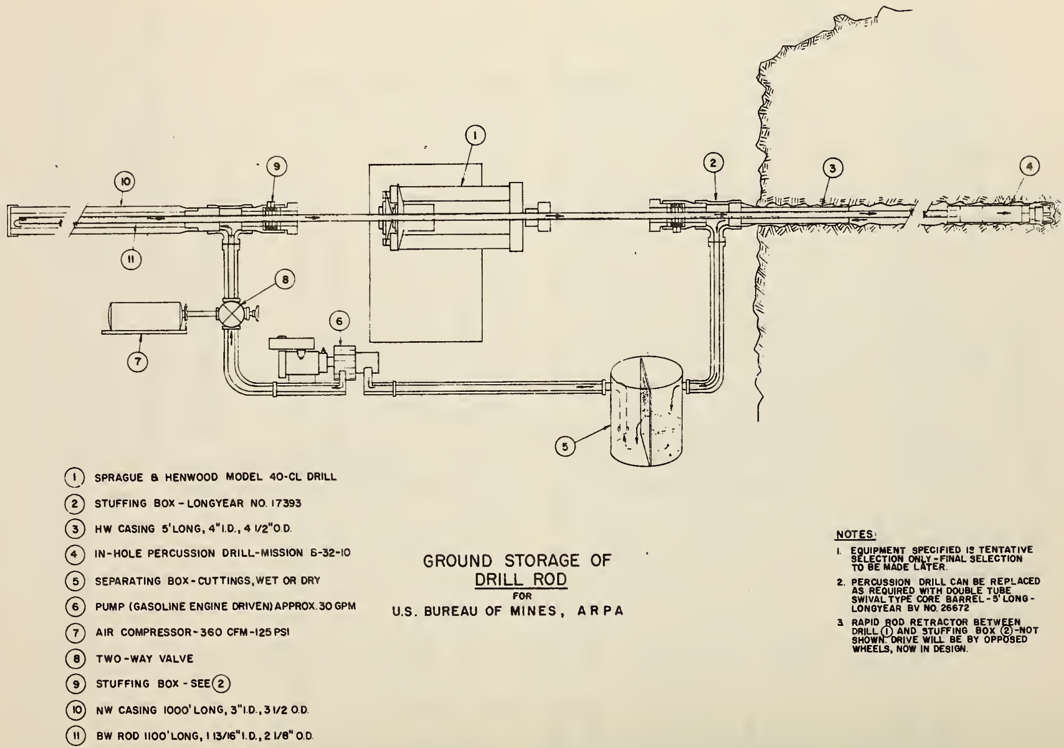


Figure 6.17 - Horizontal Down-Hole Percussive Drilling

A modified Sprague and Henwood 40 CL diamond drilling rig was used to rotate and thrust on the drill string. Minimal thrust and torque input are required since the energy required to drill the rock is being produced by an air compressor and transmitted to the bit pneumatically. The air which powers the down-hole drill also serves as the flushing fluid for chip removal. Figure 6.17 also shows the preassembled 1,100 ft (335 m) drill string and alternative wet flushing system used in the Jacobs program. This equipment allowed a rapid change to diamond coring procedures to obtain intermittent core samples. When core samples were required, (1) a rapid rod retractor was used to withdraw the drill string from the hole in a single piece, (2) the percussion drill was replaced with a double tube core barrel, (3) the rod retractor ran the drill string back into the hole, (4) water or drilling mud circulation was begun, and (5) core drilling operations commenced. After coring operations were completed, the procedure was reversed and percussive drilling was continued.

Apparently the only modification to the drill rig was the inclusion of a hydraulic drive unit between the engine and transmission. This allowed accurate torque figures to be computed and, in addition, provided a capability for stepless variation of rotational speed.

Presumably the procedures employed in the Jacobs program could be applied with any similarly modified diamond drilling rig, and any down-hole percussive drill capable of operating in a horizontal orientation.

6.1.3.2 Equipment

Down-hole percussive drills are available in outside diameters ranging from 3.5 to 9 inches (89 - 229 mm). A drill unit is illustrated in Figure 6.18. Rated air consumption values for down-hole drills vary from manufacturer to manufacturer, but Table 6.7 presents approximate values.[21]

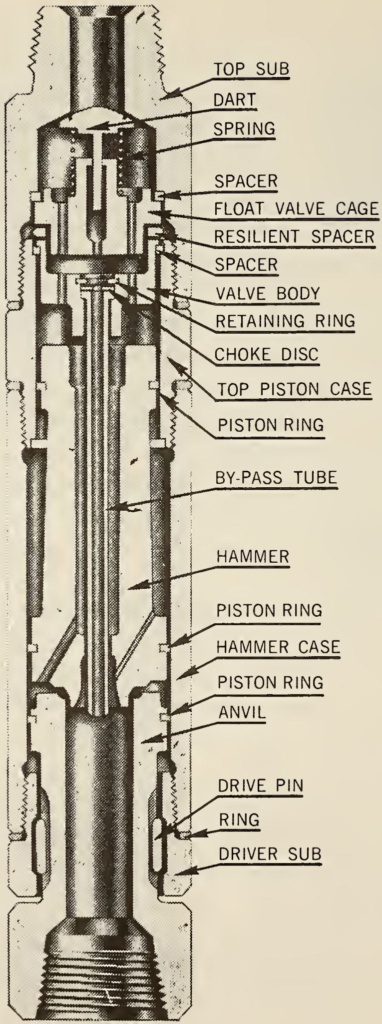


Figure 6.18 - Downhole Percussion Drill

Table 6.7 - Approximate Air Consumption for Down-Hole Percussion Drills
(Does not include chip removal requirements)

Hole Diam.	Drilling	
	ft^3/min	m^3/min
3-3.5 in (76-89 mm)	80	2.26
4 in (100 mm)	100	2.83
4.75-5 in (120-125 mm)	150	4.25
6.25 in (158 mm)	350	10.00
9 in (230 mm)	600	17.00

Bits for down-hole percussive drills are available in 4 to 12 inch (102 - 305 mm) diameters. Thrust requirements for down-hole bits are low with thrusts of less than 2,000 lbs (907 kg) being recommended for 6 - 7 inch (152 - 178 mm) bits.[18] A typical percussion bit is illustrated in Figure 6.19.

Down-hole percussive drill and bit manufacturers are listed in Appendix A. Jacobs Associates used drills made by Ingersoll-Rand and Mission Manufacturing Co. in their program.[10]

6.1.3.3 Capabilities

Down-hole percussive drills are not designed for horizontal drilling, they are designed primarily for blast hole drilling in vertical and near vertical applications. The Ingersoll Rand-Model DHD14 performed satisfactorily in horizontal drilling, as did a unit made by Mission Manufacturing, but there is no experience to indicate whether other drills will or will not perform in a satisfactory manner in horizontal applications.

The subject of drill guidance will be discussed in more detail in Section 6.4, but it should be noted that there was no attempt to perform guided horizontal drilling in the Jacobs program.

The capabilities of down-hole percussive drilling as a technique for drilling horizontal holes must be based on an assessment of the Jacobs Associates program since this program represents the only source of data on this technique. On this basis, down-hole percussive techniques are classified as being suitable for horizontal penetrations to 1,000 feet (305 m) in hole diameters from 4 to 6 inches (102 - 152 mm). Further development and testing are necessary to determine whether the entire range of available percussive drilling equipment is suitable for horizontal applications. The estimated horizontal drilling capabilities of this technique are presented graphically in Figure 6.20.

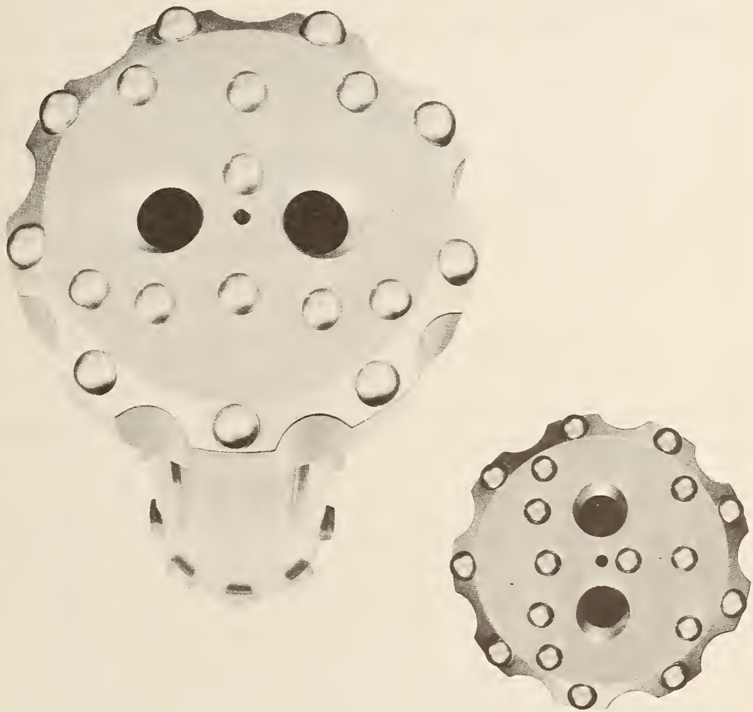


Figure 6.19 - Percussion Bit
(Courtesy, Hughes Tool Co.)

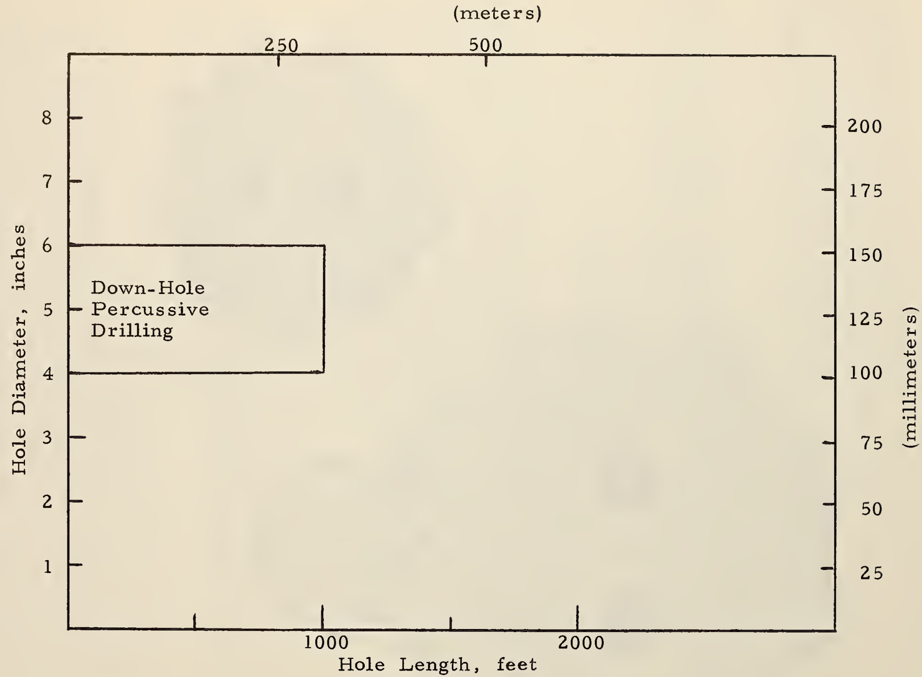


Figure 6.20 - Horizontal Down-Hole Percussive Drilling Penetration Capability

6.1.4 Down-Hole Motor Drilling

Down-hole motors do not represent a different class of material disengagement device but rather a different approach to providing torque to diamond or rolling cutter bits. Down-hole motors apply torque directly at the bit, whereas the diamond and rolling cutter techniques discussed in Sections 6.1.1 and 6.1.2 provide torque to the bit by rotating the drill string from the surface. Electric motors, turbines, and positive displacement mud motors have been used as down-hole motors. However, the positive displacement mud motor (Dyna-Drill) manufactured by Dyna-Drill Co., Long Beach, California appears to be the only down-hole motor device which has been successfully applied to long horizontal drilling.

6.1.4.1 Operating Procedures

Application of down-hole motors to hole straightening and hole deflection will be discussed in detail in Section 6.4.

In a straight or curved horizontal drilling application the Dyna-Drill can be used with practically any surface rig which is capable of providing the necessary thrust to the drill string. The Joy 22, Koken FS400 and several Longyear Co. machines have been used for horizontal drilling with the Dyna-Drill. (Items 1, 9, 10, 12, and 15; Table 2.1) The Dyna-Drill is driven hydraulically by a pump on the surface. Flow rate to the tool is adjusted to specified values and the thrust on the tool is adjusted until a pressure gage indicates that the recommended differential pressure exists across the motor. The pressure gage reading is directly related to the torque output of the motor. Increasing thrust will increase the pressure and torque and reducing thrust reduces both pressure and torque. Therefore, the rig pressure gage monitors motor performance and serves as a drilling thrust indicator. Recommended operating procedures for the Dyna-Drill and tables giving recommended flow rates, pressure drops, etc., for the various sizes are provided in the Dyna-Drill Handbook, 2nd Edition.[22]

6.1.4.2 Equipment

The Dyna-Drill may be used with full-hole diamond bits, rolling cutter bits, and, in softer materials, drag bits. The diamond and rolling cutter bit manufacturers listed in Appendix A provide bits which can be used with the Dyna-Drill.

Dyna-Drills are manufactured in 5, 6.5 and 7.75 inch (127, 165, 197 mm) sizes for directional drilling and 5, 6.5, 7.75 and 9.675 inch (127, 165, 197, 245 mm) outside diameter models for straight hole drilling. Micro-Slim Dyna-Drill tools are available in 1.75, 2.75, and 3.75 inch (45, 70, 95 mm) outside diameter models. The 1.75 inch (45 mm) size (3 inch (76 mm) hole typical) and 5 inch (127 mm) sizes (6.75 inch (172 mm) hole typical) have been used in the horizontal drilling applications referenced in the previous section. The Dyna-Drill is illustrated in Figure 6.21.

6.1.4.3 Capabilities

The Japanese envision the use of down-hole motor techniques to drill holes to 15,000 feet horizontally.[20] Both the Dyna-Drill and an electrically powered down-hole motor of Russian manufacture are reported to have been used in the Seikan Tunnel work.[23,24] The best available evidence indicates that in actual use the longest range application of these devices was the use of a 5 inch (127 mm) Dyna-Drill to control hole deflection between 3,325 feet (1013 m) and 3,895 feet (1187 m) in a 5,300 foot (1615 m) hole.[4] (Item 1, Table 2.1)

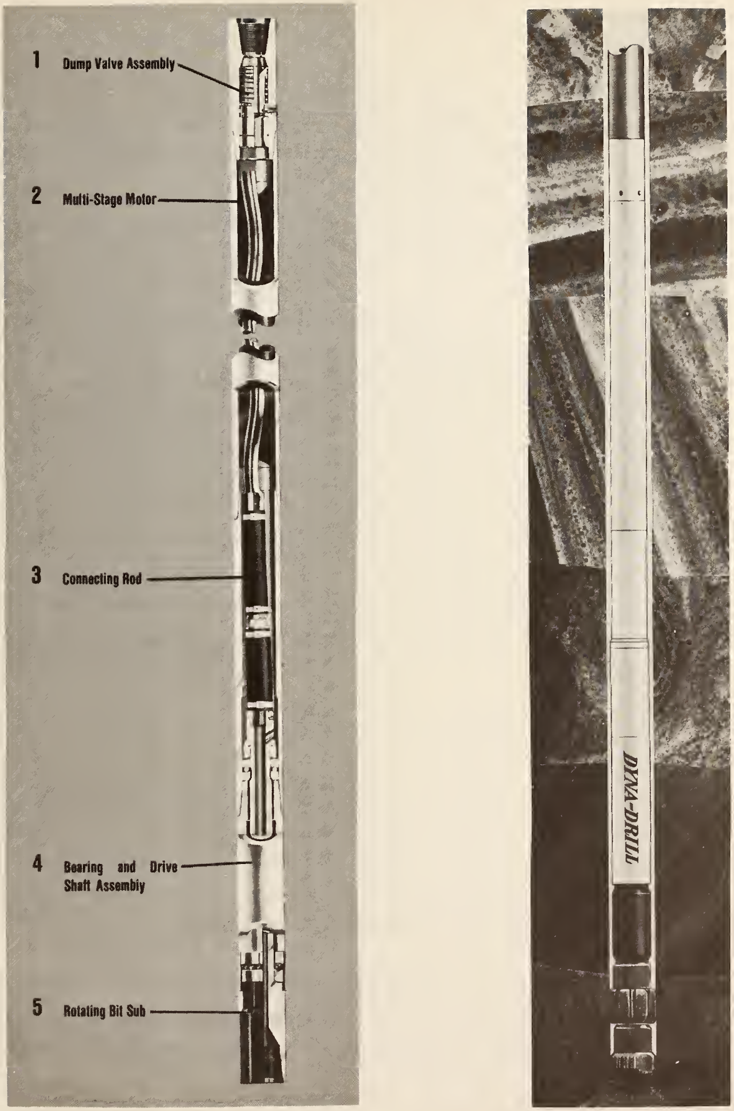


Figure 6.21 - The Dyna-Drill Positive Displacement Down-Hole Motor (Courtesy, Dyna-Drill Co.)

The 1.75 inch (44 mm) tool has been used to drill to approximately 1,600 feet (488 m) in soil and to 1,700 feet (518 m) in a hole which was started essentially vertically and then curved to a horizontal trajectory in a coal seam. (Items 9 and 10, Table 2.1) The 1.75 inch (45 mm) tool has also been used successfully as a steering tool for horizontal drilling in coal.[11, 25, 26]

In assessing the horizontal drilling capabilities of down-hole motor techniques, which in terms of the state-of-the-art comes down to Dyna-Drill capabilities, one is faced with a great deal of speculation and very little documented "real world" experience. This is true to a greater or lesser degree of all candidate horizontal drilling techniques. Keeping speculation to a minimum, the 1.75 inch (45 mm) tool can be considered a proven technique out to 2,000 feet (609 m) and the 5 inch (127 mm) device out to 4,000 feet (1,219 m). No down-hole motor device, other than the Dyna-Drill, can realistically be considered a state-of-the-art tool for horizontal drilling. This capability assessment is illustrated graphically in Figure 6.22.

6.1.5 Continuous Core Drilling

Continuous core drilling or continuous ejected coring is a drilling technique using reverse circulation of the drilling fluid with a drill pipe consisting of two concentric tubes. The drilling fluid enters the hole through the annulus between the two pipes and returns in the center pipe carrying the drill cuttings and/or cores.

Since the drilling fluid does not touch the hole wall, the technique is reputed to be very effective when drilling through loose, broken, or caving zones. Good recovery of weak, friable, or plastic cores is claimed.[4]

This technique may be used with diamond coring bits to allow continuous coring. (See Figure 6.23) The technique has

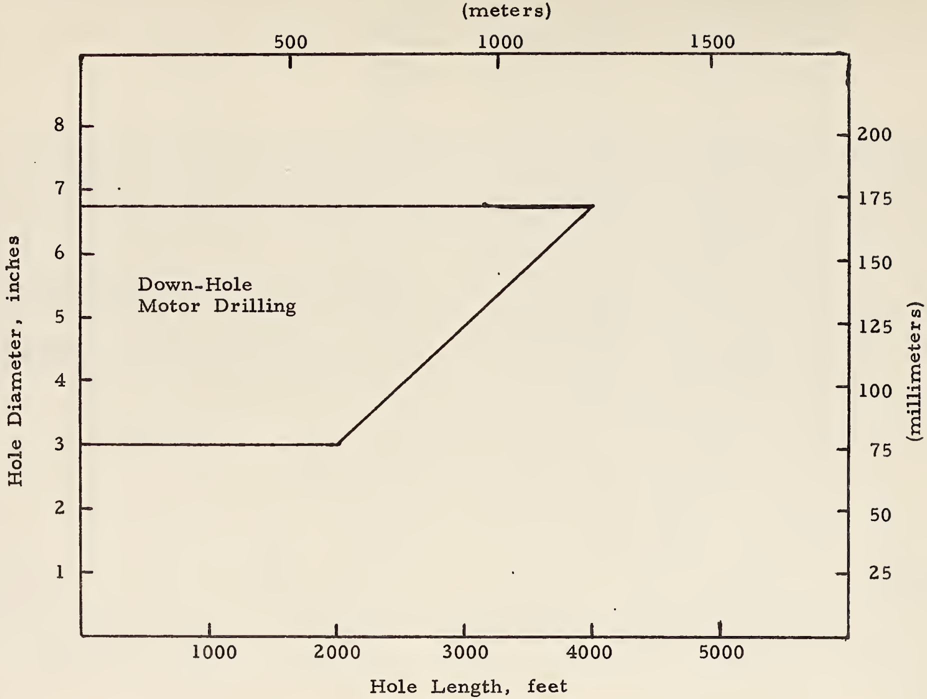


Figure 6.22 - Horizontal Down-Hole Motor Drilling Penetration Capability

the considerable advantage of allowing core to be taken continuously without interrupting the drilling operation.

The two tube technique can also be used as a technique to gather geological data with drag bits, roller bits, and even down-hole hammer techniques. (See Figure 6.24) Since the chips return up the center of the drill string and are not contaminated through contact with the hole wall or by material eroded from the hole wall, they are a source of geological data on the area being drilled.

Continuous coring drilling is a developed technique for vertical drilling but it has not been adapted to horizontal drilling. One instance of double tube, reverse circulation drilling has been noted on the Seikan Tunnel project (item 11, Table 2.1) but details on this work are not available.

Continuous core drilling is a strong "next generation" horizontal drilling candidate where core sampling is required along the entire length of the hole.

6.2 Chip Removal

Reference has been made previously to the importance of removing the rock debris or "chips" created by the material disengagement technique. Chip removal is accomplished by the use of a flushing fluid. The fluid may be air, water, or drilling "mud". Drilling mud is typically a colloidal suspension of bentonite in water combined to form a thixotropic fluid. Other additives may be included in the mud to achieve a particular set of properties.

In drilling a hole, the ideal fluid velocity is that velocity which is sufficient to pick up and carry away the largest particles created in the drilling operation, at the rate at which they are created.

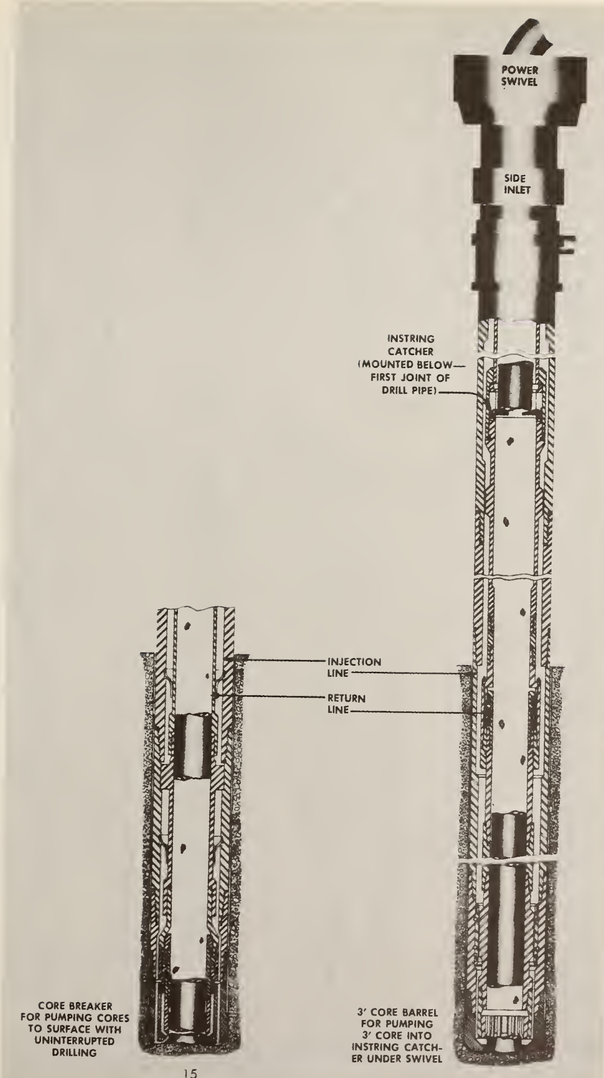


Figure 6.23 - Continuous Core Drilling
(Courtesy, Drilco Industrial Operations)

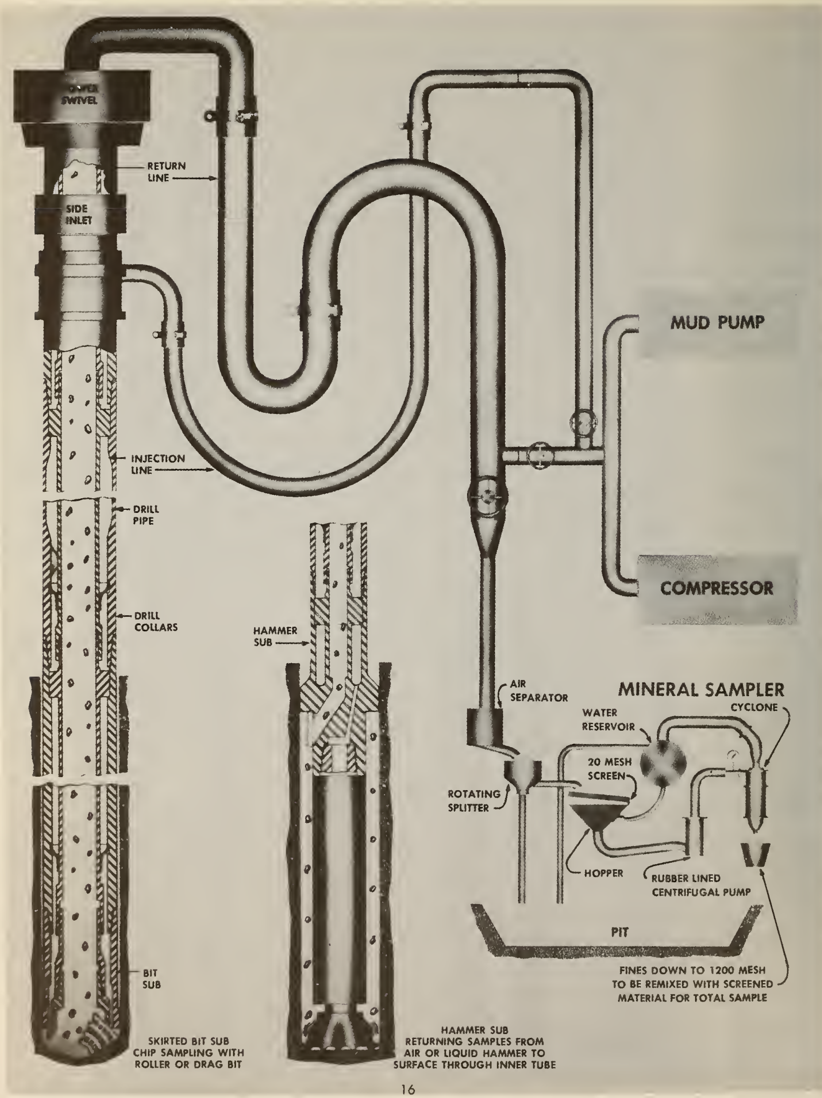


Figure 6.24 - Continuous Cuttings Sampling (Courtesy, Drilco Industrial Operations)

Lower velocities will leave chips in the hole where they will be further broken up by the drilling operation, wasting energy and slowing the bit penetration rate. Velocities higher than necessary may errode the sides of the hole, leading to hole stability problems.

A secondary function of the drilling fluid is to act as a bit coolant and lubricant. The cooling function is particularly important in diamond drilling where the interruption of fluid flow can lead to a "burnt" bit. Drilling mud is the best lubricant among the drilling fluids and materials are sometimes added to the drilling mud to further enhance its lubricating properties.

The generally accepted level of air velocity adequate for chip removal in a vertical hole is 3,000 ft/min (15.24 m/sec).[11,20] When drilling with water or mud, the accepted optimum velocity is 120 ft/min (0.61 m/sec).[21,27] A number of correlations for the minimum fluid velocity required for the horizontal transport of solids are available in the literature. These correlations are of an empirical or semi-theoretical nature. In general their use requires detailed information about the drilling - penetration rates, density of solids, chip size and size distribution, etc. they are complicated to calculate, and are predominantly for the transport of uniformly sized solids in smooth, round, non-rotating pipes. Even with these restrictions imposed, one finds variations of more than an order of magnitude in the predicted minimum transport velocity. The minimum velocities predicted for horizontal transport do tend to be higher than the velocities predicted for vertical transport.

There is very little data from which to develop fluid velocity rates for horizontal drilling. There are certainly no "accepted optimum velocities" as there are in vertical drilling. Based upon the experience of Jacobs Associates in pneumatic horizontal drilling, Williamson concluded that the optimum velocity for flushing horizontal holes with air is 7,000 ft/min (35.6 m/sec).[10] In horizontal coal drilling with water, Fenix and Scisson noted that, with a fluid volume flow rate of 25 gpm, "penetration rate was nearly maximum and hole cleaning was good."[11] This corresponds to a flow velocity of 145 ft/min. (0.74 m/sec) for the equipment used in this work. Based on the information available, the figure of 7,000 ft/min (35.6 m/sec) for air flushing and 150 ft/min. (0.76 m/sec) for liquid flushing represent a starting point from which to determine the equipment required for chip removal.

Once a flushing medium has been chosen, and the hole diameter and length and drill string size have been selected, the rule of thumb flushing velocity can be used to estimate volume flow rate and pressure drop. From these estimates, equipment can be selected.

The following sections present criteria for the selection of the flushing medium and estimates of required volume flow rates and pressure drops for pneumatic and hydraulic flushing of horizontal holes.

6.2.1 Selection of a Flushing Fluid

Selection of the flushing fluid is the first step in determining equipment requirements for chip removal in horizontal drilling. This section presents general considerations as well as current practice and specific recommendations for each of the four candidate drilling techniques.

Of the three flushing fluids under consideration, air is generally termed the best scavanger, water the best coolant, and mud the best lubricant.[21] However, there are other factors which can dictate the choice of a flushing medium. If there is a water shortage in the drilling area, air flushing may be the only alternative available. On the other hand, when drilling below the water table or in any situation where water inflow is encountered, water or mud may have to be used.

In petroleum drilling and some deep diamond drilling, drilling mud is the preferred drilling fluid for several reasons. Some of the most significant are; (a) the ability of mud to seal "lost circulation" zones, (b) the lubricating properties of mud with respect to increasing bit performance and reducing friction between the drill string and hole wall, (c) the thixotropic nature of mud which keeps the chips in suspension and prevents them from settling to the bottom of the hole when drilling is interrupted, and (d) the ability of mud to prevent collapse of the hole. (Control hole stabilization) Items (a), (b), and (d) are significant in horizontal drilling, but item (c) is not particularly important. The application of drilling mud to hole stabilization problems is discussed in detail in Section 6.3, while the frequently related problem of lost circulation is covered in Section 6.2.3. In general, the need for control of lost circulation, hole stabilization, and lubrication of the drill pipe to hole interface favor the use of water or drilling mud as a flushing fluid in long horizontal drilling. Current practices and specific recommendations for each of the candidate drilling techniques are discussed in the following paragraphs.

Diamond core drilling conducted in competent rock has usually been conducted using water as the flushing medium. (Items 2, 3, 4, and 5, Table 2.1) In cases where lost circulation and hole stability problems have been encountered, drilling mud has been used. (Items 6 and 11, Table 1.1) These procedures represent logical recommendations for horizontal drilling with diamond wireline equipment.

In horizontal rotary drilling the Japanese have used drilling mud for drilling in the soft, broken materials encountered in the Seikan Tunnel work. (Items 1 and 12, Table 1.1) Horizontal rotary drilling in this country has been conducted using water as the flushing fluid. (Items 14, 15, 17, Table 1.1) Generally the flushing fluid recommendation for horizontal drilling are the same as for wireline core drilling, water should be satisfactory when drilling competent rock if no circulation problems are encountered, and drilling mud is recommended to control lost circulation and hole stability problems.

The recommended chip removal procedures for downhole motor drilling are the same as those recommended for diamond wireline core drilling and rotary drilling. It is particularly important to minimize the free solids content in the drilling fluid when drilling with fluid powered downhole motors. Dyna-Drill recommends that sand content be held to an absolute minimum with less than 1% recommended.[22] Sand accelerates bearing and motor element wear in fluid driven downhole motors.

Pneumatic flushing must be used with down hole percussive drilling. Water injection into the air flushing stream may be employed to enable percussive drilling to be utilized in slightly wet or "sticky" formations. One part of water per 1,000 parts of free air is used.[21] The requirement that air flushing be used with percussive drilling limits the application of this technique to competent rock.

6.2.2 Hydraulic Chip Removal

As indicated earlier, the recommended velocity for hydraulic flushing of horizontal holes is 150 ft/min. (0.61 m/sec.) The left hand vertical axis of Figure 6.25 gives liquid flow rates in gallons per minute (GPM) for various hole diameters and standard drill rod sizes. Figure 6.26 gives estimated pressure drops for different hole diameters and drill rod sizes. These pressure drop estimates were arrived at by assuming a friction factor, f, of 0.005.

Liquid volume flow rates are obtained from Figure 6.25 by entering the horizontal axis at the value for the hole diameter. This point is followed vertically to the appropriate line for drill rod size and then horizontally to the left hand vertical axis where the flow rate in GPM is obtained. For example, a 5'' (127 mm) diameter hole with NW drill rod will require approximately 111 GPM (420 LPM of water or mud. Estimated pressure drops are obtained in a similar fashion from Figure 6.26. The right hand side of the horizontal axis is entered at the appropriate drill rod size. This point is followed vertically to the correct hole diameter

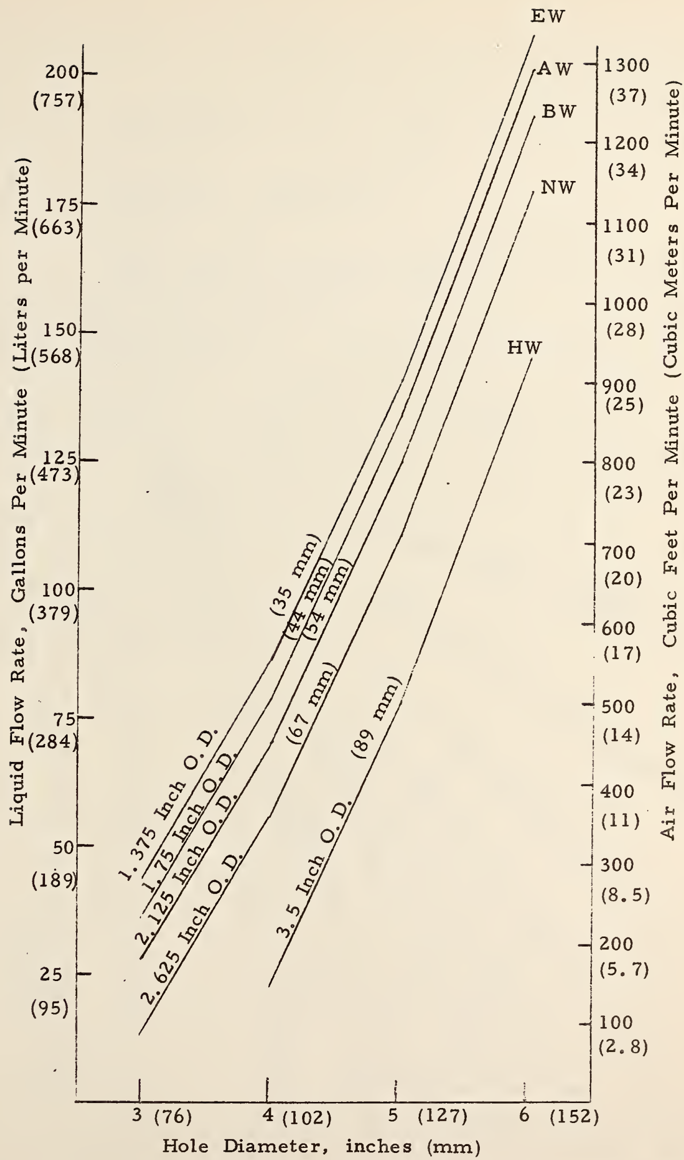


Figure 6.25 - Flushing Fluid Flow Rate Versus Hole Diameter For Various Drill Rod Sizes

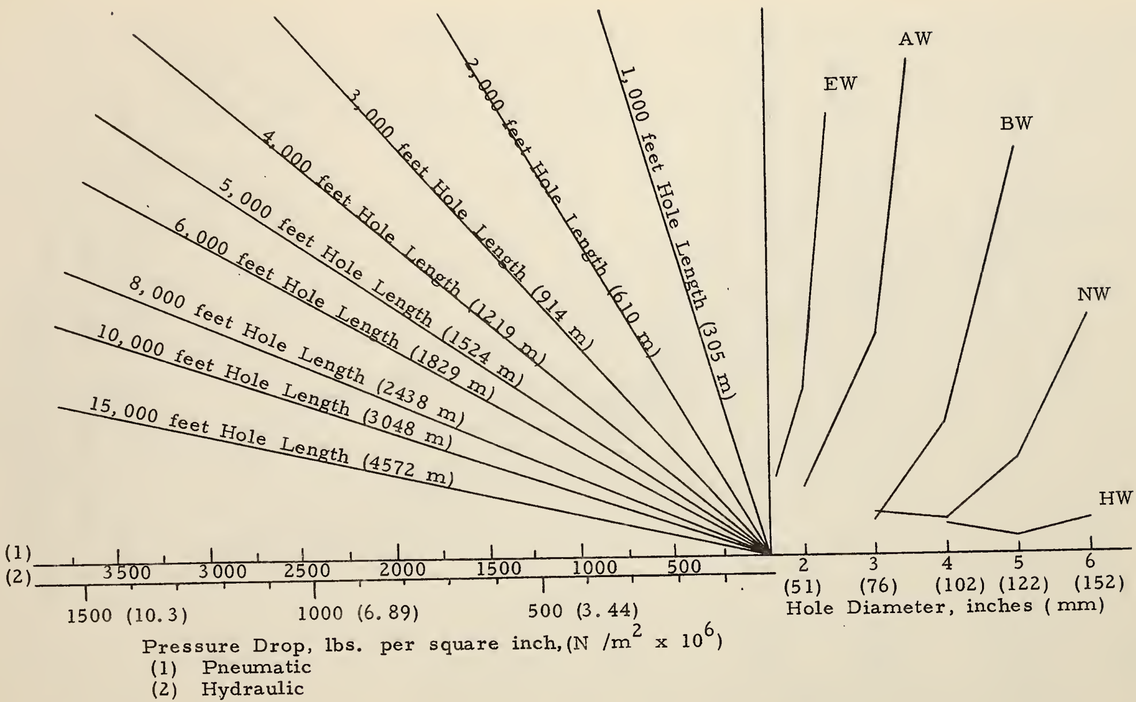


Figure 6.26 - Pressure Drop as a Function of Hole Size, Drill Rod Size, and Hole Length for Hydraulic and Pneumatic Chip Removal

line. This point is followed horizontally until it intersects the appropriate hole length line. The abscissa of this point gives the estimated pressure drop. For example, NW drill rod in a 5" (127 mm) diameter, 10,000' (3048 m) hole gives a pressure drop of approximately 614 psi (4.23×10^6 N/m^2).

6.2.3 Pneumatic Chip Removal

As indicated previously, the recommended velocity for pneumatic flushing of horizontal holes is 7,000 ft/min (15.24 m/sec). The right hand vertical axis of Figure 6.25 gives air flow rates in cubic feet per minute (CFM) for various hole diameters and drill rod sizes. Estimated pressure drops as a function of hole diameter, hole length and drill rod size are given in Figure 6.26. This figure assumes a uniform friction factor and air density throughout the entire pipe length. The effect of air density changes can be easily introduced but, owing to the other approximations involved, was not included. The use of Figures 6.25 and 6.26 is described in Section 6.2.2. For example pneumatic flushing of a 5" (127 mm) hole, 10,000' (3048 m) long, with NW drill rod will require approximately 710 CFM (20 m^3/min) and have an estimated pressure drop of 1500 psi (10.34×10^6 N/m^2).

6.2.4 Lost Circulation

Lost circulation occurs when the drilling fluid flows into the formation being drilled rather than returning to the surface with its load of debris. In some rare instances lost circulation can be tolerated but this is not usually the case for several reasons. When drilling is interrupted the debris which have been carried back into the formation can return and clog the hole. A second consideration is the cost of the drilling fluid. In arid regions water may have to be transported to the drill site and lost circulation places an increased burden on water transportation requirements. When drilling mud is used mud costs are a significant part of the hole cost, so the mud must be recovered and recycled. Lost circulation can be caused by porous formations, faulted or broken formations, or any other formation characteristic which provides an alternative flow path for the drilling fluid. The pressure of the drilling fluid itself may cause formation faults or "blow outs" which allow the fluid to escape.

There are three methods for controlling lost circulation, in order of preference; (a) the use of drilling mud and drilling mud additives, (b) grouting, and (c) casing of the hole. When air flushing is employed, alternative (a) is eliminated. In the single documented case of long horizontal drilling with pneumatic flushing, lost circulation was cured by pumping slugs of very wet sand-cement grout into the hole, alternating with slugs of water.[10] Drilling mud controls lost circulation by forming a cake on the hole wall. The cake is formed when some of the mud liquid phase flows into the formation, allowing the solids phase to form a coating on the hole wall. This solids coating prevents further liquid loss to the formation. When formation faults are coarser, and the caking mechanism is no longer effective, bran, sawdust, rice hulls, walnut shells, or proprietary preparations, available from drilling mud companies, may be added to the drilling mud in an attempt to block lost circulation paths. The next step to be employed would be an additive which is pumped into the formation and allowed to gel. From here, the next step is cementing or grouting in which the lost circulation zone is isolated with packing devices and cement or grout is pumped into the zone. After the material hardens, drilling is resumed. Should the preceeding techniques all prove ineffective, the hole must be cased to seal the lost circulation zone.

The subjects of drilling mud and grouting can become quite complex. Within the drilling industry, application of these techniques is handled by service companies when the expertise required is beyond the capabilities of the drilling contractor. Material suppliers and service companies are listed in Appendix A.

6.3 Hole Stabilization

In an ideal situation, the horizontal drilling operation would be conducted in competent rock and no special steps would be required to stabilize the hole. This is likely to be the case for a substantial percentage of horizontal drilling in rock. When hole stability problems are encountered during the drilling operation, the steps which can be taken to solve the problem are, in order of preference:

(1) Use of drilling mud.

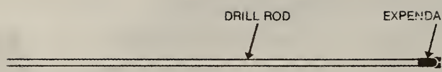
(2) Grouting.

(3) Casing.

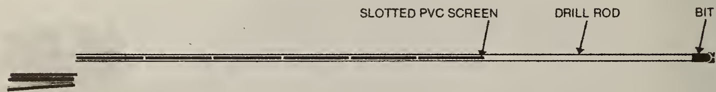
Note that these are the same steps discussed in Section 6.2.4 in connection with lost circulation problems.

If a borehole is to be used for geophysical experiments, the hole may have to remain open for up to one year after drilling is completed. Drilling mud contributes to hole stability only during drilling operations. Therefore, grouting and casing are the only techniques available to ensure long term hole stability. Sensing requirements can prohibit the use of metallic casing. (See Section 5.1) The procedures followed for each of the three techniques are as follows:

(1) Drilling mud aids hole stabilization in much the same manner as it controls minor circulation loss. The drilling mud forms a cake on the hole wall and the pressure across the cake stabilizes the hole walls and prevents their collapse. In vertical drilling the required pressure differential is provided by the hydrostatic head of the drilling mud column. In horizontal drilling a packing gland must be used to seal the drill string so that pressure can be applied to the mud column. This technique is illustrated in the discussion of the operating procedures to be followed with various drilling techniques in Section 6.1. As noted above drilling mud does not affect hole stabilization after the drilling operation is completed. Cementing, grouting,

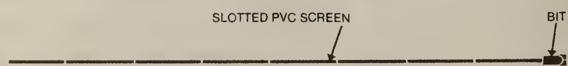


Horizontal hole is drilled by conventional rotary method. The Aardvark offers a wide range of height and angle positioning.



Upon completion of the boring, P.V.C. well screens are inserted inside the drill rod to the full length of the hole.

Floating locking piston is inserted, holding the screens in place by hydraulic pressure while the drill rod is withdrawn.



Completed drain installation. Screens of fine slot size prevent clogging and formational mining. Collector lines or ditches can be installed.

Figure 6.27 - Installation Procedure for Horizontal Drainage Screens (Courtesy, Tigre Tierra, Inc.)

or casing is required to ensure long term stability. A recent survey of drilling mud technology is provided in Reference 37.

(2) Grouting is used where drilling mud cannot control hole stability problems and where stability is required for a period of time after drilling is completed. Grouting is conducted by withdrawing the drill string, inserting a packer, and injecting the grout into the unconsolidated zone. After the material hardens, it is drilled through and the operation continues. In some cases the grout may be injected through the drill string without recourse to a packer. If collapse of the hole wall is triggered by ground water, drilling may be continued while the ground water flow is controlled with the packing gland or water flow can be stopped with the packing gland and grouting conducted. Appendix C contains a more comprehensive presentation of grouting technology.

(3) Steel is the only successful casing material developed to date despite extensive development efforts in fiber reinforced plastic casing.[27] Normal practice would be to case a hole when the techniques discussed above are not successful or when long term hole stability is required. Essentially all the holes drilled in the petroleum industry are cased.

Hole stability problems have been the most significant problem encountered in long horizontal holes on the Seikan Tunnel project.[23] All of the techniques described above have been successfully applied to solving hole stability problems on the Seikan project.[5,23,24,28]

Soil Sampling Services of Puyallup, Washington, has developed a technique for placing horizontal drains which may have application as a "next generation" casing technique. This technique is illustrated in Figure 6.27. In a casing application, the PVC pipe would not be slotted as it is when used as a well screen. Since the pipe is inserted inside of the drill pipe it does not have to be driven as normal casing would. However, the fact the pipe must fit inside of the drill string results in a considerable loss in hole diameter. This technique shows promise as a "last resort" non-metallic casing method of insuring hole stability.

6.4 Borehole Guidance

As discussed in Section 5, borehole guidance involves two distinct operations, (1) survey of the borehole to determine its attitude and position and thus determine the deviation of the hole from the desired trajectory, and (2) steering of the drilling system, first to limit deviation from the desired trajectory and second to correct deviations and direct the hole to the desired trajectory. The goal of this study is to keep maximum hole deviation to 30 feet (9.14 m) over the entire hole length.

Borehole survey and the steering actions are distinct operations. However, the functions are often confused as the steering is dependent upon the results of the survey. This has led to quoted results of guided drilling accuracies which are often misleading. The survey provides the reference standard against which drilling and steering accuracy is measured. Thus steering accuracy is represented as the ability to direct the borehole along a trajectory indicated by the survey system. The survey system has random errors and cumulative bias errors. However, the opportunity to check the accuracy of the basic survey by external calibration usually does not exist. Thus, the true drilling errors are the vector sum of both the survey and the steering contributions, but only the steering portion of this sum can be reported.

6.4.1 Factors Affecting Hole Trajectory

6.4.1.1 Gravitational Effects

In horizontal drilling, gravitational effects would normally tend to make the drilling assembly move in a downward arc from its intended horizontal course. However, with the proper drill string configuration, it is possible to use gravitation forces to cause the drill assembly to steer up or down from a horizontal trajectory. These procedures are discussed in Section 6.4.2.

6.4.1.2 Rock Hardness

Some studies have noted that as rock hardness increases, problems of directional control intensify.[11] Case histories appear to support this assumption. In horizontal drilling in soft materials effective directional control has been achieved by varying drill string configuration and drilling parameters[11,29] while in horizontal drilling in medium to hard rock, hole correction with wedges has sometimes been required at 10 foot intervals.[14]

6.4.1.3 Formation Effects

There are a number of theories which seek to offer explanations of the effect of formation characteristics on hole deviation. None of these theories is rigorous and none seems to apply in all cases. John Melaugh reviews several of these theories in his paper titled, "Directional Drilling: A Survey of the Art and the Science."[30] A portion of that discussion is reproduced here.

"The anisotropic formation theory assumes formations to possess different drillability parallel and normal to the bedding planes with the result that the bit does not drill in the direction of the resultant force. Each formation is characterized by its dip angle and an empirical constant anisotropic index.

The formation drillability theory seeks to explain deviation angle change as a result of the difference in drilling rates in hard and soft formations where the drill bit is not normal to the formation plane. The bit drills slower in that part of the hole in the hard formation (Figure 6.28).

The drill collar moment theory proposes that the weight on bit causes a moment when drilling from one formation to another of different hardnesses because the harder formation takes more of the weight (Figure 6.29). The side forces present at the bit are different depending on whether progress is from hard to soft or soft to hard.

The miniature whipstock theory is based on the tendency of relatively brittle formations to fracture perpendicular to the bedding plane (Figure 6.30). If these fractures occur in real formations and if such whipstocks are created, this could explain the generally accepted idea that the bit turns up dip.

Another whipstock theory, exemplified in S. R. Knapp's papers, could be considered to conflict with the foregoing miniature whipstock theory.[31] This theory is based on a bit's ability to cut sideways with a reaming action when unbalanced side forces exist due to crossing a bedding plane (Figure 6.31). This theory is also said to apply to steeply dipping formations. Another idea that has been generally accepted in the past is that in steeply inclined formations the bit tends to turn and follow the bedding planes (Figure 6.32)."[30]

Other references support the general conclusions that:

(1) The drilling assembly will tend to drill perpendicular to the formation bedding planes when the planes are intersected at an angle greater than 45°.[11,14,32]

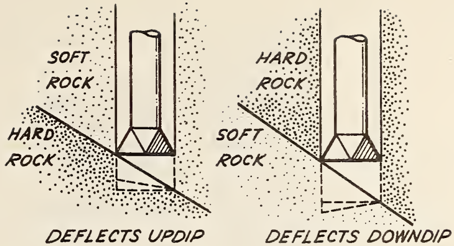


Figure 6.28 - Formation Drillability Theory of Hole Deviation

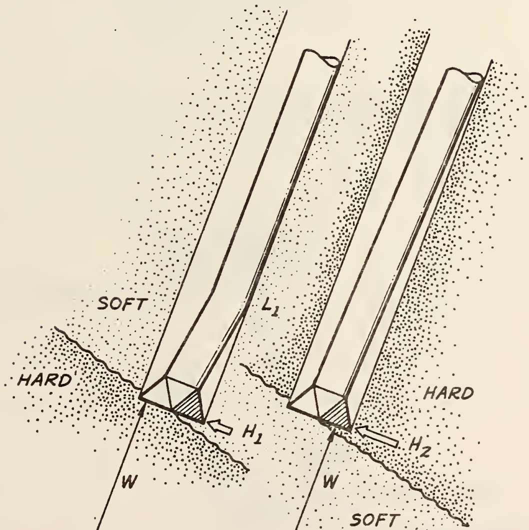


Figure 6.29 - Drill Collar Moment in Drilling Dipping Formations

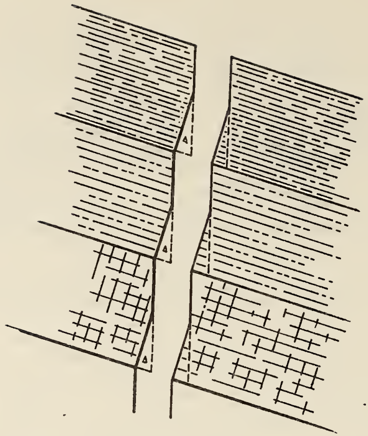


Figure 6.30 - Tendency of Bit to Drill Perpendicular to a Moderately Inclined Bedding Plane

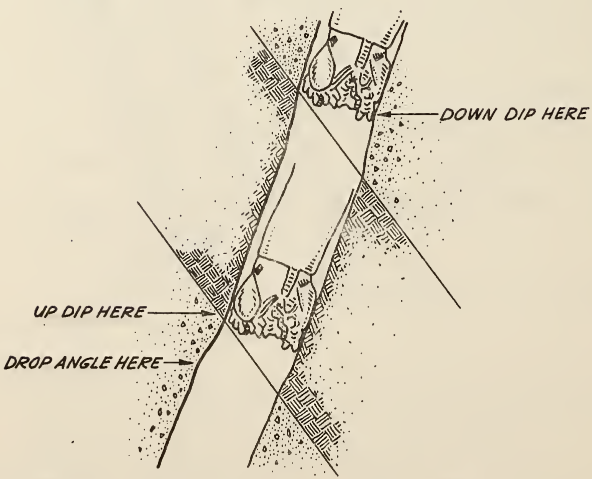


Figure 6.31 - Whipstock Effect Caused by Change in Formation Hardness in Steeply Dipping Beds

(2) The drilling assembly will tend to drill parallel to the formation bedding planes when the planes are intersected at an angle less than 45^{o}.[11,32]

6.4.1.4 Drilling Torque

The direction of rotation of the bit and drill string is clockwise. It is generally accepted that this creates a tendancy for horizontal holes to drift to the right.[29] A review of the hole data on AEC horizontal drilling in Table 6.8 (see p. 6-113)supports the right hand drift theory.

6.4.2 Guidance Procedures

6.4.2.1 Survey

The survey of the hole is such a specialized process that it is normally accomplished by a service company. However, some drilling contractors have obtained and modified their own tools for horizontal drilling.

The exact methods of survey and computation depend upon the design of the particular tool, and the preferred computational techniques of the individual service companies. However, they all are derivable from a common vector approach. Essentially, they are three-dimensional derivations of chain and compass surveying.

As the hole is drilled, the bearing with respect to North, and the elevation angle with respect to the vertical are measured at discrete intervals. The locations of these measurements are referred to as stations. The hole between stations is assumed to be represented by a line vector, the length of which is also measured.

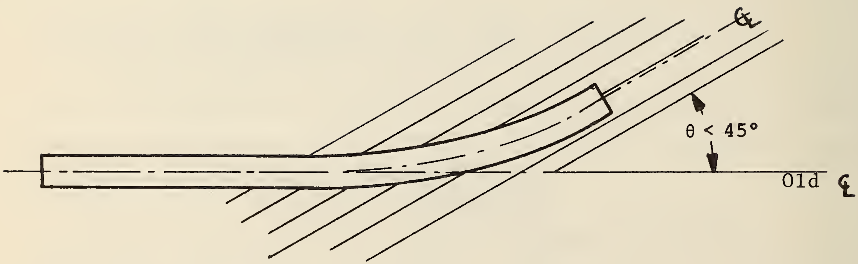


Figure 6.32 - Tendency of Bit to Follow Bedding Plans
Intercepted at a High Angle

These three measured quantities are sufficient to locate the surveyed station, with respect to the last station previously surveyed. It should be emphasized that this is only a relative, incremental measurement. The true location of the hole is obtained by carrying this survey, plus any new incremental changes from station to station thus any bias errors are cumulative and any random errors add as the square root of the sum of the squares (rms value).

There are only two types of tools for in-hole surveys generally in use today, the magnetic single-shot and the magnetic multi-shot. In-hole steering tools which rely on either gyroscopic or magnetic principles, or a combination of both are either available on a custom design basis, or are expected to be available as a service in the near future.

Single-shot and multi-shot equipment really differ but little. A single-shot takes only a single survey point each time it is used. A timer is set on the surface to allow sufficient time for the instrument to come to rest. The timer turns on a light and takes a picture of a two-dimensional compass card, and the instrument is withdrawn. A multi-shot uses a film strip and sequential timer which takes a picture at equal increments of time. The timer simply turns on the light, takes the picture, and advances the film strip. The time increment can be set to take a picture as frequently as every few seconds or to almost any extended increment.

The single shot is normally owned or rented by the drilling contractor. It is usually operated by a directional drilling specialist on the drilling crew.

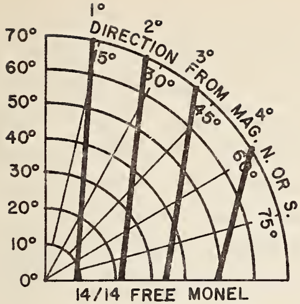
Standard practice for precision surveys is to take a single shot survey every 30 feet (9 m). This is a convenient length, since 30 feet (9 m) is the standard single section length of drill pipe in vertical drilling. Horizontal drilling normally uses 10 or 20 foot (3 or 6m) sections. Thus a survey point would be taken every length, or every other length of drill rod.

Magnetic survey instruments must be isolated from the influence of the drill string if they are to give accurate results. It is common practice to use non-magnetic drill collars in the drill string around the point where the in-hole survey tool will rest. There are charts available for slant hole directional drilling to define the length of drill collar required to reduce the survey error below specified amounts. Figure 6.33 is one such chart. It can be extrapolated that if the hole is horizontal (90°), even the longest drill collars listed are not recommended beyond 30 degrees east or west of north or south.

The normal procedure is to pump the survey instrument down the center of the drill rod. This is also known as "go-deviling." The package has non-magnetic extension rods attached so that it will be properly located within the drill string with respect to the non-magnetic drill collars behind the bit. Normally, there is a mule shoe sub in the drill string which orients the survey tool through cam alignment at the bottom of the hole.

The timer on the single shot is set to allow sufficient time for the tool to be go-deviled down the string at fluid velocity and come to rest. The picture is taken and drilling continues. When it is time to add a new length of drill rod, the single shot is retrieved by a wire line. The drill string is broken to add the new section and the single shot is retrieved. The directional driller disassembles the package, removes the film, reloads and resets the timer. The tool is then reassembled, and inserted in the drill string and the process is repeated.

With wireline core drilling equipment, the drill string is withdrawn from the hole bottom approximately 20 feet (6.1 m) and the survey instrument, in the instrument barrel with 15 feet (4.7 m) of non-magnetic spacer bars behind, is pumped down <u>through</u> the core barrel and bit. No mule shoe device is used to orient the instrument. In this case the instrument is retrieved before drilling resumes.



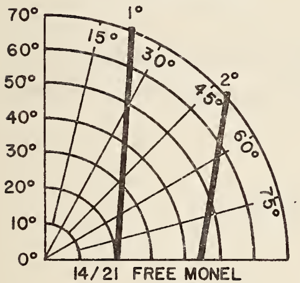
Approximate Compass Error
Due to:

1. Drill stem pole strengths of 3000 ± EMU above monel and 500 ± EMU below monel and 250 ± EMU between tandem collars.

NOTE: These are assumed values arrived at from various field tests.

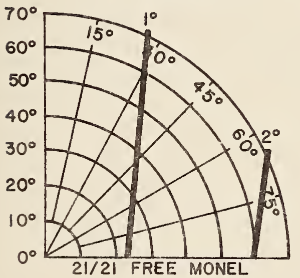
2. Compass position 1/2 up from the bottom of the free monel of the bottom collar.

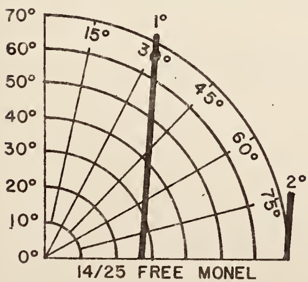
3. Earth's horizontal intensity of: .26.



NOTE: These curves are intended only as a guide in the selection of the proper K-Monel collar. The compass errors are theoretically true for the above conditions, but are NOT to be used to correct records taken in the hole, as the pole strength will vary in an unpredictable fashion.

NOTE: Numbers on axis indicate lengths of paired tandem collars.





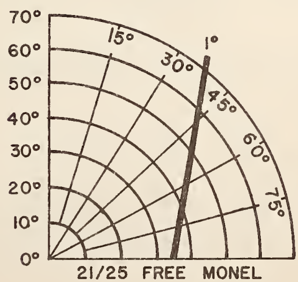


Figure 6.33. Guide for Selecting Non-Magnetic Drill Collars

The film is developed and read. Each manufacturer has specialized equipment to enable the driller to read the film, only three pieces of data are common to all. The azimuth angle is read with respect to magnetic north. The elevation angle is read with respect to the lccal vertical, and the orientation of the muleshoe sub with respect to either the high or low side of the hole. A fourth piece of data, the survey depth, is taken from either an odometer on the wireline, or from the drillers records of the lengths of drill rod in the hole. All the information necessary for survey, navigation or steering can be derived from these four quantities.

The survey technique involves standard chain and compass procedures. Figure 6.34 shows the geometry involved. Let:

ϕ = The Azimuth, Degrees from North

θ = The Elevation Angle, Degrees from Vertical

L = The cable length, feet

X = The North Component, Feet

Y = The East Component, Feet

Z = The vertical component, Feet

n = The number of survey points.

$\Delta(\ )_n$ = The change in any of the above from the previous (n-1th) reading.

From the geometry in Figure 6.34 it can be derived that:

$$\Delta Z_n = \Delta L_n \cos \theta$$

$$\Delta X_n = \Delta L_n \sin \theta \cos \phi$$

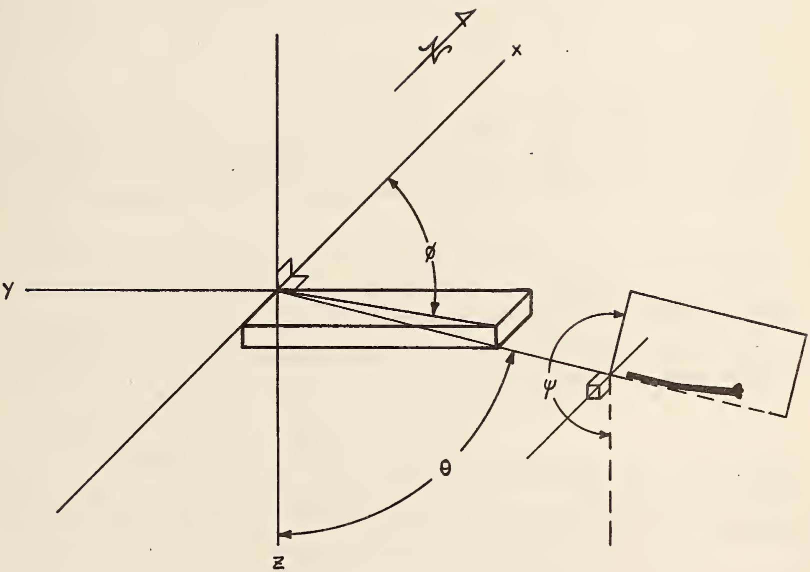


Figure 6.34 - Survey Coordinate Systems

$$\Delta Y_n = \Delta L_n \sin\theta \sin\phi$$

$$Z = \sum_1^n \Delta Z_n$$

$$X = \sum_1^n \Delta X_n$$

$$Y = \sum_1^n \Delta Y_n$$

Note θ and ϕ are true angles corrected for both magnetic declination and deviation errors. The values of X, Y, and Z are in the form necessary to make direct progress plots of both plan and elevation view of the hole.

The actual summations can be either numerical or graphical. The progress of the hole as surveyed is normally plotted against the projected plan and elevation view of the drilling plan. This provides the driller with the information necessary to determine the needed corrections.

Survey calculations can easily be computerized. In programming the computation, it is assumed that changes in bearing and inclination are uniform between survey stations, and changes are distributed over the survey increment.

6.4.2.2 Steering

The first step in steering is to attempt to minimize drilling assembly deviations. The ability of the drilling assembly to resist factors which cause deviations (see Section 6.4.1) is proportional to the stiffness of the drilling assembly. In petroleum drilling, stabilizers, collars, and reamers are used to stiffen bottom-hole drill assemblies. (See Figure 6.35)

Stabilizers are usually placed immediately behind the bit and at intervals along the drill string. Since stabilizers have an outside diameter only slightly smaller than the hole diameter, they serve to center the drill string and minimize whipping or bending.

The function of drill collars in providing weight to the bit in vertical and directional drilling has been discussed previously. Being heavy and of a diameter only slightly smaller than the hole, drill collars are also very rigid. Square drill collars go one step further in that they are comparable to drill collars with full length stabilizers.

Reamers are sometimes placed behind the bit to keep proper hole gage. Reamers may have rolling cutter blades or diamond studded blades. They also serve to center the drill string and minimize whipping and bending, in much the same manner as stabilizers.

Figure 6.35 illustrates (a) stationary and (b) blade type stabilizers. A normal length of drill pipe (c) is illustrated along with round (d) and square (e) drill collars. A roller reamer is also illustrated (f). Figures 6.36 thru 6.38 illustrate the procedures followed in employing stabilizers, collars, and reamers to stiffen bottom hole assemblies.

Documentation on the use of stabilization techniques in horizontal drilling is very limited. Fenix and Scisson noted success in limiting hole deviation through the use of stabilization procedures in horizontal drilling in coal.[11] An assembly utilizing a stabilizer immediately behind the bit, a 20 ft (6.1 m) collar, and a 2nd stabilizer gave minimal lateral deviation and allowed vertical deviation to be controlled by varying thrust and rpm.

This latter point brings up the "art" facet of the steering procedures. "Drilling technique, one of the most important means of preventing deviation, is hard to define as it is an art depending

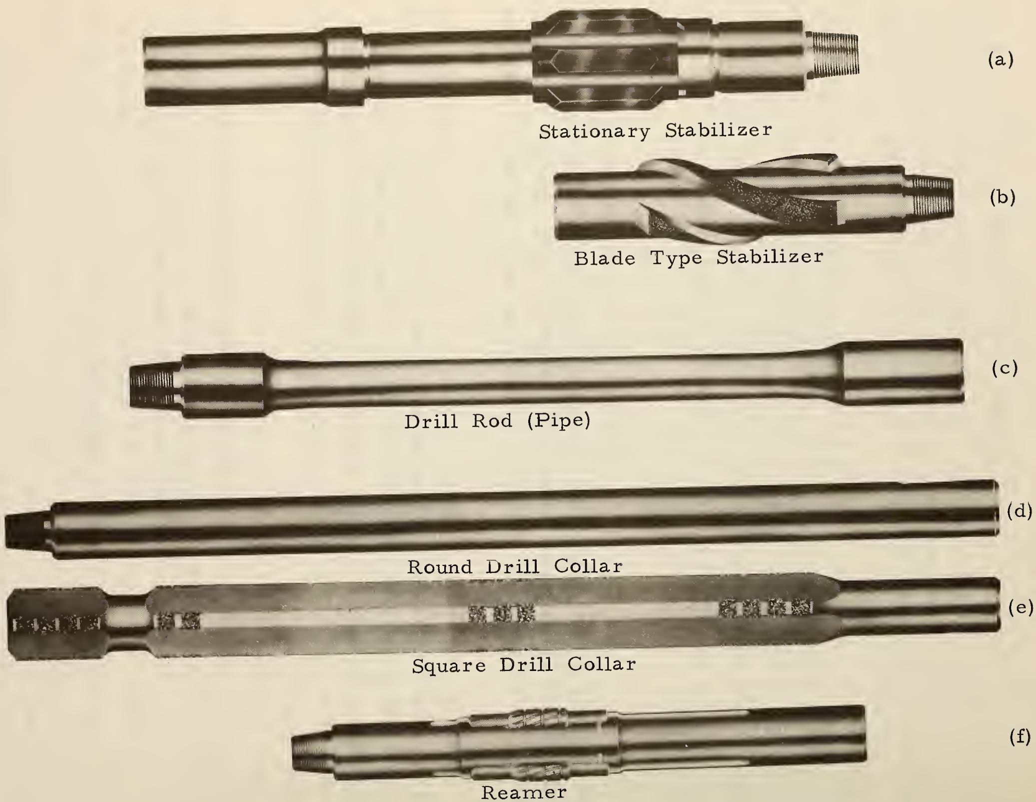


Figure 6.35 - Drill String Elements (Courtesy, Drilco Division of Smith International, Inc.)

SIMPLE STIFF BOTTOM HOLE ASSEMBLIES

HARD FORMATIONS

The assembly at left will:

1. Assure a full gage hole with no reaming back to bottom.
2. Increase bit life through improved stabilization.
3. Further increase penetration rates because optimum weights are higher on stabilized bits.
4. Reduce offsets and spiralling in hole.
5. Limit sudden hole angle changes and doglegs.
6. Moderately resist hole angle build-up.

MAINTENANCE TIPS

1. Keep bottom reamer in good shape, near hole size. See pages 41-44
2. Use the Knobby®, tungsten carbide insert, cutter for abrasive formations.
3. Keeping stabilizer at 30' level near hole size increases its effectiveness.
4. Excessively rapid wear on Rotating Blade Stabilizers may be overcome by using Rubber Sleeve Type.

← FOR HARD FORMATIONS

SOFT FORMATIONS

The assembly at right will:

1. Increase bit life through improved stabilization.
2. Further increase penetration rates because optimum weights are higher on stabilized bits.
3. Reduce offsets and spiralling in hole.
4. Limit sudden hole angle changes and doglegs.
5. Moderately resist hole angle build-up.
6. Reduce pressure-differential sticking tendencies of this section of assembly.

MAINTENANCE TIPS

1. Suggest maximum permissible wear on bit stabilizer be about 1/8" on diameter. The tungsten carbide insert Rotating Blade stabilizer is specially recommended at bit.
2. Limit wear on stabilizer above 30' level to about 1/4".

Note: Use rotating blade stabilizers in "non-abrasive" formations.

FOR SOFTER FORMATIONS →

Figure 6.36 - Stiff Bottom - Hole Assemblies (Courtesy, Drilco Division of Smith International, Inc.)

STIFFER BOTTOM HOLE ASSEMBLIES

HARD FORMATIONS

1. Assure a full-gage hole with no reaming back to bottom.
2. Increase bit life through improved stabilization.
3. Further increase penetration rates because optimum bit weights go higher with more effective stabilization.
4. Greatly reduce offsets and spiralling in the hole.
5. Greatly restrict sudden hole angle changes and dog-legs.
6. Restrict hole angle build-up.

MAINTENANCE TIPS

1. Keep bottom reamer in good shape, near hole size. See pages 41-44.
2. The closer the stabilizers to bottom, the more essential it is to keep them near hole size.
3. In abrasive formations, a good combination for the reamer is, Knobby® Cutters at bottom and "Q" cutters at top.
4. Excessively rapid wear on Rotating Blade Stabilizers may be overcome by using Rubber Sleeve Type.

← FOR HARD FORMATIONS

SOFT FORMATIONS AND NON-ABRASIVE HARD FORMATIONS

The "Drilco Full-Flo Assembly" at right will:

1. Increase bit life through improved stabilization.
2. Further increase penetration rates because optimum bit weights go higher with more effective stabilization.
3. Greatly reduce offsets and spiralling in hole.
4. Greatly restrict sudden hole angle changes and dog-legs.
5. Greatly resist hole angle build-up.

MAINTENANCE TIPS

1. Bottom square stabilizer section should be maintained very close to hole size. In some cases the tool is made with zero clearance and is allowed to wear only 1/16" on diameter. Somewhat more wear can be tolerated in the larger hole sizes.
2. Maintenance of lowest Rotating Blade Stabilizer is almost as critical as for the Modified Short Square Drill Collar.
3. Stabilizers higher up the hole may be allowed to wear somewhat more, depending on distance from the bit.
4. In 6½" holes, 1/16" wear is twice as great, proportionately, as in 12¼" holes.
5. Very close maintenance to gage is more expensive, but in critical situations it is worth it.

FOR SOFT FORMATIONS AND NON-ABRASIVE HARD FORMATIONS →

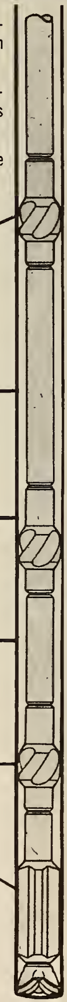


Figure 6.37 - Stiff Bottom - Hole Assemblies (Continued)

STIFFEST BOTTOM HOLE ASSEMBLIES

CONSOLIDATED FORMATIONS

Caution: This assembly must be reamed to bottom if part of the hole was drilled without a square collar.

The Assembly at left will:

1. Increase bit life through effective stabilization.
2. Permit highest drilling rates because stabilization is maximum and optimum bit weights are highest.
3. Provide maximum resistance to hole angle build-up.
4. Provide maximum resistance to offsets and spiralling in the hole.
5. Provide maximum resistance to sudden hole angle changes and dog-legs.

MAINTENANCE TIPS

1. If formations are abrasive and bits tend to drill under gage hole, be sure to use the reamer and keep it out to bit diameter. This is best accomplished with a Drilco Knobby® Reamer.

2. As with other "packed hole tools", Square Drill Collars lose their effectiveness as wear progresses. Maximum permissible wear depends on how critical situation is.

3. Rebuilding square drill collars should be done by controlled metallurgical procedures. Drilco service shops are specially equipped and their people trained to rebuild square collars for maximum, trouble-free performance.

UNCONSOLIDATED FORMATIONS

4. If you need some help on any of these procedures, contact your Drilco man.

Where formations are such that the hole enlarges as it is drilled, wall support becomes intermittent, at best. To compensate for this a very long wall-contact assembly is recommended. The Tandem-Square Assembly lends itself well to this service because it has long wall contact surfaces.

THE TANDEM SQUARE ASSEMBLY at right will:

1. Provide all 5 of the benefits attributed to the regular square assembly on the opposite page.
2. Make "Tattle Tale" technique feasible.

Here's a technique some drillers have found useful in Air and Gas drilling. With this long rotating square assembly in the hole, any side force on the bit will cause a noticeable build-up in torque. Such side forces normally make the hole go crooked.

Employing the Tattle Tale technique, the driller reduces weight when the torque goes up and thereby reduces the force tending to make the hole go crooked. This gives the driller a tool to control deviation.

This technique is particularly effective when drilling with air.

MAINTENANCE TIPS

The recommendations for single squares also applies to tandem squares.

Figure 6.38 - Stiff Bottom - Hole Assemblies (Continued)

on the driller's "feel" for what is happening down the drill hole. This art, acquired only through experience, accounts for such variables as the proper control of bit pressure, rotary speed, pumping pressure, etc."[8] The art aspect of deviation control can be minimized through wider use of instrumentation and subsequent documentation of drilling parameters. Drilling "by the numbers" has been successfully employed as a technique for training inexperienced drillers.[14] However, this approach does not have much support from the drillers themselves, and the practice is not widely employed. Consequently, no drilling parameter data base exists for horizontal drilling.

When the driller establishes that a pattern of hole deviation is developing he must make a correction. This is accomplished by making the hole deviate at an angle which will tend to bring the trajectory of the hole back onto the proper projected path called for in the drilling plan.

The procedure of controlling vertical hole deflection by the use of a fulcrum effect has been applied in horizontal drilling in coal and the AEC horizontal drilling program conducted at Mercury, Nevada.[11] Figure 6.39 presents the principles involved. A stabilizer, a few tens of thousandths of an inch smaller than the hole diameter is placed on the drill string near the bit. This acts as a fulcrum to balance the forces involved. The weight of the bit is balanced against the weight of the drill string suspended by the stabilizer. For any drill rod configuration, the rod creates a lever arm, which is constant depending on the weight per foot of the rod and its flexibility. Far removed from the stabilizer, the rod will lie on the bottom of the hole. Thus, there is only a relatively short section of rod to actually contribute the balancing force. This is shown in Figure 6.39 a. Figure 6.39b shows the drill rod configuration used to cause the hole to climb. The stabilizer is placed close to the bit. The net downward force due to gravity is thus behind the stabilizer and produces an upward force on the bit. The force can be amplified by replacing the standard flexible rod with a heavy drill collar. This not only adds weight because of the increased mass, but also adds force amplification due to the increased lever arm from the more rigid collar. This is illustrated in Figure 6.39c which shows this configuration. To make the hole fall, the stabilizer is moved back from the bit and the heavy collar now adds its weight to the bit and overbalances the suspended drill rod behind the stabilizer.

Control of thrust and rpm are also used. The drilling contractor at the Nevada Test Site of the AEC has employed a system quite similar to the one in Figure 6.39 except that the stabilizer location is not changed. The configuration of Figure 6.39b is used to cause the resultant hole to climb. To cause the resultant hole to fall, the standard stabilizer is replaced with a diamond encrusted stabilizer which thus becomes a reamer. With these configurations, it has been found that upward deflection is increased with increased thrust and standard rpm's, while the hole can be made to drop with the diamond stabilizer, at increased rpm's and reduced thrust.

Rommel and Rives[11] used a configuration similar to Figure 6.39 and found that thrust and rpms became important control parameters. They did not indicate how it was applied.

Logic would indicate that thrust and bit speed can be used to produce variations, primarily to amplify or reduce a tendency, wherein any particular drill string, and bit configuration in specific formation will climb or fall. There seem to be no hard and fast ground rules for their application. It is believed their effects will have to be learned empirically in each new hole and each new configuration. This merely reinforces the fact that much of the success of the operation will rest in the human factors of the drilling art.

The fulcrum procedure has not been developed as an effective steering technique in medium or hard rock.

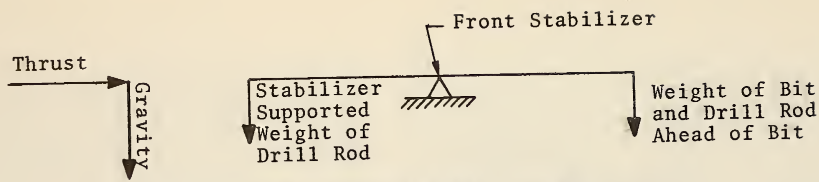


Figure 6.39a - Fulcrum Effect on Bit Forces

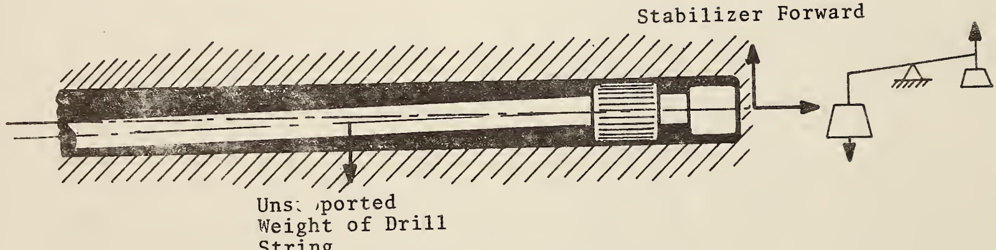


Figure 6.39b - Climbing Configuration

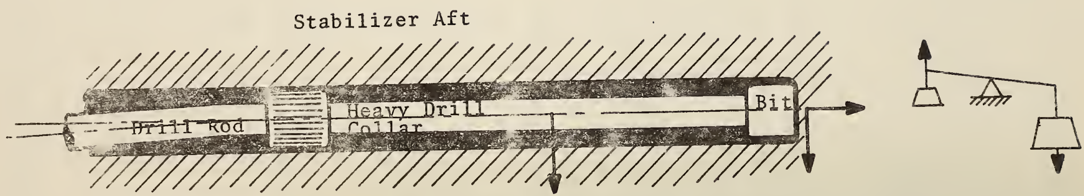


Figure 6.39c - Falling Configuration

When the fulcrum procedure is not effective or when azimuthal corrections are required, a deflecting tool must be employed.

The correction must be made in a different coordinate system than the survey coordinates. The driller simply determines how far the hole is to the left or right and above or below the planned course. The correction angle, ψ may be computed with respect to the high or the low side of the hole and is also shown on Figure 6.34.

Let ϵ_V = the vertical error

ϵ_A = the azimuthal error

ψ = the deflection angle

Then for high side reference

$$\psi = \tan^{-1} \frac{\epsilon_A}{\epsilon_V}$$

$$\psi = \cot^{-1} \frac{\epsilon_A}{\epsilon_V} \quad \text{for low side reference}$$

A deflecting tool is then used to deviate the hole at the angle ψ, to the reference side of the hole. Deflecting tools apply a lateral force to the drill bit at the proper angle and cause the hole to develop along a new angle. The force angle and the new hole angle are not necessarily the same, as bit rotation creates an orthogonal reaction torque.

When the time comes to deviate the hole, engineering data is required to orient the deflection tools accurately. First the directional engineer must know the present course of the hole. Since the directional surveys have been repeatedly taken and plotted, this information is available. Second, he must know where the next 30 feet of the hole should bottom out. Third, he must know the degree to which the selected deflection tool is capable of deviating the hole. This can range from a fraction of a degree all the way up to 5° or more.

Common deflecting tools include whipstocks, and down-hole motors on bent subs. Other less frequently used tools are discussed in Section 6.4.3.

Whipstocks are special wedges which, when properly oriented and anchored, force the drill bit to drill into the side wall near the bottom section of the hole. It is simply a long metallic wedge which is anchored or cemented into the bottom of the hole. A smaller diameter bit is used which follows the side of the wedge until it reaches the bottom. The whipstock then maintains the proper hole angle by warping the drill string. The small pilot hole is continued ten to thirty feet below the bottom of the old hole. Then the drill string and, usually, the whipstocks are withdrawn. A full gage reamer is placed behind the pilot bit, and the new hole is reamed to full size. The normal drillstring assembly is then attached and drilling continues at the new angle. This procedure is shown in Figure 6.40.

Anchoring the whipstock can be a problem. Originally, whipstocks were cemented in and left in the hole. This technique has fallen in disfavor because of the possibility that the wedge will break loose in some future operation and jam in the hole. This can cause an expensive and time consuming fishing operation.

Today's recoverable whipstocks operate with chisel point ends and fluid passages to wash any debris from the bottom before the whipstock is set.

Initially, the tool is directly connected to the drillstring by shear pins. After it has been inserted in the hole, and oriented at the proper angle, sufficient force is applied to the drillstring to cause the pins to shear, and the chisel point to anchor the wedge. This procedure is not applicable to all formations. Frequently, in soft formations the chisel will not provide a sufficiently firm anchor and the whipstock will turn with the drill. Resetting the whipstock now becomes an exercise in the ingenuity of the driller. The whipstock

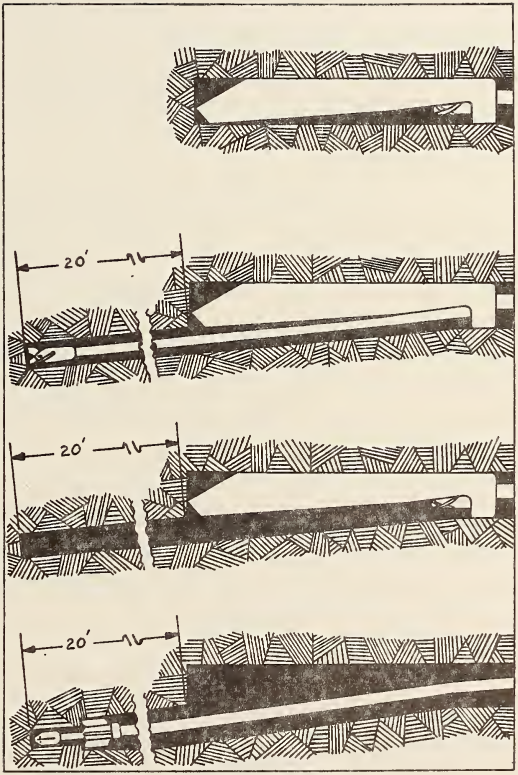


Figure 6.40. Deviating a Hole with a Whipstock

frequently can be cemented with a plug in the bottom of the hole. However, this will not always work; many factors are involved. There are some ground waters with mineral content that will not allow cement to harden properly.

Temperature also plays an important role, for example, in current practice in drilling diversional holes for mineral exploration cement hardens beautifully in Arizona, while in the Zinc-Tin Belt of Tennessee the cement never seems to harden. An ingenious technique frequently employed is to drive a dry, end grain, piece of wood into the hole, set the chisel point, then wait for the wood to swell, and lock the whipstock.

The use of the down-hole hydraulic motor, on a bent sub has been increasing. The bent sub is simply a short section of drillstring with the threaded ends at an angle with each other. The drill string is attached to one end, the motor at the other. As with the whipstock, a number of surveys with angular corrections are required to orient the rotational angle of the bent sub. An additional factor in orientation rests in the fact that the down-hole motor generates a considerable reaction torque. This causes the drill string to twist to the left (counterclockwise) in opposition to the normal rotation of the motor. This angle must be taken into account in orienting the sub. The twist of the drill string is governed by the depth of the hole, the rigidity of the drill rod, and the torque of the motor. The torque in turn is governed by the fluid flow rate, the force on the bit, and the drilling characteristics of the formation.

The ability to accurately deviate a hole with this technique depends upon close control of drilling parameters and frequent timely surveys.

6.4.3 Equipment

The following sections describe directional drilling equipment. Survey devices, drill string stabilization equipment and deflection tools are discussed. Some additional information on the procedures employed with the various items of equipment are also included.

6.4.3.1 Survey Devices

(a) Magnetic Single Shot and Multi-Shot Devices

The state-of-the-art in available survey instrumentation for horizontal drilling is typified by the magnetic multi-shot and single shot devices available from such companies as Eastman Whipstock Inc. and Sperry-Sun Inc. A typical magnetic multi-shot instrument is illustrated in Figure 6.41. These instruments have a 1.75 inch (44.5 mm) outside diameter.

In addition to the survey device there is auxiliary equipment which must be used in conducting a survey.

In order to survey down hole, the instrument is normally mounted in a protective case with either spring-mounted or pneumatic shock absorbers. The case is selected for the size of the pipe so it can be pumped (go-deviled) down the drill string.

Above the drill bit is a set of non-magnetic drill collars. Their length is selected so that the magnetic field will not be distorted by the iron of the pipe above, nor the drill motor or deflection tools below, the survey point. The common practice is to position the survey tool about one-third of the way up the collars. To accomplish this a series of non-magnetic extension bars are assembled

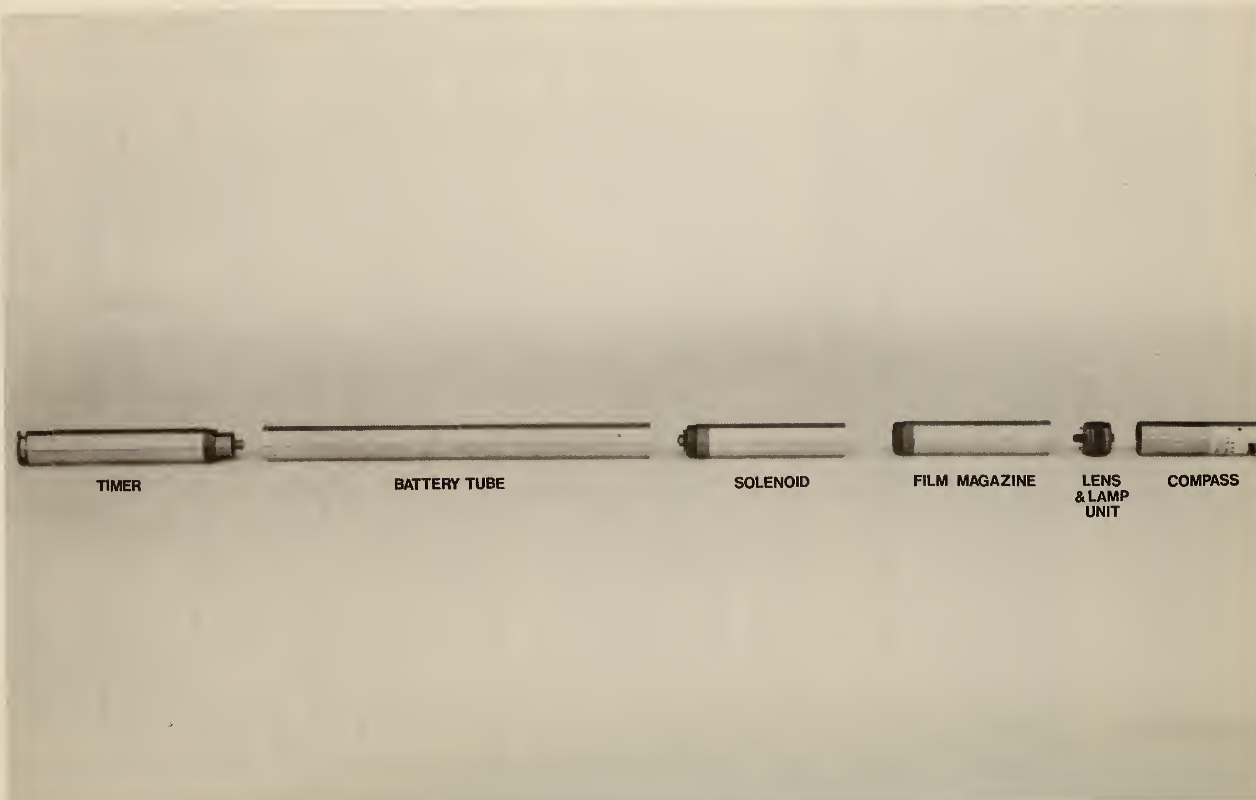


Figure 6.41. Typical Magnetic Multi-Shot Instrument

below the protective case. These come in assorted lengths, so that they can be assembled in combination to fit the particular lengths of drill collars being run. (See Figure 6.42.)

In order to determine the orientation of the tool face with respect to the survey package, a mule shoe alignment cam is attached by a sub to the steering tool. A mule shoe is a set of mating cams which are shouldered to guide the instrument into a certain angular orientation as it seats itself. The cam flanges of the reference portion of the cam mate with pins or shoulders on the tool to be oriented. Regardless of its initial orientation, they rotate it to the proper angle prior to seating. Some subs are available so that the mule shoe can be pin-aligned with the face of the steering tool. Others use scribe marks for the alignment. The angle between scribes must be measured. This then becomes a bias angle which must be subtracted out in subsequent computations.

If the survey package is a single shot, it is retrieved by a wire line running through the swivel (rotating joint on the drill rig) which feeds the drilling fluid from the pump to the drill string. At the end of the wire line is an overshot. This is a self-engaging device which attaches itself to the head of the single shot. After the overshot is pumped down and attaches itself, the single shot is retrieved. If the device is a multi-shot, it is go-deviled down just before it is necessary to pull the drill string. Usually the timer is set to take a picture every 20 seconds as the drill string is removed. On development, those pictures which were taken while the pipe was moving will be blurred. It is necessary to stop the pipe each time a length of drill rod is removed. Thus, pictures taken during this interval will be clear. Some multi-shots also include a watch which is synchronized with a similar watch on the surface. Thus, correlation between the time shown on the pictures and the logged time for removal of individual sections provides an additional method of checking the location of multi-shot readings.

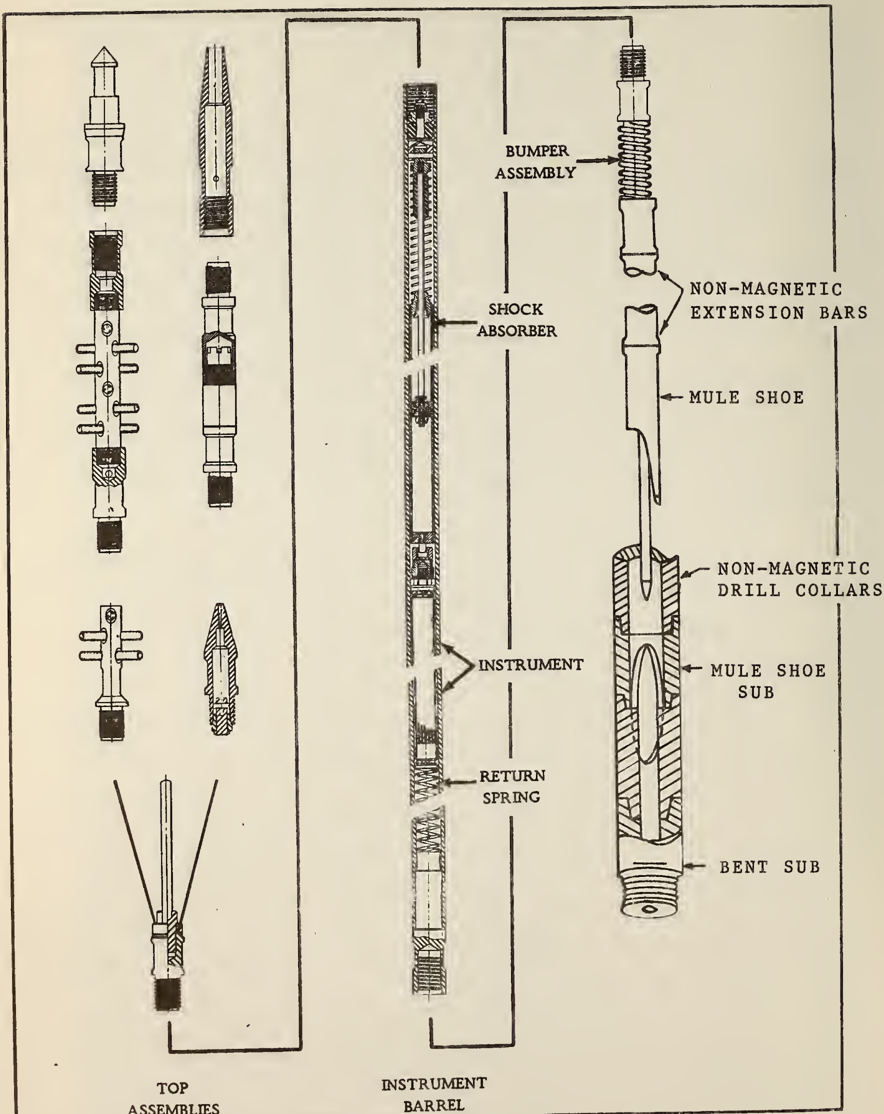


Figure 6.42. Typical Directional Instrument Assembly

(b) <u>Gyroscopic Devices</u>

Humphrey Inc. builds both gyroscopic and fluxgate magnetometer survey devices. This equipment can be ordered on a custom basis in configurations suitable for surveying horizontal holes. The equipment transmits data to the surface by wireline and is monitored on a "real time" basis at the surface. A gyroscopic survey system is illustrated in Figure 6.43. This equipment is typically 1.75 inch (44.5 mm) in diameter.

(c) <u>Survey Steering Tools</u>

Survey steering tools are survey devices which are pumped down the drill string to provide "real time" survey information when a direction change is carried out. The devices are basically magnetic survey instruments which transmit data to the surface through a wireline. A steering tool system is illustrated in Figure 6.44.

Survey steering tools are widely used for directional drilling operations in the petroleum industry where they have been instrumental in making the Dyna-Drill the preferred hole deflection tool. The continuous surface read out allows the driller to determine how much the drill string is twisting due to the reaction torque of the down-hole motor. This enables the driller to set the angle of the bent sub under dynamic conditions. He can then hold this angle by control of: the drill string orientation, the thrust of the bit, and the fluid flow rate. This is a truly dynamic reading, under full power. It takes the guesswork out of the survey setting. Thus, it provides a capability not achieved by any other means.

One such system consists of a down-hole probe, surface data processor, digital mini-computer, tape printer, X-Y plotter, and angle read-out. Optionally, a digital cassette recorder is provided to record all data for future processing.

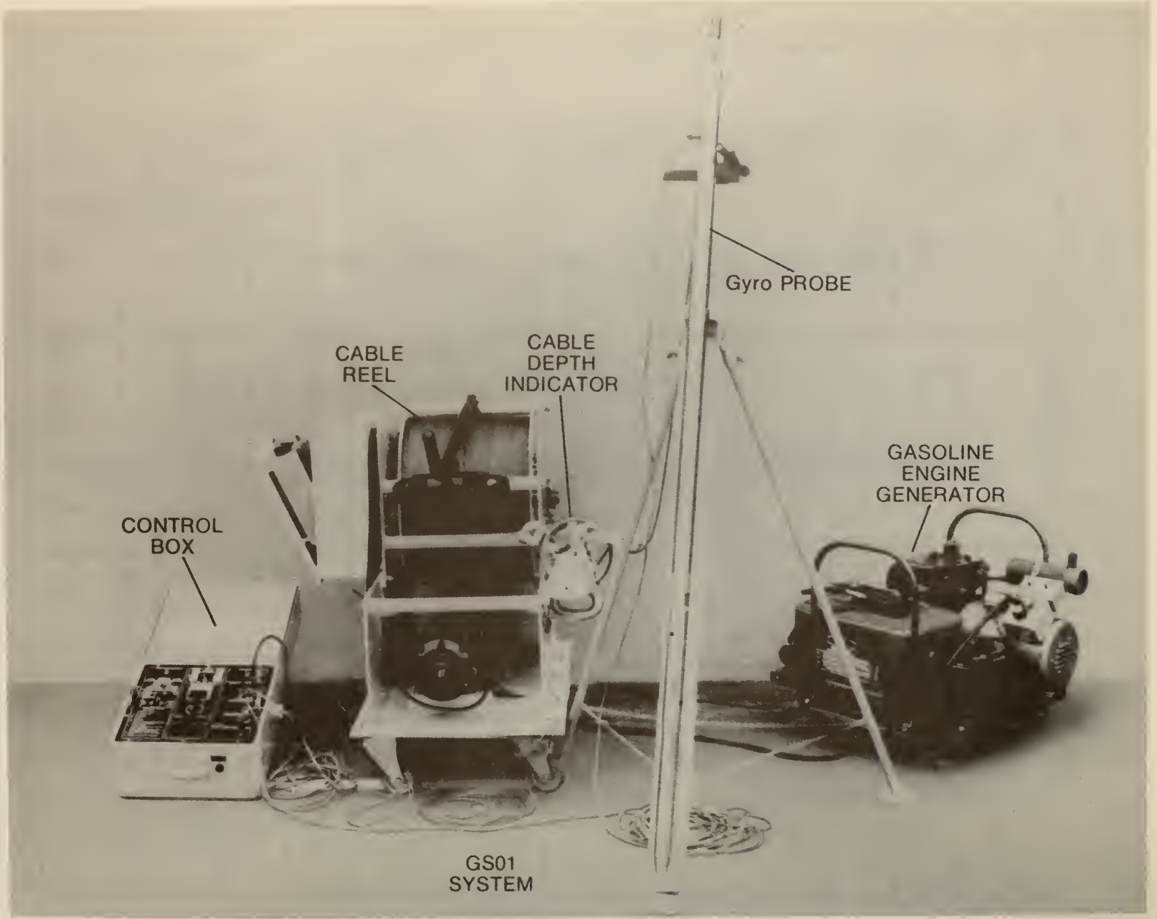


Figure 6.43. Gyroscopic Survey System

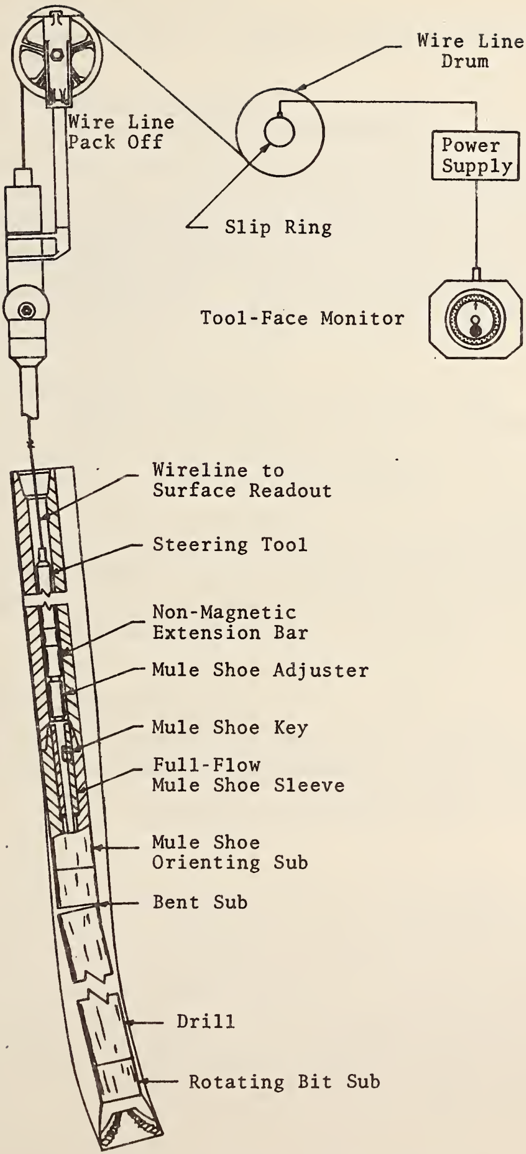


Figure 6.44. Survey Steering Tool

All equipment is field portable or is mounted in a truck which also contains a single conductor wire line unit.

The probe utilizes magnetic sensors and accelerometers to determine the direction of the magnetic and gravitational vectors relative to the axes of the probe. A gyro can be used to replace the magnetic sensors if the survey is to be performed inside drill pipe or casing. The sensor data is conditioned and multiplexed by electronic circuitry contained within the probe and transmitted to the surface via a single conductor wire line. The wire line also provides power to the probe.

At the surface, the sensor signals are reconstructed by a data processor. Tool or drill face alignment is provided directly to an angle readout for drill steering. Sensor data along with measured depth information is fed to a digital mini-computer where all necessary survey computations take place. Completed survey data from the computer is immediately presented by a tape print out and/or X-Y plot of the plan and elevation view of the hole. Simultaneously a recording of the survey data can be furnished for future computer processing.

The computational speed and accuracy of the digital computer allows almost instantaneous print out of survey data to a high degree of resolution and repeatability which eliminates human errors in interpretation and computation.

Survey steering tools are generally available for applications up to 70° from vertical. Horizontal versions of these devices are said to be available on a custom order basis, and several companies have indicated that they intend to provide them as a service in the near future. Scientific Drilling Controls, Inc. of Newport Beach, California and Sperry-Sun Inc., of Houston, Texas manufacture survey steering tools and provide related services. These devices have a typical outside diameter of 1.75 inch (44.5 mm).

Survey device manufacturers are listed in Appendix A.

6.4.3.2 Stabilization Equipment

As noted in Section 6.4.2.2 stabilization equipment consists of (1) stabilizers, (2) drill collars, and (3) reamers. This equipment is supplied by manufacturers servicing the petroleum drilling industry. Drilco Division of Smith International, Inc., Midland, Texas is a major supplier of stabilization equipment. Listings of other suppliers can be found by consulting the references in Appendix A.

6.4.3.3 Steering or Deflection Tools

(a) The Whipstock

The whipstock is a wedge-shaped steel casting with a tapered or concave guide channel for the bit (Figure 6.45). Whipstocks can be permanently installed, or they can be of a removable type. The permanent whipstock is cemented in and remains in the hole. It was used in the early days of directional drilling, but is seldom used today. Experience has taught the drillers that circulation and drilling operations may loosen a permanently set whipstock and cause it to dislodge into the new hole. This could result in a costly fishing operation or even the loss of the hole. Except for very special cases, removable whipstocks are now used almost exclusively.

The removable whipstock is an old reliable deflection tool, but it has some major disadvantages compared to down-hole motors. It does not allow a full gauge hole to be drilled. Its use requires considerable trip time because a small undersize rat-hole must first be drilled. The rat-hole must then be reamed to full size after the whipstock is removed. Although the whipstock is gradually being displaced by down hole motors, in certain cases it is still the best tool for the job.

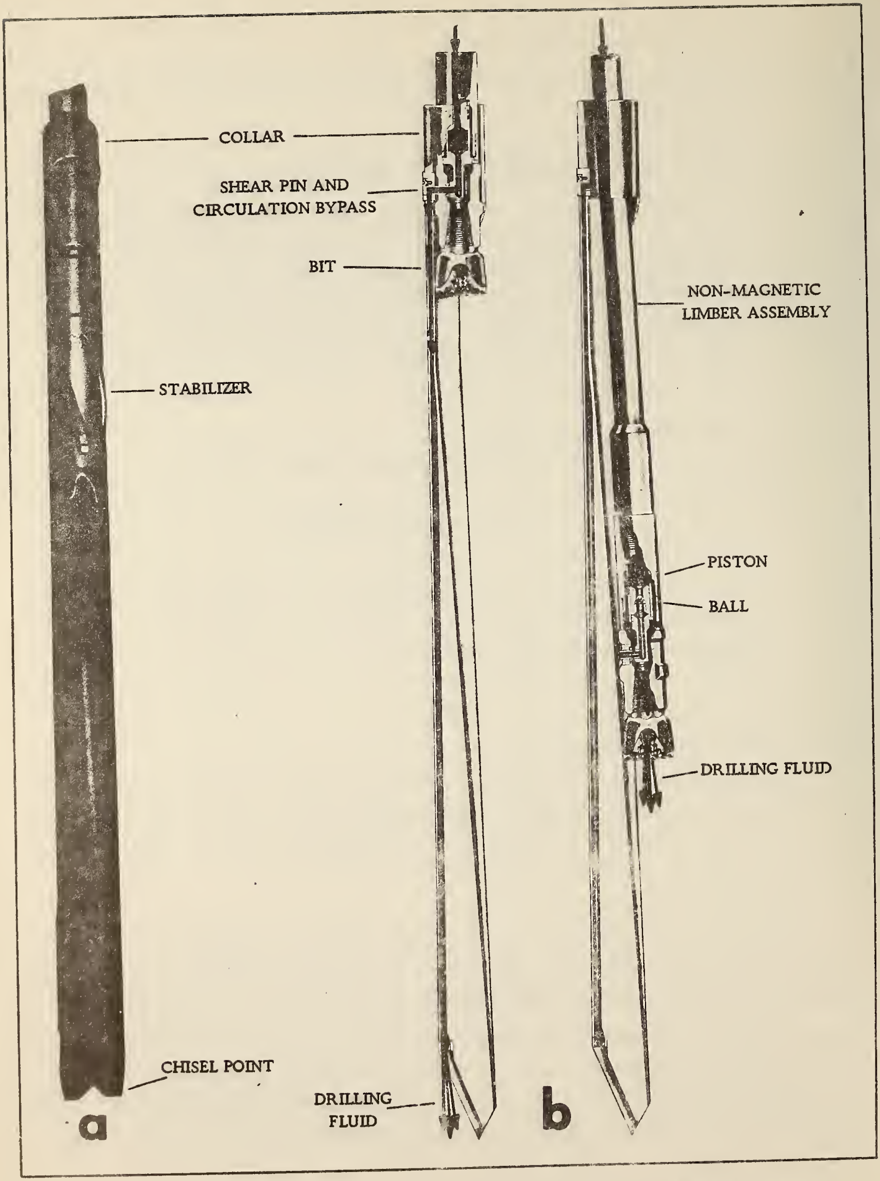


Figure 6.45. Whipstocks: (a) Noncirculating Whipstock; (b) Cross Section of Circulating Whipstock

(b) Knuckle Joints

The knuckle joint (Figure 6.46) is basically a pilot reamer, (an undersize bit ahead of a full gauge bit) with a universal joint principle built into its connection with the drill stem. We have found no record of knuckle joints being used in existing horizontal holes. However, the reason for its lack of use seems to be that these tools are not made in the smaller gauges currently used for directional high-angle holes. The universal, which is usually a splined ball and socket joint, enables the lower drilling assembly, consisting of bit and reamer, commonly called the stinger, to rotate at a different angle from the drill stem. This changes the drift angle and direction of the hole. When the joint enters the new hole, the knuckle straightens out, and the drill pipe takes care of the necessary curvature for continuing the hole in the new direction.

As with other directional tools, the knuckle joint is oriented and set on the bottom in this position. The tool is worked in and out to form a recess for the lead bit on the stinger. When no more progress can be made, heavy thrust is applied, the tool is set and rotation is started at 20 to 40 rpm, with steady circulation. Drilling is continued until 15 to 20 feet of hole have been made.

In operating the knuckle joint it is important to maintain proper force (weight) and to keep the tool cutting or biting into the formation. If this action slows up, the tool has a tendency to crawl around the hole and change its direction. Applying the weight is the only means of holding the desired direction. The knuckle joint gives greater deviations than the whipstock as the deflection takes place in a distance equal to the length of the tool. The deviation will vary with the formation and the manner in which the tool is being used. In slant drilling, the knuckle joint is commonly used in soft formations which will not hold whipstocks.

Figure 6.46. Knuckle Joint (Courtesy Houston Oil Field Material Co.)

(c) <u>Spudding and Jet Bits</u>

These bits are used only in extremely soft formations. They are used to deviate holes where the formation can be directionally eroded by a jet of water. They do not seem to be used in high angle holes because of their relatively uncontrollable washing action. This can cause the hole to collapse. Other bits and directional tools which lessen damage to the formations seem to be preferrable in high angle holes.

(d) <u>Down-Hole Hydraulic Motors</u>

Today the most common tools used to deviate a hole are the down-hole hydraulic motors, of which there are two types, positive displacement and turbine. Both types of down-hole motors have several advantages over the older types of deflection tools.

They drill full gauge holes so that no follow-up run to ream the rat-hole is required.

Multiple deviations and corrections can be made without coming out of the hole.

The motors can be made to clean out bridges in the hole, and can clean out bottom hole cuttings before deviation is started.

They are unique in that they utilize the flow of drilling fluid down the drill string to turn the bit, thus eliminating the need to turn the drill stem.

They drill to a smooth arc of curvature rather than a series of sharp, abrupt doglegs, associated with conventional wedging or whipstocking techniques.

The systems carry their own bending force along as they drill. Thus, they describe a smooth arc of a circle, the radius of which is established by the degree of fixed bend in the bent sub.

(e) Down-Hole Turbine Motors

Down-hole turbine motors (Figure 6.47) consist of a turbine section, a replaceable bearing section, and a rotating bit sub on which a conventional bit is made up. Turbines operate only with mud as a circulating medium.

The turbine section contains blade-like rotors and stators. The stator is attached to the outer case of the tool and is held stationary by it. The rotor is attached to the drive shaft. Each rotor and stator combination are termed a "stage" and several stages constitute the turbine section. In operation, drilling mud is pumped down the drill string and into the tool. The blades in each of the stationary stators guide the mud onto the rotor blades at an angle. Mud flow forces the rotors (and thus the drive shaft) to rotate to the right.

Turbine drills typically run from 1,500 to 3,000 rpm. Thus, it is difficult to get a good match between their speed-torque characteristics and those of the bit. They are also very sensitive to loading of the bit, and will stall if overloaded.

There are several directional drilling organizations using them. However, we have found no cases where they have been used for controlled directional drilling of horizontal holes.

(f) Positive Displacement Motors

Positive displacement motors differ from turbines in that they generate their motor action through

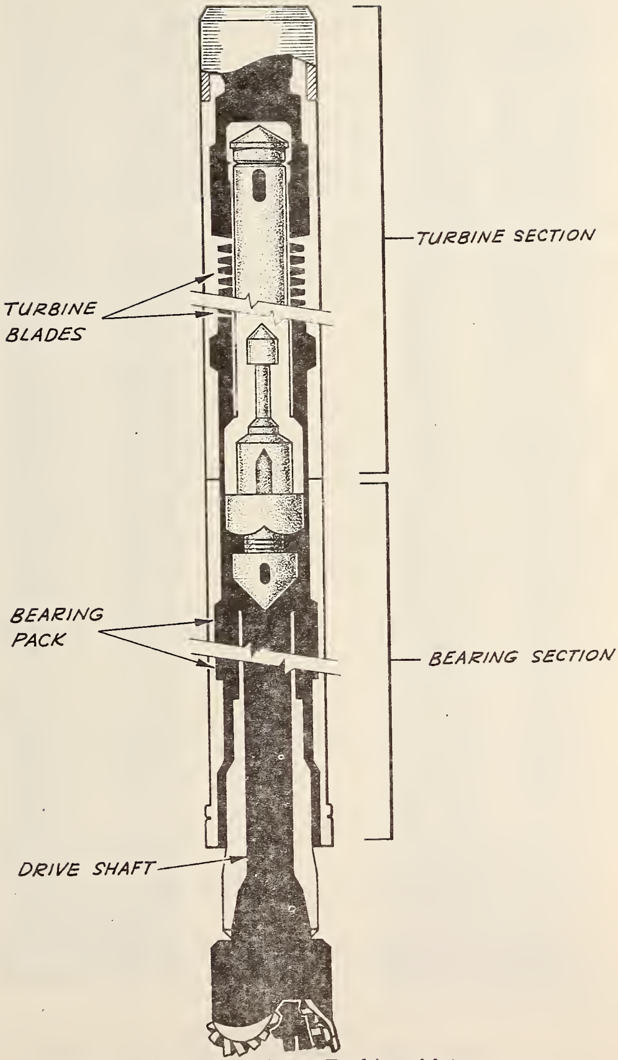


Figure 6.47 - Downhole Turbine Motor

physical displacement rather than by the inertial impact of the fluid. They fall in the category of low speed hydraulic motors. Conceptually, there are many ways this action can be achieved. However, the only positive displacement down-hole motor in current use seems to be the Dyna-Drill. This is essentially a Moyno pump used in reverse application. The assembly is shown in Figure 6.21. It consists of a dump valve above the motor proper to enable the filling and draining of the drill string before and after operation, a three-stage motor assembly (comprised of a rotor and stator), a connecting rod assembly, a bearing and drive shaft assembly, and a rotating sub to which a conventional bit can be made up.

The Dyna-Drill can be obtained either for use on a bent sub, or in a bent housing configuration. The design of the tool includes a flexible connecting rod, so that the drill housing can be bent at this point without affecting the tool's operating characteristics, Figure 6.48. With this modification the bend in the assembly is located much closer to the bit than with the conventional bent sub-assembly.

There are several advantages to this configuration:

There is less lateral displacement of the tool in the borehole.

The tool is easier to orient.

There is less damage to the borehole.

The drill bit approach angle to the formation is increased.

For any bend angle, the ratio of the angle changes to the length of hole drilled is increased.

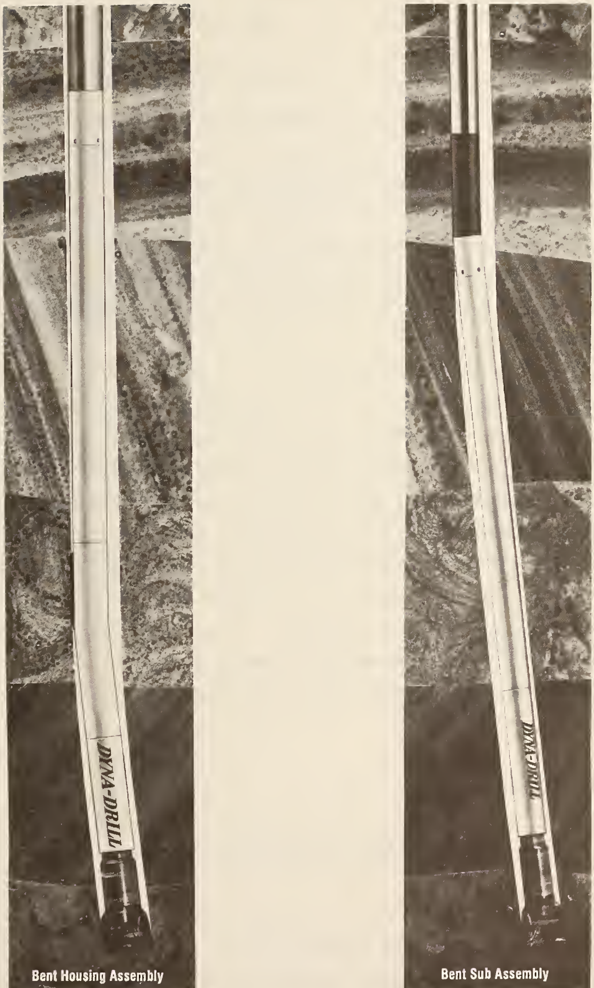


Figure 6.48 - Bent Housing and Bent Sub Dyna-Drill Assemblies
(Courtesy, Dyna-Drill Co.)

It provides a stiffer, more stable configuration.

In operating both the turbine and the Dyna-Drill, there is a characteristic that other types of deflection tools do not have. This is the generation of reaction torque. Reaction torque is the result of the drilling fluid flowing against the stator, trying to rotate the drill string to the left while the rotor and bit rotate to the right. This phenomenon must be taken into account when orienting down hole motors. The direction in which the tool faces, as determined by a single shot survey will in general not be the direction it will go when drilling commences.

Experience in a specific geological area, with a specific drill string, is the only way to truly learn how to compensate for reaction torque in that configuration. One rule of thumb often used is to allow 10^{o} per 1,000 feet when drilling in soft formations and 5^{o} per 1,000 feet for hard formations. In other words, the motor is faced 5^{o} to 10^{o} to the right (clockwise) for each 1,000 feet of hole length. Thus, when the motor is activated, reaction torque will turn the tool back in the proper direction. Even with the above rules of thumb, reaction torque presented a vexing problem until the advent of the survey steering tool discussed in Section 6.4.3.1.

Manufacturers of deflection tools are listed in Appendix A.

6.4.4 Guidance Capabilities

For the most part, adequate statistical test data are lacking to evaluate what the limits of guidance accuracy are. No truly objective projection of what can be achieved can be made without such a base line.

Two reasonable samples of data have been obtained, one set for survey accuracy and one set for steering accuracy. Neither set is truly representative of the long-range horizontal drilling problem. However, they are adequate to establish a point of departure, to serve until better data are available.

6.4.4.1 Survey Accuracy

The state-of-the-art in horizontal and near horizontal survey instrumentation is represented by the single shot and multi-shot magnetic survey devices.

In January of 1963, Sperry-Sun conducted a controlled experiment to determine the degree of accuracy of Sperry-Sun survey equipment. Hurricane Mesa, St. George County, Utah, near Zion National Park, was selected as the test site. A string of aluminum pipe was laid from the top along the mountainside of the Mesa. After an initial 250 foot (76 m) drop, the average angle of inclination was 55° over a course of 2580 feet (786 m) long.

Tests were run on magnetic multi-shot and slim-hole gyroscope multi-shot devices. An independent survey organization was called in to survey the pipeline with third-order accuracy.

To fully exploit the checking and accuracy of Sperry-Sun directional survey services, a series of both continuous magnetic surveys as well as slim-hole gyroscopic surveys were run.

In these tests different components of instruments were utilized to eliminate biases caused by individual units. Three (3) different surveying engineers were used to eliminate interpretive biases that otherwise might cloud results. The gyro equipment is not available for horizontal surveying. A different gimbal mounting would be required. Therefore, only the results of the magnetic multi-shot will be discussed.

Four surveys of the pipeline were made using the continuous magnetic multi-shot method. These consisted of three different runs at 30 foot (9 m) intervals and one run at 100 foot (30 m) intervals. The 30 foot (9 m) intervals could be expected to give better statistical accuracy, but the 100 foot (30 m) interval was run as more representative of oil field operations.

Figure 6.49 is a picture of a 0-90° display of a magnetic multi-shot. It can be read to an accuracy of about $\pm$ 1/2 degree in elevation and probably a little better than one degree in azimuth. An estimate of a combined reading error of one degree would seem reasonable.

With a survey interval of 30 feet (9 m) a 2580 foot (786 m) run would have 86 points, while a 100 foot (30 m) interval would provide 25 points.

The equation for total error, ϵ, in feet is:

$$\epsilon = \epsilon_f + \left(\frac{\pi I}{180}\right) \left[\epsilon_r (N)^{1/2} + \epsilon_b (N) \right]$$

Where:

ϵ = Root Mean Square (rms) Error in Feet.

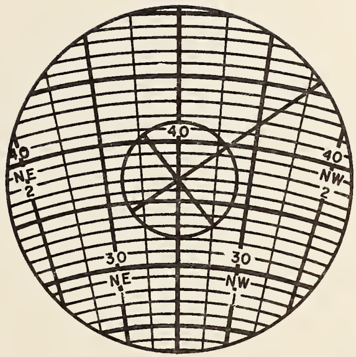
ϵ_f = Fixed Offset Error in Feet (normally negligible)

ϵ_r = Resulting Error in Degrees (random errors)

ϵ_b = Bias Error in Degrees (mostly calibration error)

I = The Reading Interval in Feet

N = The Number of Stations Read.



Interpretation:

Inclination = 37°
Direction = 0° Magnetic

Figure 6.49. 0-90° Compass Angle Picture

Since these tests were initiated to establish a baseline instrumental survey, it is safe to assume that all possible steps were taken to eliminate both calibration and bias errors.

Thus, we can assume the following:

$\epsilon_f = \epsilon_b = 0$

$\epsilon_r = 1°$

I = 30 ft. (9 m), N = 86, and

I = 100 ft. (30 m), N = 25.

For these conditions:

$$\epsilon = .0175 \; I \; \epsilon_r (N)^{1/2} \text{ ft.}$$

or

ϵ = 4.85 feet for the 30 foot (9 m) interval

and

ϵ = 8.73 feet for the 100 foot (30 m) interval.

Figure 6.50 is a planview of the last fifty feet of the survey. The rms error of the three, 30 foot (9 m) interval runs is 5 feet (1.5 m).

It is dangerous to try to extrapolate data from a 50° inclination to the horizontal or 90° inclination, because a completely different set of parameters becomes dominant. The basic high-angle compass, (0-130°) card (Figure 6.51) has somewhat better resolution than the 0-90° card. Possibly a basic resolution of $\pm$ .25 degrees with an operational reading accuracy could be achieved. Bias errors will probably predominate if a reasonable survey increment is used. In general, maximum bias errors would be expected to fall within $\pm$ 1° in elevation and $\pm$ 2.5 degrees in azimuth. These would be under normal operating conditions, where results can be expected to degrade.

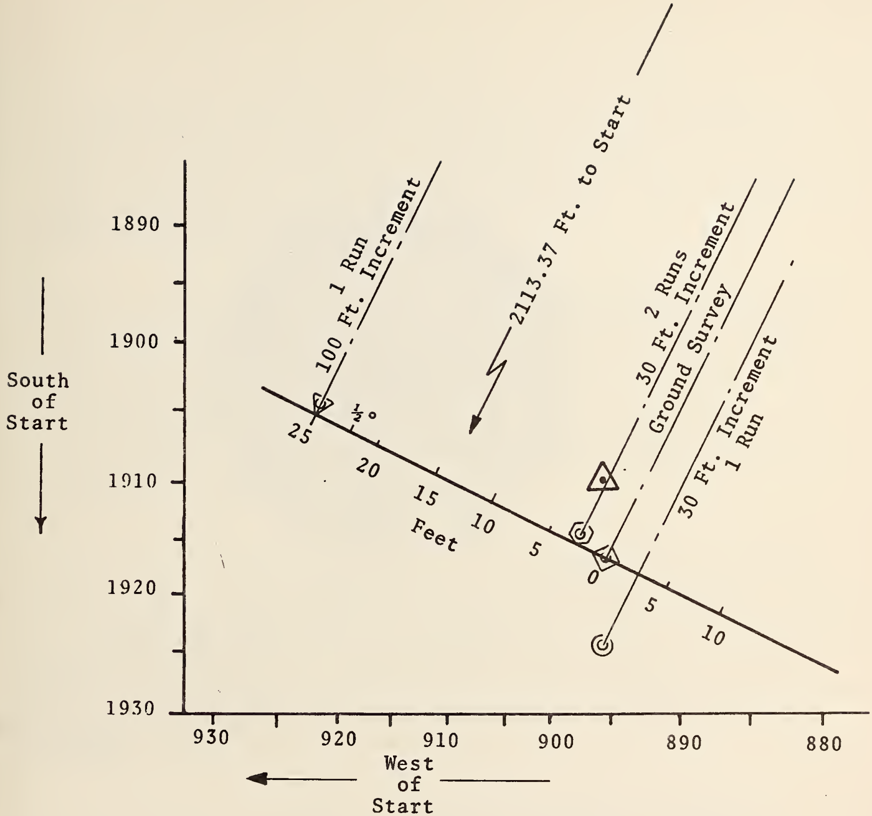
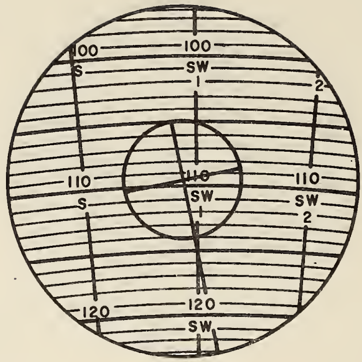


Figure 6.50. Sperry-Sun Calibration Accuracy Determination



Interpretation:

Inclination = 109 3/4°

Direction = 9° Southwest
Magnetic

Figure 6.51. 0-130° (High Angle) Compass Angle Picture

For utmost accuracies, field procedures can evolve which would probably diminish these bias errors by a factor of four or five to minimum values in the order of $\pm .25°$ in elevation and possibly $\pm .5°$ in azimuth. These procedures will require repeated calibration, and exploitation of any peculiarities of the local conditions.

Claims for gyroscopic survey accuracy equipment are about an order of magnitude better than magnetic instruments. [± 1 ft (0.305 m) deviation for 1,000 ft (305 m) linear distance.][29] However, this equipment must be custom built for horizontal applications and its probable cost is 2 to 4 times that of available magnetic survey devices.[33] In addition, the devices have not yet been proven in horizontal applications.

The survey steering tool would be a valuable aid in controlling the accuracy of direction changes. However, as in the case of gyroscopic survey instruments, the device must be custom made for horizontal applications and it has not yet been applied to the horizontal drilling problem. Daily charges for total costs associated with survey steering tools can run to 20 times the cost of available magnetic survey tools.[32]

6.4.4.2 Steering Capability and Accuracy

Review of horizontal drilling case histories leads to the conclusion that there are essentially three available state-of-the-art techniques for steering horizontal drilling. These include:

(1) Variations in drilling assembly configuration along with adjustments in rotational speed and thrust to achieve vertical deviation control. (The fulcrum principal.)

(2) Use of the whipstock or wedge to control vertical and azimuthal deviation.

(3) Use of the Dyna-Drill with a bent sub or bent housing to control vertical and azimuthal deviation.

The fulcrum principal has proven successful in horizontal drilling programs conducted in soft materials with both diamond coring bits and rolling cutter bits. (Items 4, 15, and 17, Table 2.1) The effectiveness of this procedure has not been determined in medium and hard rock.

Whipstocking (wedging) has been employed in all long horizontal drilling in medium and hard rock conducted with diamond coring equipment. (Items 2, 3, 5, and 16, Table 2.1) Whipstocking has been noted to be relatively ineffective in soft materials.[11,29]

The 1.75 in. (44.5 mm) Dyna-Drill has been an effective deflection tool in soft materials with both diamond and rolling cutter bits but information on its performance in medium and hard rock is lacking. The 5 in. (127 mm) Dyna-Drill has been effective in deflecting horizontal holes drilled in soft materials and angle holes in soft, medium, and hard rock.

Table 6.8 is a summary of the drilling accuracies of twenty holes made by the Atomic Energy Commission. All these holes are in the same locality. Thus, conditions are probably as thoroughly standardized as possible to provide a reasonable base line estimate.

If these data are classed into two groups by date, the holes drilled between 1967 and the end of 1971 have a mean error of 26.8 feet. The holes drilled in 1972 and 1973 have a mean error of only 6.2 feet. There seems to be a very obvious learning curve effect.

Table 6.8 : Long Underground Horizontal Exploratory Drill Holes and Target Results

Nevada Test Site 1967 - 1973

HOLE NO.	HOLE DEPTH IN FEET	DEVIATION FROM 10' x 10' TARGET HORIZONTAL	VERTICAL	DATE COMPLETED
U12e.11 - 1	830	.2' LT	6.10' LOW	11-67
U12t.01 - 1	2001	1.3' LT	5.85' HIGH	12-68
U12t.02 - 1	1142	28.25' RT	-0-	1-69
U12t.02 - 2	2443	83.2' RT **	4.04' LOW	3-69
U12t.02 - 3	2700	212.0' RT *	0.4' HIGH	6-69
U12e.12 - 1	906	21.81' RT	40.72' LOW	7-69
U12e.12 - 2	858	7.36' RT	5.69' LOW	8-69
U12e.07 - 1	1452	24.46' RT	20.44' LOW	11-70
U12e.05 - 2	2389	21.3' RT	16.83' LOW	1-71
U12e.05 - 3	1114	.90' LT	12.5' LOW	2-71
U12e.06 - 1	1488	17.6' RT	1.19' HIGH	4-71
U12e.15 - 1	1404	1.33' LT	-0-	3-72
U12e.15 - 2	2500	3.86' RT	-0-	7-72
U12e.14 - 2	335	-0-	8.36' LOW	ABAND. 8-1-72
U12e.14 - 2A	1024	11.79' LT	1.9' HIGH	8-72
U12t.03 - 1	3690	186.49' RT ***	227.25' LOW	11-72
U12c.02 - 1	2649	2.96' RT	6.5' HIGH	11-72
U12c.14 - 3	1376	8.2' RT	-0-	12-72
U12t.03 - 2	1544	1.9' RT	5.0' HIGH	12-72
U12c.07 - 3	2653	3.36' RT	-0-	2-73

* NO ATTEMPT WAS MADE TO CORRECT FOR EXCESSIVE HORIZONTAL DEVIATION TO RIGHT.

** 5 WHIPSTOCKS TO LEFT WITH NO BENEFIT.

*** HOLE PERMITTED TO DEVIATE TO RIGHT AND DOWN.

Figure 6.52 is a plot of this data. There seems to be no observable angular error as a function of distance. It is believed that these holes have probably not penetrated to a depth where the angular effect has become appreciable. As holes get deeper and torsional and frictional affects become greater, the errors can be expected to increase. This data could only be considered typical of small diameter diamond core drilling with whipstock steering.

The early data from these holes is probably more representative of what could be obtained in a new hole in an undefined location. Thus, on the average, this hole could be expected to be steered within a 30-foot (9 m) radius. It would seem reasonable that the later data could be considered representative of an experienced crew, working to achieve the utmost in accuracy. Thus, steering to within a 6-foot (1.8 m) radius should be a realistic goal. However, re-direction and re-drilling portions of the hole would have to be expected.

6.4.4.3 Conclusions

When survey and steering error are combined, total guidance error in feet is:

$$E_T = \sqrt{E_S^2 + \left(\frac{\pi}{180}\right)^2 \left(E_C^2 L^2 + E_R^2 LI\right)}$$

where

E_T	Total error in feet.
E_S	Steering error in feet.
ϵ_c	Calibration error in degrees.
ϵ_r	Random error in degrees.
L	Hole length in feet.
I	Survey interval in feet.

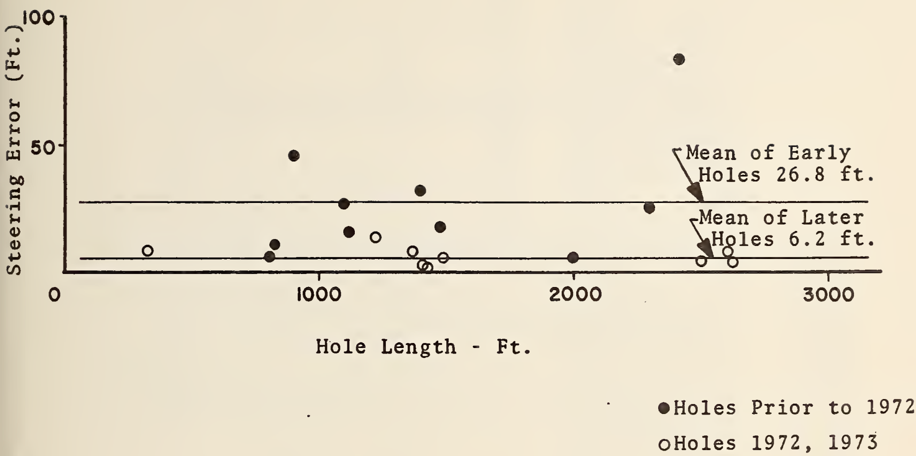


Figure 6.52. Steering Error Versus Length

Table 6.9 - Maximum and Minimum Expected Values for Surveying and Steering Parameters

Variable	Maximum Value Feet/Degrees (Meters)		Minimum Value Feet/Degrees (Meters)		Nominal Value Feet/Degrees (Meters)	
	Azimuth	Elevation	Azimuth	Elevation	Azimuth	Elevation
E_S	-	-	-	-	$\pm$ 6 (1.82)	$\pm$ 6 (1.82)
ϵ_c	$\pm 2.5°$	$\pm 1°$	$\pm .5°$	$\pm .25°$	-	-
ϵ_r	$\pm 1°$	$\pm .5$	± 2.5	$\pm .25$	-	-
I					30 (9.1)	

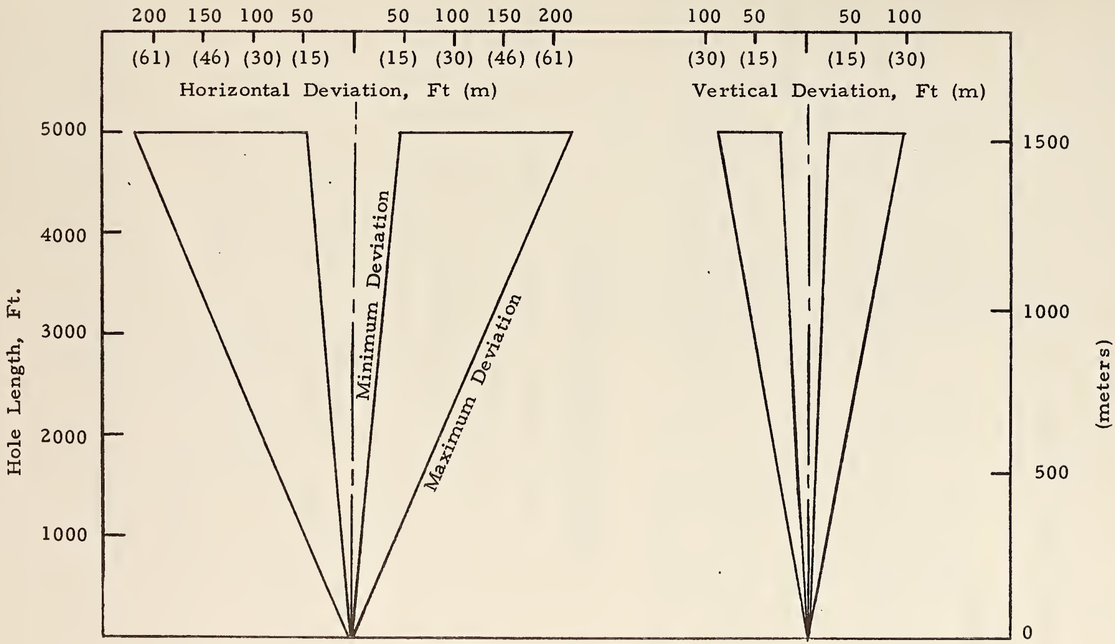


Figure 6.53. State-of-the-Art Guidance Capabilities

Table 6.9 indicates maximum and minimum or nominal values for the appropriate parameters projected from Sections 6.4.4.1 and 6.4.4.2. When these numbers are plugged into the equation above, the results can be plotted as maximum and minimum anticipated guidance errors as in Figure 6.53.

6.5 Fishing

The term "fish" is used to describe any piece of equipment in the bore hole which the driller does not want in the hole and which cannot be retrieved at will. The term "fishing tool" applies to special equipment which is added to the drill string to engage and retrieve the fish. The term "fishing" applies to the application of fishing tools and associated procedures to remove the fish from the bore hole. The discussion which follows owes much to the Rotary Drilling Handbook by J.E. Brantly.[34] Chapter XXI of this reference presents a detailed discussion of fishing procedures.

6.5.1 Causes of Fishing Operations

The most common cause of fishing jobs is a drill string failure which results in the string breaking in two. This is commonly referred to as a "twistoff". The section of drill string above the break can be withdrawn in the usual manner, but a fishing operation is required to recover the section of drill string below the twistoff.

Another common cause of fishing jobs is sticking the string. If excessive torque or tension are applied to free the drill string a break can occur. Normally, if the string cannot be freed, it is intentionally separated by reversing the drill string rotation. A fishing operation is again required to remove the drilling equipment below the point of failure or intentional separation.

Bit failures are another common cause of fishing jobs. Bit components from failed bits are practically undrillable and must be removed before drilling can resume.

Other causes of fishing jobs are the loss of instruments in the hole and wireline breakage.

6.5.2 Prevention of Fishing Operations

The incidence of twistoff failures can be decreased by careful torquing of drill pipe connections and frequent inspection of drill string components.

The most important element in preventing sticking of the drill string is careful control of the drilling mud program. The ability of the drilling mud to stabilize the hole and its lubricating properties are factors in preventing sticking of the string.

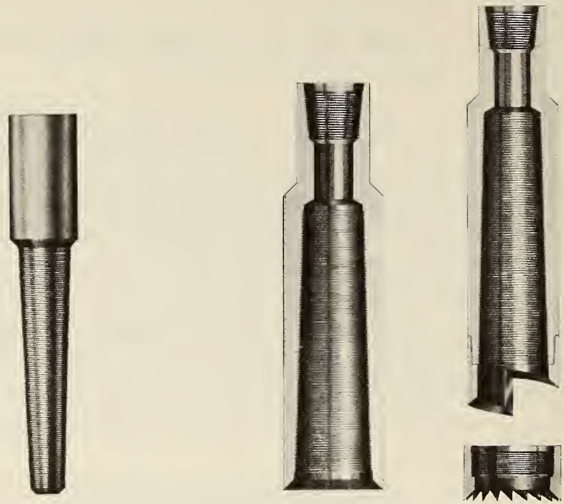
Bit failures can be avoided by ensuring that the proper bit weight and rotational speed are employed. Bit performance must be carefully monitored so that worn bits are replaced before they fail.

6.5.3 Fishing Tools

Primary fishing tools include:

(1) Rotary taper taps and rotary die collars.
(2) Circulating and releasing overshots.
(3) Fishing magnets.
(4) Junk baskets.

Rotary taper taps (Figure 6.54(a)) have tapered case-hardened male threads which screw into a fish, and rotary die collars (Figure 6.54(b)) have tapered case-hardened threads which screw onto a fish. Both devices are used to retrieve lost sections of drill string.



(a) Rotary Taper Tap

(b) Rotary Die Collars

Figure 6.54 - Primary Fishing Tools (Courtesy, Houston Engineers, Inc.)

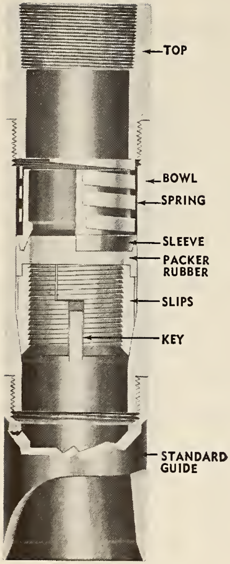
The single bowl and double bowl releasing and circulating overshots (Figure 6.54 (c)) are lowered over the fish to grasp it. The overshot can engage and release the fish as often as may be necessary to free it, giving it a clear advantage over the non-releasing taper taps and die collars. The circulating overshot is sealed to the fish when engaged so that circulation may be resumed to aid in freeing the fish.

Fishing magnets are used to retrieve broken bits and other smaller objects from the hole (Figure 6.54(d)).

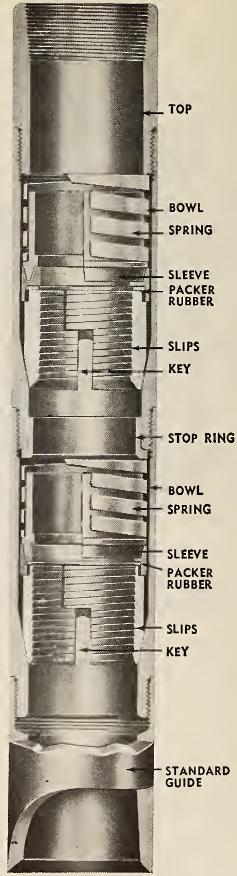
The junk basket (Figure 6.54 (e)) is made up of a long hollow barrel and a shoe on the lower end with hard-faced teeth capable of drilling into hard formations. Inside the shoe is a catcher having hinged fingers. The junk basket is lowered over the fish and rotated so that the shoe cuts a core from the formation. The hinged fingers of the catcher fold back as the tool is being rotated and driven over the fish and the core. When the junk basket is pulled back, the fingers of the catcher dig into the core and cut off a section, thus retaining the fish and core within the barrel.

The tools described above are designed to engage the fish and permit force to be exerted on it so that it may be withdrawn from the bore hole.

There are a number of other important fishing tools, sometimes called accessory fishing tools, which are used to aid and safeguard the operation of the basic engaging tools, to provide means for exerting unusual forces against the fish, to loosen the fish or separate it into removable lengths, or to prevent the need for fishing jobs in the first place. Fishing tools which fall into this category include rotary jars, bumper subs, safety joints, free point indicators and backoff shots, wash-pipe, external cutters, bumper safety joints, and jar safety joints. These tools are discussed below.



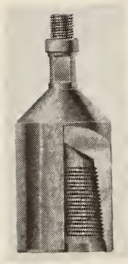
Single Bowl Type Series "AI"



Double Bowl Type Series "AI"

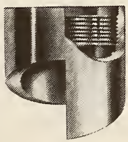
(c) Releasing and Circulating Overshots

Figure 6.54 - Primary Fishing Tools - Cont. (Courtesy, Hendershot Tool Co.)



Wire Line Adapter

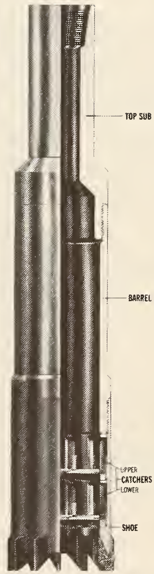
Optional Guides



Lipped Guide

Mill Guide

(d) Fishing Magnet



(e) Junk Basket

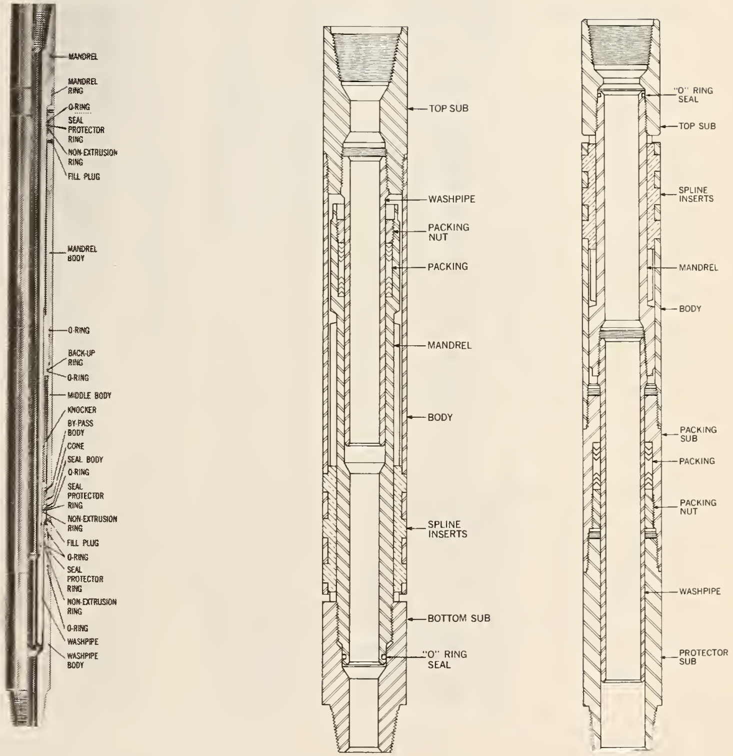
Figure 6.54 - Primary Fishing Tools - Cont. (Courtesy, Bowen Tools, Inc.)

(1) "Rotary Jars: Rotary jars are installed in fishing strings to enable the driller to strike heavy upward blows against an engaged fish to jar it loose from its stuck position. They are also included or made up in strings during testing, coring, and washing-over operations to act as safeguards and to provide the means with which to loosen the string should it become stuck.

"All rotary jars have in them a restraining mechanism which holds the telescopic elements of the tool in a closed position until sufficient upward pull is exerted to trip the restraining mechanism and allow the telescopic elements to move into their extended position. In operation, the strain of the upward pull will stretch the drill pipe and, when the jar trips, the upward surge of the drill pipe in returning to its normal length will cause it to strike a severe blow. In order to concentrate the jarring blow at the fish and make it effective, it is important to include several drill collars in the fishing string immediately above the jar.

"Some rotary jars depend upon the constant maintenance of torque in the string to trip their restraining mechanisms. Other more widely used rotary jars incorporate simple mechanical or hydraulic restraining mechanisms, and are tripped with a straight upward pull of the fishing. (Figure 6.55(a).)

(2) "Bumper Subs: To assure the driller further of the ability to release the overshot in the event it proves impossible to pull the fish, it is good practice to install a bumper sub in the fishing string immediately above the safety joint. Most bumper subs are merely expansion joints whose two sections are free to move vertically in relation to each other, but are prevented from rotating independently. With this tool in the string, the driller or the man on the brake is able to deliver the sharp downward blow which is required to break the engagement of the gripping member of the overshot with the fish, and the bumper sub will also transmit the torque required to complete the releasing operation. The presence of a bumper sub in the string is also definitely advantageous in releasing the overshot from a recovered fish at the top of the hole. It simplifies the operation and eliminates the necessity of resorting to awkward and dangerous measures (Figure 6. 55(b).)



(a) Rotary Jar (Courtesy, Bowen Tools Inc.)

(b) Bumper Subs (Courtesy, Baash-Ross Div., Joy Mfg. Co.)

(c) Safety Joints

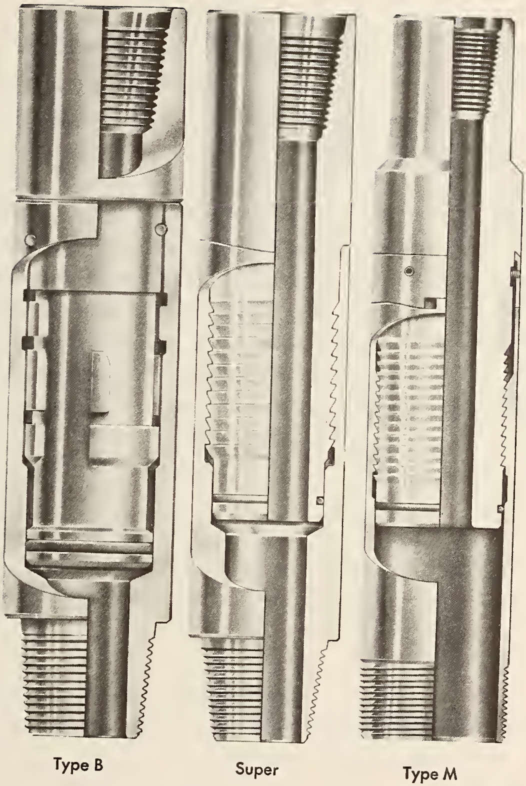
Figure 6.55 - Accessory Fishing Tools

(3) "Safety Joints: The sole purpose of the many types of safety joints is to provide the fishing string operator with a connection readily releasable at any point in the string at which it is placed. Such tools provide definite safety advantages in both fishing and drilling operations.

"The importance of using a 'releasing' overshot to retrieve a lost section of the drilling string has been stressed previously herein. As a precautionary measure against the possibility of failure on the part of the overshot's releasing mechanism, it is good practice to install a safety joint in the fishing string and to locate it immediately above the overshot. Neither tool is adversely affected by the other, because overshots are released with rotation in a screwing (right-hand) direction and the safety joints are released with rotation in an unscrewing (left-hand) direction. Thus the driller has double assurance of the ability to disconnect and withdraw his entire string should it be found impossible to pull the fish.

"Safety joints, the outside diameters of which correspond to the outside diameters of the tool joints in the drill pipe, should be selected. This will simplify any fishing operations which might necessitate engagement of the safety joint with an overshot. In order not to impair circulation and to permit the running of wire line equipment, the inside diameter of the safety joint should be equal to the inside diameter of the tool joints on the drill pipe.

"In washing-over operations, it is good practice to install a special safety joint, called a washover safety joint, at the top of the wash-pipe. If the wash-pipe should stick, this tool can be separated and the portion of this special safety joint which is left in the hole has the same inside diameter as the wash-pipe. Thus there will be no impairment at the top of the fish, and proper tools can be lowered into the stuck wash-pipe to perform recovery operations. (Figure 6.55(c).)



(c) Safety Joints

Figure 6.55 - Accessory Fishing Tools - Cont. (Courtesy, Homco International, Inc.)

(4) "<u>Freepoint Indicators and Backoff Shots</u>: As the name implies, freepoint indicators are lowered into stuck strings and operated to determine the lowest point at which the string is free. Thereafter, the weight of the unstuck portion of the string is picked up the left-hand torque is applied, and a companion tool, called a 'backoff shot,' is detonated within the lowest connection of the free portion of the string. The combination of these forces will cause the tool joint to back off and separate the drilling string at this point.

"All freepoint indicators have contact points at the upper and lower extremities of the tool, and these contact points engage the inside of the drill pipe either mechanically or magnetically. The tools are electrically operated and, when their contact points are in engagement, an upward pull in the string will record a degree of stretch if the string is free and no stretch if the string is stuck. Thus, by setting the instrument at various depths in the drilling string, and then stretching the string, it is possible accurately to locate the lowest point at which it is free.

"Whenever it becomes necessary to separate a stuck string, it is important to do so at the lowest point in order to leave as little as possible for subsequent recovery. (Figure 6.55(d).)

(5) "<u>Wash-Pipe</u>: Wash-pipe and rotary shoes are used to cut clearance between a stuck fish and the walls of the hole to loosen it and to permit its removal.

"The pipe selected to perform this operation must have an outside diameter small enough to operate in the drilled hole, and an inside diameter large enough to pass over the fish. Though threaded and coupled casing is frequently used for wash-pipe, the torque strains of the operation often exceed the limits of these connections. Special washover pipe or wash-pipe casing with shouldered connections is recommended.

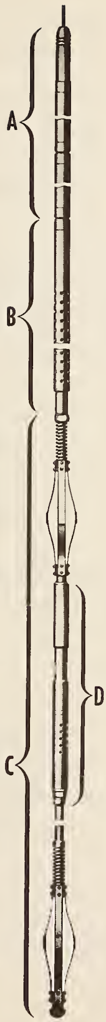
DESCRIPTION OF THE DIA-LOG "FPI" FREE POINT INDICATOR

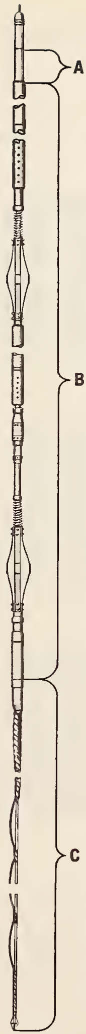
A. WEIGHTS: Ample weights are run above the tool to overcome resistance of the belly springs and assure passage of the tool through heavy mud, lost circulation material and minor bridges.

B. TUBULAR JARS: The jar section of the "FPI" Indicator provides means for separating the weights from the electronic strain gauge element of the tool. Thus, by raising and clearing the weights with the jar travel, the belly springs support only the strain gauge section while torque or stretch readings are being made.

C. UPPER & LOWER BELLY SPRING ASSEMBLIES: The Electronic Indicating Element is held in place in the pipe by two sets of adjustable belly springs. Use of coil springs in combination with the flat belly springs assures greater spring flexibility, permitting the tool to pass through comparatively small openings without losing its holding power in larger pipe. For example, with the springs set to hold in 4½" drill pipe, the tool will operate efficiently in 2" I.D. drill collars—or will pass through openings in fishing tools as small as 1¾" I.D. Weight of the tool itself (less weights and jars) is only 16 lbs.—a weight easily supported by either set of belly springs.

D. ELECTRONIC STRAIN GAUGE ELEMENT: This highly-sensitive strain gauge measures stretch and torque movement in the pipe, and transmits the signal to the surface equipment.





DIA-LOG COMBINATION FREE POINT INDICATOR AND BACK-OFF SERVICE

The Dia-Log String Shot Back-Off can be run in combination with the Dia-Log Free Point Indicator (as shown at left) to recover any size of stuck drill pipe, drill collars, wash pipe or tubing. By applying reverse torque at the connection to be backed-off—and firing the Dia-Log String Shot across this connection—the desired joint can be unscrewed. The Back-Off shot is positioned at exactly the right place across a connection by means of the electronic Dia-Log Collar Locator.

A Back-Off can be accomplished in straight or directional holes, and in holes where high temperatures and high pressures are encountered. The explosive jar is specially designed to prevent any damage to the pipe or to the threaded connection.

A Dia-Log String Shot may be run in combination with any of the three sizes of Dia-Log Free Point Indicators described on the facing page. By using the Combination Free Point Indicator and Back-Off Service *one* run is all that is required to determine the deepest point of free pipe and to effect recovery of the pipe at the deepest free connection.

Illustrated at left is a typical Dia-Log Combination Free Point Indicator and String Shot Back-Off assembly for both indicating the deepest free point of the stuck pipe and pin-pointing the desired connection to be backed off—both on one trip into the hole, thus saving valuable rig time and increasing operating efficiencies. "A" is the electronic Collar Locator, "B" is the Dia-Log Free Point Indicator (described in greater detail on page 1361) and "C" is the String Shot that effects recovery of the stuck pipe (in conjunction with reverse torque) at the deepest free connection.

(d)

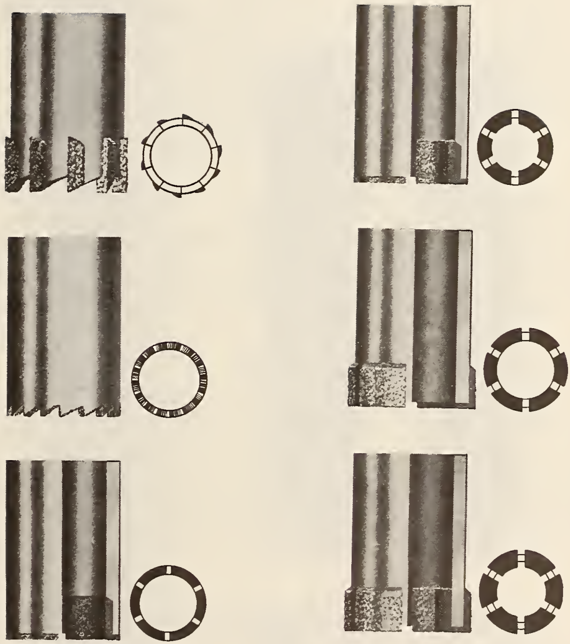
Figure 6.55 - Accessory Fishing Tools - Cont. (Courtesy, The Dial-Log Co.)

"The hole conditions and the amounts of clearance which exist between the wash-pipe and the drilled hole and between the wash-pipe and the fish are important factors in determining the length of fish which can be washed over safely in any one run. Crooked holes and tight clearances restrict safe operations to short strings of wash-pipe. Straight holes and generous clearances permit the safe operation of longer strings of wash-pipe.

"The rotary shoe which is installed at the bottom of the wash-pipe should have hard-faced teeth of the proper type to cut the material against which it will be lowered and rotated. The tooth form should be coarse if the formation is soft, and fine if the formation is hard. If metal is to be cut, the teeth should be faced with granular tungsten carbide. The outside diameter of the shoe should be larger than the outside diameter of the wash-pipe, and the inside diameter of the shoe should be slightly smaller than the inside diameter of the wash-pipe to protect the latter from sticking. (Figure 6.55(e).)

(6) <u>"External Cutters:</u> External cutters are resorted to when all other means have failed, and a stuck string of drill pipe can be recovered only by cutting it into removable lengths.

"The fish must first be washed over in the usual manner. Then an external cutter is installed in the bottom of the wash-pipe in place of the rotary shoe and run into the hole and lowered over the stuck drill pipe to the proper depth. A cutting operation is then performed and, upon its completion, the cut section of the drill pipe will be retained inside the wash-pipe by the external cutter, and it will be recovered as the wash-pipe and external cutter are pulled from the hole. These steps must be repeated until all of the stuck drill pipe is recovered. (Figure 6.55(f).)



(e) Rotary Washover Shoes

Figure 6.55 - Accessory Fishing Tools - Cont. (Courtesy, Tri-State Oil Tool Industries, Inc.

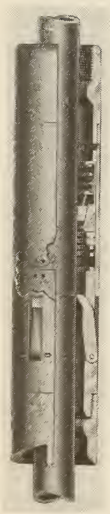


FIG. 178
External Upset Joints. Dogs catch under the upset, actuating the knives and also retain the cut-off pipe.

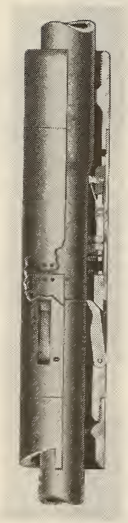


FIG. 177
API JOINTS. Overshot Spring catch under a tool joint or coupling to actuate the knives and retain the cut-off section.

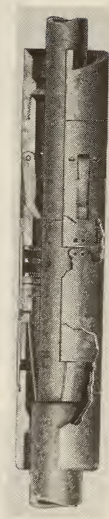
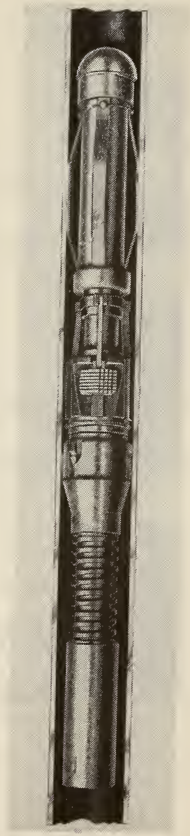


FIG 179
External Flush Joints Straight Slips grip into flush pipe at any point, both actuating the knives and retaining the cut-off pipe.

(f) External Pipe Cutter



(f) Internal Pipe Cutter

Figure 6.55 - Accessory Fishing Tools (Courtesy, Baash-Ross Div., Joy Mfg. Co.)

(7) "Bumper Safety Joints: Bumper safety joints are combination tools which provide the services of both a bumper sub and a safety joint. Thus, at the will of the operator, they can be operated to deliver heavy downward blows, or they can be separated.

"They are used most effectively in drilling strings to prevent fishing jobs or to simplify them if they do occur. With a bumper safety joint in place, if the drilling string is pulled into a keyseat as it is being withdrawn from the hole, or if it should stick from any other cause, it is probable that this tool can loosen the stuck pipe. Otherwise, the tool can be separated and the fishing job is probably simplified.

(8) "Jar Safety Joints: Jar safety joints are combination tools which provide the services of both a rotary jar and a safety joint. In other words, they can be called upon to deliver heavy upward blows or they can be separated at the will of the operator.

"Because of these dual characteristics, these tools are widely used as safety devices to prevent fishing jobs completely or to simplify them when they do occur. With a jar safety joint in place during drilling, coring, testing, or washing-over operations, it is most probable the string can be jarred loose should it stick -- and, if not, the tool can be separated and the fishing job thereby simplified."[34]

6.5.4 Conclusions

The tools and procedures described in Section 6.5.3 have been developed primarily for petroleum drilling; in other words, vertical and near vertical drilling. This equipment and the procedures associated with its use should be applicable to horizontal drilling as well. However, fishing experience is very limited in horizontal drilling and documentation in this area is practically nil. Jacobs Associates did report several instances of successful fishing jobs on their horizontal drilling program.[10] These jobs involved the retrieval of twistoffs, and a rotary taper tap was the fishing tool used. At this point we must assume that fishing operations in horizontal drilling will follow petroleum drilling practice. Fishing tool suppliers and fishing service companies are listed in Appendix A. Further detail on fishing practices in petroleum drilling can be found in Chapter XXI of Brantley.[34]

6.6 Sample Taking and Retraction Techniques

One of the most likely purposes of a horizontal drilling project is to obtain core samples along the proposed tunnel alignment. A second requirement prescribed for this study is to investigate techniques for recovering undisturbed samples from gouge. The state-of-the-art of techniques to accomplish these tasks in horizontal bore holes is discussed in the following sections.

6.6.1 Core Sampling

The "standard" technique for obtaining core samples in long horizontal drilling is the diamond wireline technique. The standard wireline core barrel has a bearing system which allows the inner tube, which accepts the core, to remain stationary while the outer tube rotates. This allows good recovery in a wide range of formations. Triple tube wire line core barrels have a third chrome plated, low friction tube located inside the inner tube. This allows good recovery in highly crushed or fractured formations.

Exploration type wireline core barrels are available in the A thru P sizes. Table 6.10 gives the hole diameters and core diameters corresponding to these letter notations. As noted in Section 6.1.1, the B and N size barrels are the most widely used sizes for horizontal drilling. Suppliers of wireline coring equipment for the exploratory field are listed in Appendix A.

Diamond wireline equipment has been developed for core sampling in the petroleum field. The equipment consists principally of coring bits and core barrels which are substituted for the rolling cutter bit on a rotary drilling system. Coring bits for this application are available in outside diameters from 4 to 12.25 inches (102 - 311 mm). Cores

TABLE 6.10

WIRELINE CORE BARREL SIZES

Size of Barrel	AQ Inches (mm)	BQ Inches (mm)	NQ Inches (mm)	HQ Inches (mm)	PQ Inches (mm)
Hole Diameter	$1\frac{57}{64}$ (48)	$2\frac{23}{64}$ (60)	$2\frac{63}{64}$ (75.8)	$3\frac{25}{32}$ (96)	$4\frac{53}{64}$ (122.6)
Core Diameter	$1\frac{1}{16}$ (27)	$1\frac{7}{16}$ (36.5)	$1\frac{7}{8}$ (47.6)	$2\frac{1}{2}$ (63.5)	$3\frac{11}{32}$ (85)

from 1.75 to 5.25 inches (45 - 133 mm) in diameter and lengths to 60 feet (18 m) may be obtained with this equipment. Sleeve type core barrels which protect the core from washing are available to improve recovery in soft or broken formations. To our knowledge this equipment has not been applied to horizontal drilling.

Milled tooth and insert type rolling cutter bits have been used as coring bits in vertical drilling. Scripps Institute of Oceanography has reported good results in wireline core drilling with insert type rolling cutter bits.[35]

The continuous core drilling technique discussed in Section 6.1.5 has also been a successful technique for obtaining core samples in vertical applications. With further development work, this technique should be a viable technique for obtaining continuous core samples in horizontal drilling.

6.6.1.1 Split Tube Core Barrels

Split tube core barrels alleviate the problems encountered in trying to remove fractured or fragile core samples from a solid core barrel. Figure 6.56 illustrates a split tube core barrel and incidates how the split tube barrel separates to allow core evaluation. Among the claims made for the split tube core barrel are:

(1) The undisturbed or as-drilled quality of the recovered core permits a near in situ evaluation of the core.

(2) The core is easily transferred from the inner tube to the core box without disturbing the sample.

(3) The split tube design facilitates the removal of expansive or sticky formations from the inner tube.

Split tube conversion kits are available for both wireline and conventional core barrels. Conversion assemblies are available for the B, N, and 3.5 x 2.125 inch (89 x 54 mm) sizes. Lengths of 5 (1.5 m) and 10 feet (3.1 m) are available, except for the B size, which is available in 5 ft (1.5 m) lengths only. Kit costs can run from about $220 per core barrel for the smallest sizes to $340 for the largest.

Christensen Diamond Products of Salt Lake City, Utah offers split tube core barrel conversion kits.

6.6.1.2 Techniques are available to determine the in situ orientation of a core sample. Core orientation services utilize nonmagnetic core barrels with special tungsten carbide inserts. (See Figure 6.57(a).) The carbide inserts scribe a reference mark on the core sample as the core is drilled. (Figure 6.57(b).) A magnetic survey instrument is attached to the core barrel to record hole inclination, bearing, and the orientation of the scribed reference mark.

After the core is recovered, a core Goniometer (Figure 6.58(a)) is used to physically orient the core relative to its original position in the formation. The core can then be analyzed to determine the dip and strike of the bedding, foliation, cleavage, healed or broken joints, contacts, and shears. Thin sections for use in further studies may also be taken. (Figure 6.58(b).)

Another method of reading the oriented core is to assume a plane through the scribe line and the axis of the core and measure all geologic features in reference to this plane and

and the length of the hole. Each point of measurement, or the attitude of a plane measured in reference to the axis of the core, can be rotated to its correct position in space and the position determined by use of a Schmidt Equal Area net. This procedure has been computerized and is offered as a service by Charles S. Robinson and Associates of Denver, Colorado.

Core orientation is available as a service for B, N, 4.5 x 3 inch (114 x 76 mm), 5.75 x 4 inch (146 x 102 mm), and 7.5 x 5.875 inch (191 x 149 mm) size core barrels. Charges are about $325 per day for the B and N sizes and $260 per day for the larger sizes. Standby charges for the service are about $87 per day. Tools can be rented for about $150 per day.

Core orientation service is available from Christensen Diamond Products of Salt Lake City, Utah and Charles S. Robinson and Associates.

6.6.2 Undisturbed Gouge Samples

Two techniques for obtaining relatively undisturbed gouge samples that are commonly used in vertical drilling should be directly applicable to gouge sampling in horizontal drilling. ASTM method D-1587-67 (AASHTO designation: T207-70) describes the procedure for furnishing relatively undisturbed gouge samples using a thin walled sample tube for sample collection. Briefly, this method requires the borehole to be clean and free of debris. The thin wall tube is placed at the bottom of the hole, smoothly pushed into the gouge at the end of the hole, and then twisted two revolutions to break off the sample. The sample so obtained must be properly sealed and packed for shipment to the testing laboratory.

The second technique will obtain a reasonably undisturbed sample in gouge that is hard enough to prevent the smooth insertion of the thin walled sample tube as required by the first method. In this technique, the sample is again collected in a thin walled tube,

The split tube preserves the as-drilled quality of recovered core

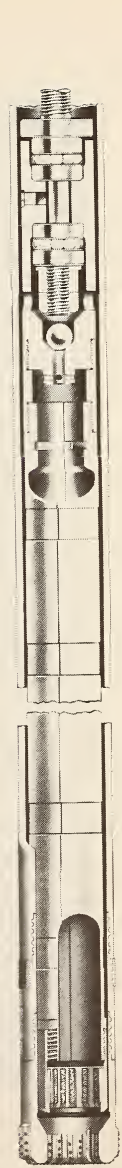


Figure 6.56 - Split Tube Core Barrels
(Courtesy, Christensen Diamond Products)

but insertion of the tube is facilitated by drilling away the gouge outside of and just behind the advancing core tube.

The Osterberg Piston Sampler, manufactured and distributed by Soiltest of Evanston, Illinois, is a device specifically designed to permit collection of a soil sample in accordance with ASTM Method D-1587. It is shown schematically in Figure 6.59(a). The sampler, attached to A or AW drill rod, is placed at the bottom of the bore hole. Drilling fluid is then pumped down the drill rod to the sampler, driving the piston-sampler head into the soil. To free the sample, the device is rotated by rotating the drill string and then retracted by pulling the drill string out of the hole. It is available in core barrel sizes ranging from 2-1/2 inches (64 mm) to 5 inches (127 mm), corresponding to overall diameter between 3-3/8 inches (86 mm) and 5-3/4 inches (146 mm). For small diameter holes, the sample is obtained by removing the drill string, attaching the sampler, sending the drill string back into the hole and removing the drill string when the sample has been obtained. The device could possible be modified to permit pumping it down the drill string on a wireline after a full core barrel has been retrieved.

The second technique can be implemented using the Denison Sampler, Figure 6.59(b), also available from Soiltest. To use the Denison Sampler, the drill string is removed, the sampler is attached to the drill string and sent to the bottom of the hole. The sampler is rotated and thrusted from the surface. The inner barrel, suspended from the outer barrel on ball bearings, advances without rotating, collecting the sample core. The outer barrel, being rotated by the drill string, cuts away the gouge surrounding the core. Minimal drilling fluid circulation during the collection process serves to clear away the small chips produced by the rotating outer barrel. The Denison Sampler is supplied in outside diameters ranging between 3-1/2 inches (89 mm) and 7-3/4 inches (197 mm), recovering samples ranging between 2-3/8 inches (63 mm) and 6-5/16 inches (160 mm) in diameter.

The Lowe-Acker improved piston-plug sampler might also be employed in gouge sampling from horizontal holes. This is

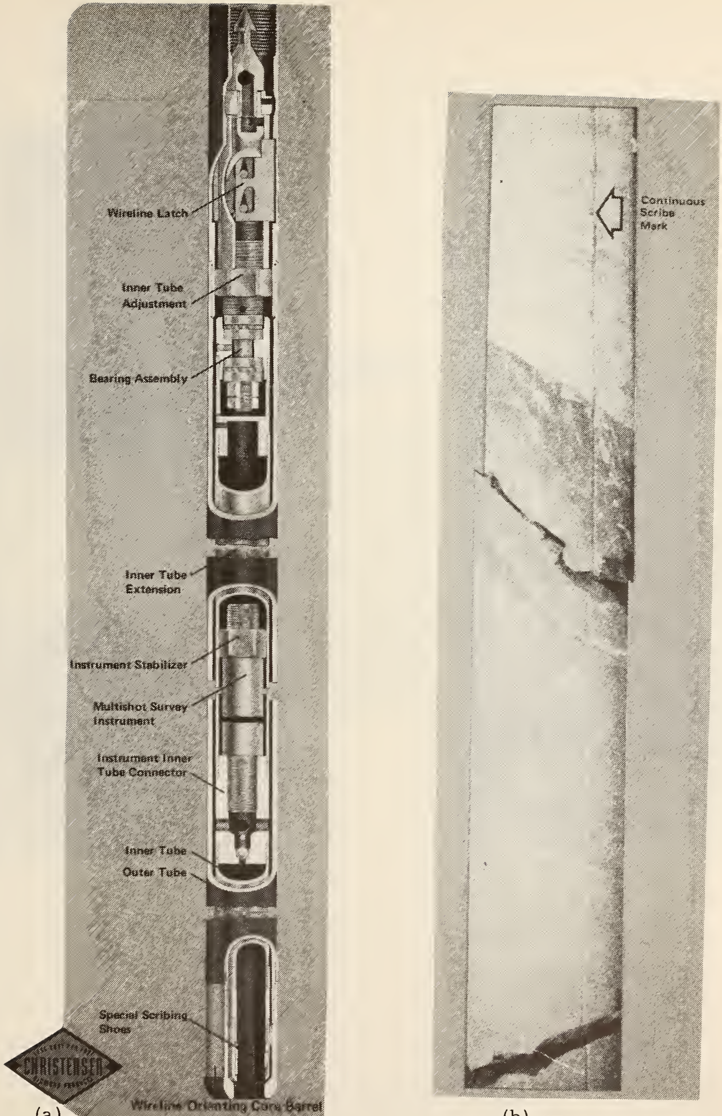
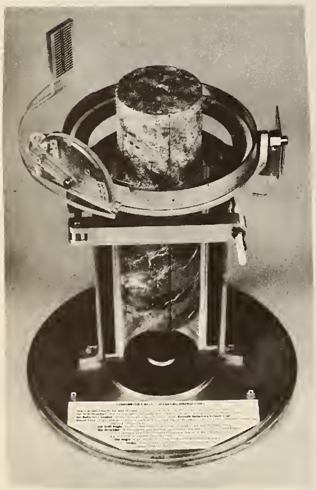


Figure 6.57 - Orienting Core Barrel
and Scribed Core Sample
(Courtesy, Christensen Diamond Products)

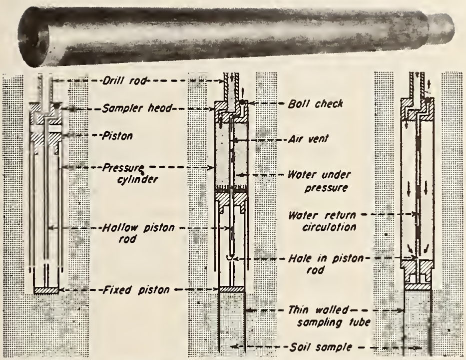
Cores scribed using knives in inner tube shoe.



(a)

(b)

Figure 6.58 - Core Goniometer and Thin Core Sections



OSTERBERG PISTON SAMPLER, NEW MODEL

(a)

(b)

Figure 6.59 - Soil Sampling Devices
(Courtesy, Soiltest Inc.)

an improved sampler which combines the features of the plug type sampler and the stationary piston sampler. This sampler is described as a rugged, heavier duty sampler particularly useful in deep sampling of heavy clay. This sampler is available from Acker Drill Company, Inc..

In considering techniques to sample gouge from horizontal holes, organizations involved in soil sampling activities should be consulted. A list of such companies is included in Appendix B. Among the major concerns involved in manufacturing and/or distributing soil sampling equipment are Acher Drill Company, Inc., Longyear Company, and Soiltest, Inc..

A study now being directed by Dr. Charles H. Dowding of Massachusetts Institute of Technology for FHWA titled, "Determination of the Feasibility of Using Horizontal Penetration Techniques for Pre-excavation Subsurface Investigation in Soft Ground Transportation Tunnels", also addresses the problem of soil sampling in horizontal holes. The report of this study should be available by the end of 1975.

There is also a class of equipment known as side wall coring devices which are capable of obtaining disturbed gouge samples from considerable depths. One such device, used in the petroleum field, obtains core samples by firing steel cups into the hole wall from a gun. The cups are held to the gun body with wires and can be retrieved with the gun on a wireline. Hunt Tool Co. of Houston, Texas manufacturers another type of side wall sampling tool which is illustrated schematically in Figure 6.60. This device can also be run in and out of the hole using wireline techniques. However, side wall coring devices have not been applied to horizontal drilling.

In considering techniques to sample gouge from horizontal holes organizations involved in soil sampling activities should be consulted. A list of such companies is included in Appendix A. Among the major concerns involved in manufacturing and/or distributing soil sampling equipment are Acker Drill Co., Inc., Longyear Co., and Soiltest, Inc.

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6.7 Water Pressure and Permeability Measurements

In investigating tunnel alignments it is particularly desirable to determine in situ ground water pressure and water permeability. The simplest technique for measuring pressure is to shut off the flushing fluid pump and measure the pressure on the fluid feed line. This is at best a gross measure however, and does not give the pressure at a particular point in the hole. Piezometers, such as the Pore Water Pressure Cell, available from Terrametric of Golden, Colorado, can be used to measure water pressure in drill holes. The following sections present specific schemes to perform water pressure and permeability measurements in horizontal holes.

6.7.1 Water Pressure Measurement

To measure the ground water pressure at a particular hole depth, the permeable water bearing strata at the location of the desired water pressure measurement must be isolated from the rest of the hole so the full ground water pressure will be measured. A pressure measuring device placed inside the isolated area will then provide the desired information.

Techniques to accomplish this task are illustrated using equipment available in the petroleum drilling industry. Basic down hole pressure measuring equipment consists of packers to isolate sections of the hole and a variety of down hole pressure recording and transmitting devices. Although this equipment is designed for use in oil well surveying and production monitoring, some of it can be used to provide the desired water pressure measurements.

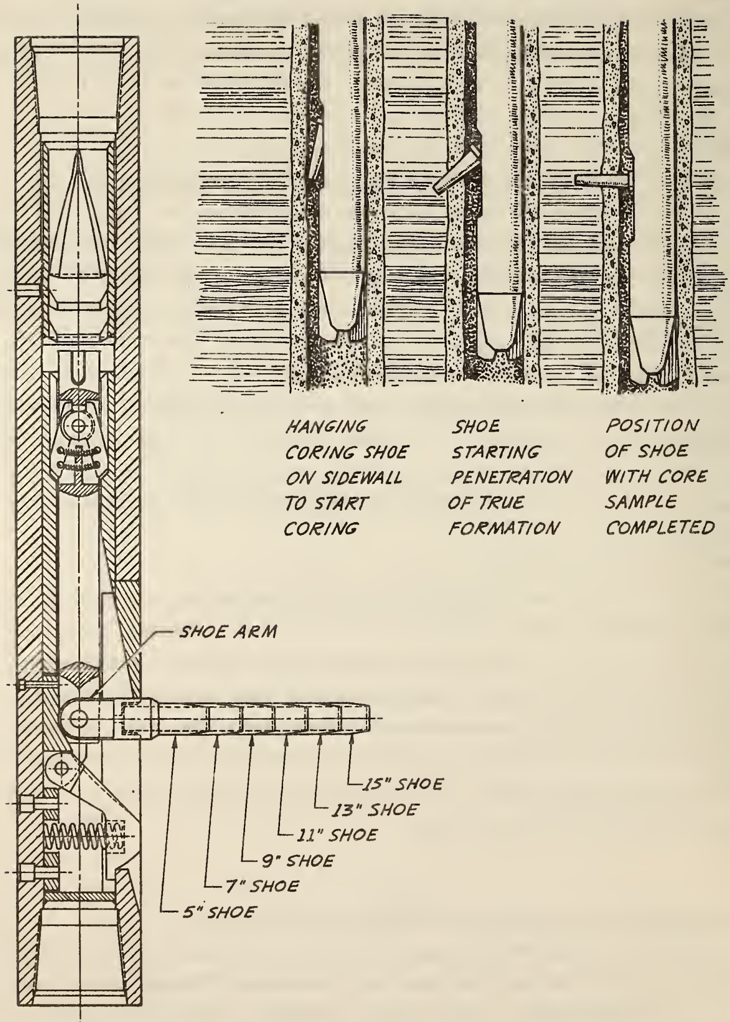


Figure 6.60 - Sidewall Coring Tool

The Lynes Sentry is a pressure transducer-transmitter supplied with compatible packers and tubing that permit assembly of the necessary packers and transducer to isolate the area of interest and take the pressure measurement. The pressure sensing-transmitting element consists of a Bourdon tube to sense the pressure and a device to encode the pressure as an 8 digit binary number which is then sent to the surface by wire as a string of pulses representing the binary number. The set up as shown in Figure 6.61 is sent down the hole on the end of the drill string to set up the pressure measurement. The minimum diameter hole for use of this equipment is 3-1/2 inches (89 mm).

The main disadvantage in using this equipment is the cost, since it is designed for the much more exacting task of providing long term oil well production monitoring. A considerably less expensive system could be assembled from packers used in grouting and the down hole "pressure bomb", although modifications would be required. (Figure 6.62)

6.7.2 Water Permeability Measurement

A technique for the measurement of the water permeability of rock and soil currently exists and is basically performed as follows. A short length of the borehole is sealed off and the wall is cleaned of all drilling mud and debris. Water is then pumped into this sealed section at a constant volume flow rate. By measuring the resulting pressure as a function of time and knowing the flow rate, hole diameter, and length of sealed section, the permeability of the ground may be determined.

The appropriate equation is

$$Q = \frac{kAh}{L}$$

where: Q = the quantity of water flowing

k = the coefficient of permeability

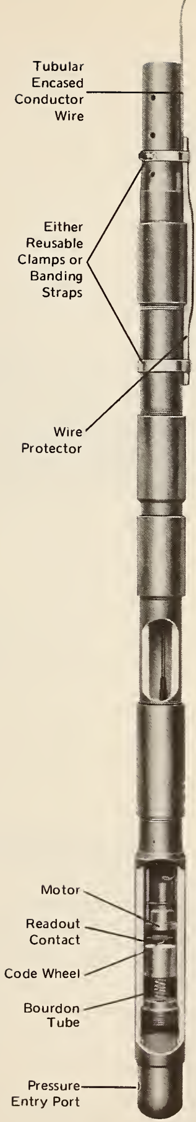
A = the cross sectional area involved

$\frac{h}{L}$ = the hydraulic gradient (ratio of head loss by friction, h, to distance, L, in the direction of flow).

If Q is expressed in cubic centimeters per second, A in square centimeters, and pressure gradient in atmospheres per centimeter, the unit for permeability is the Darcy. In the petroleum industry the millidarcy (.001 Darcy) is more commonly used.

If Q is expressed in gallons of water per day at 60^{0}F, A in square feet, h in feet of water and L in feet, the coefficient of permeability is expressed in the Meinger unit.

Although no off-the-shelf piece of equipment exists specifically for this purpose, equipment similar to that described for ground water pressure measurement may be used if an outlet is provided for pumping water into the zone sealed off by the packers. The pressure measurement is, of course, provided by the pressure sensor located within the sealed zone. The water flow rate can be measured at the surface. (Figure 6.63.)



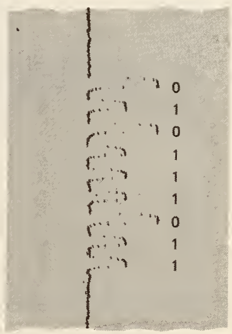


Fig. 33
SAMPLE READOUT

Printed readout of Lynes Pressure Sentry System is in the form of pulses. Short pulses have a value of one, longer pulses a value of zero. Pulses shown here read as 010111011. To convert to pressure reading, operator finds the 010111011 code on conversion chart and takes corresponding pressure reading—600 psi.

Figure 6.61 - Lynes Pressure Sentry
(Courtesy, Lynes, Inc.)

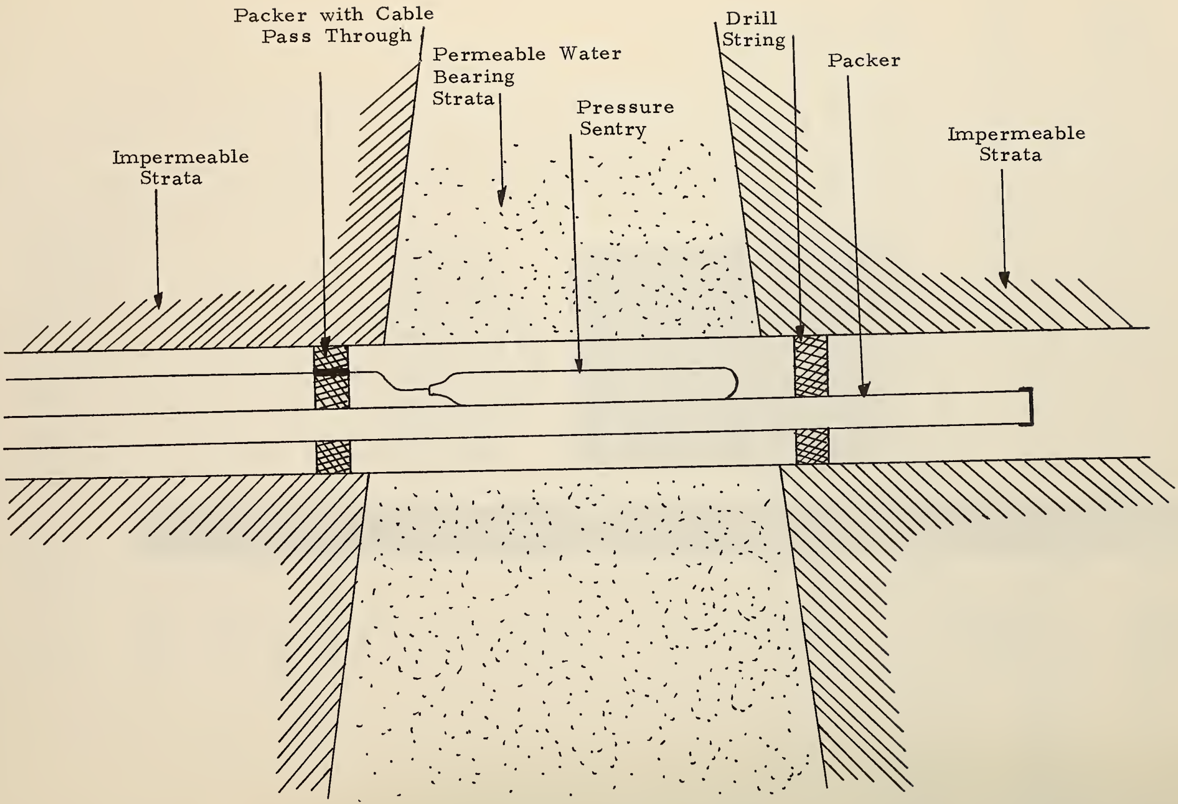


Figure 6.62 - Ground Water Pressure Measurement Using Lynes Sentry

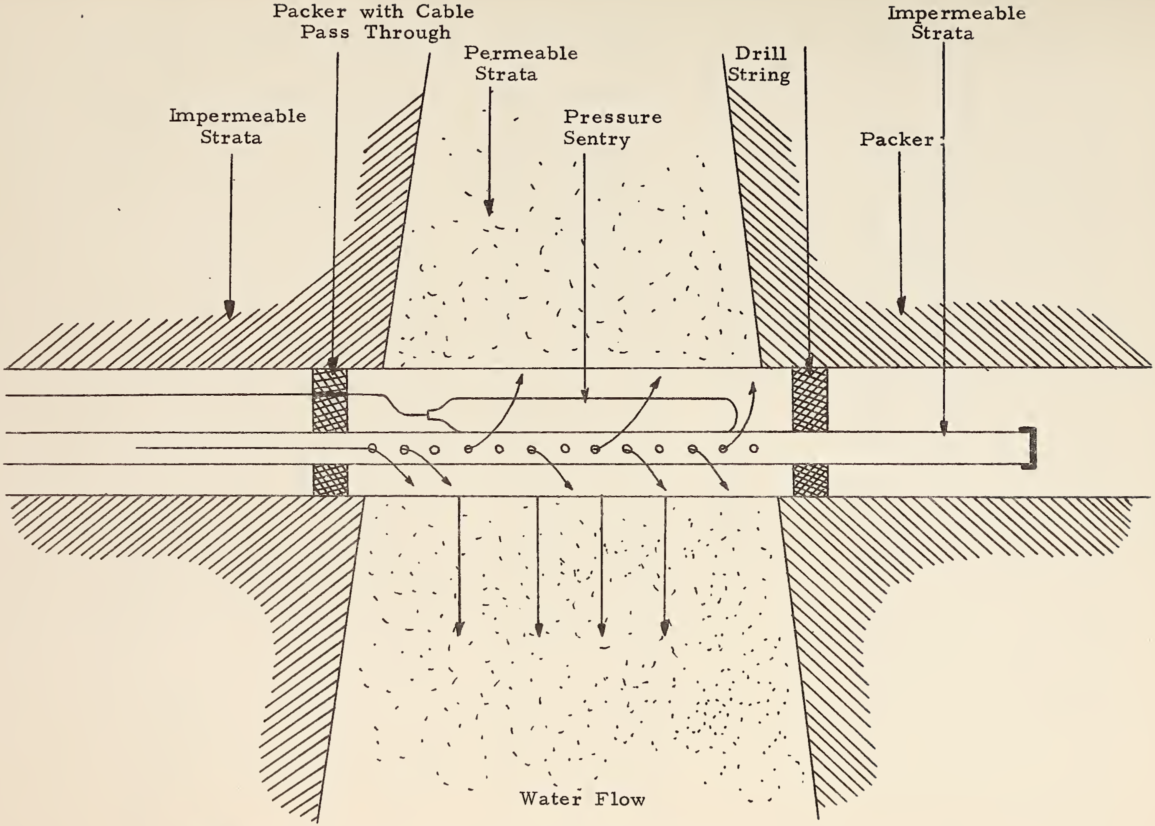


Figure 6.63 - Permeability Measurement Using Lynes Pressure Sentry

7. Assessment of Horizontal Drilling Systems

This section assesses the horizontal capabilities of state-of-the-art (off-the-shelf equipment, proven procedures) horizontal drilling systems and the possibilities for "near term" improvement in horizontal drilling capabilities. In determining near term capabilities, the following items are considered, (1) equipment which is available on a custom order basis, (2) modifications to equipment now used in other applications, and (3) procedures which have been developed for vertical and directional drilling which appear to offer promise in horizontal drilling applications.

7.1 Penetration Capability

7.1.1 State-of-the-Art Capability

The penetration capabilities of state-of-the-art systems can be evaluated by reviewing the capabilities of the various drilling techniques presented in Section 6.1. A graphical representation of the penetration capabilities of various drilling techniques as a function of hole diameter is presented in Figure 7.1. These capabilities are reviewed in order of increasing diameter in the discussion which follows.

Diamond wireline core drilling is the closest thing to a "developed" technique for long horizontal drilling. However, even in this field, holes beyond 1000 ft (305 m) in length are rare. The penetration capabilities of diamond coring are assessed at 5000 ft (1525 m) for the B size (2.360 in, 60 mm), decreasing to 4,000 ft (1219 m) for the N size (2.980 in., 76 mm). It should be noted that this assessment is related to diamond core drilling equipment which is generally termed mining equipment. There is a class of diamond drilling equipment which is used in petroleum drilling, but this equipment has not been applied to horizontal drilling. Diamond equipment used in petroleum drilling is included in the evaluation of near term capabilities.

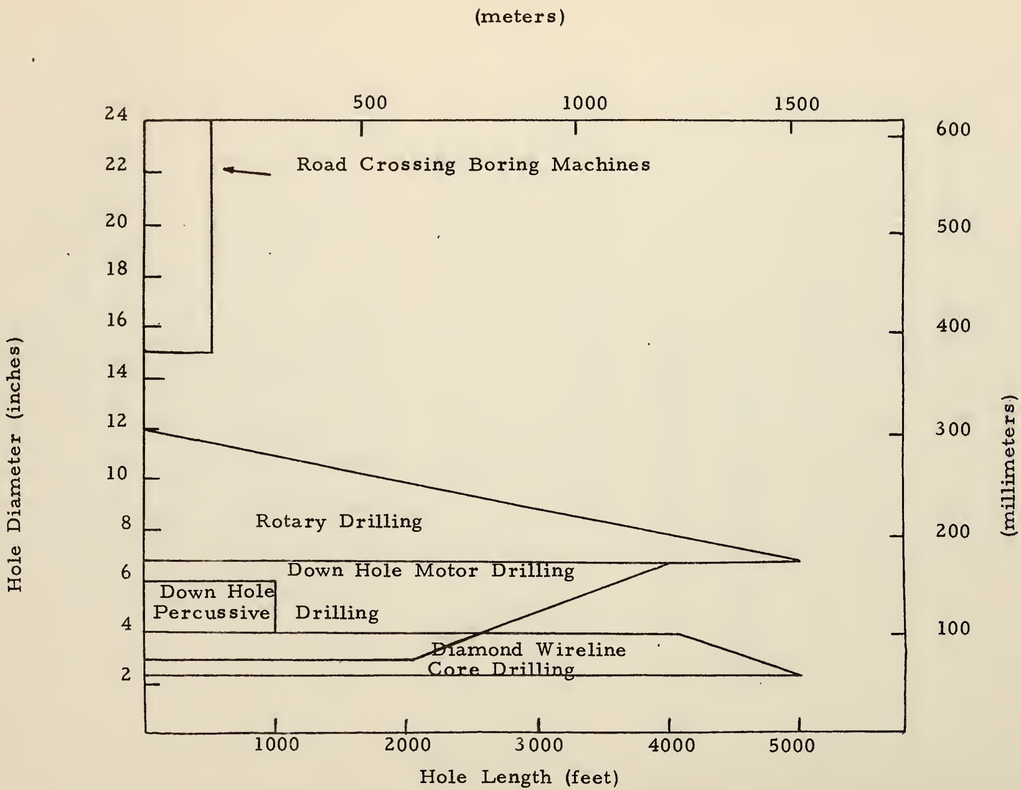


Figure 7.1 - State-of-the-Art Horizontal Penetration Capability

Down-hole percussive drilling is suitable for holes from 4 - 6 in. (102 - 152 mm) in diameter out to 1000 ft (305 m) in length. This technique should be limited to applications in medium to hard rock in areas where ground water is not expected.

An evaluation of the state-of-the-art of horizontal down-hole motor drilling is essentially an assessment of the horizontal drilling capability of the Dyna-Drill. Based on case histories to date, the Dyna-Drill is assumed to be capable of drilling to 2000 ft (610 m) with the 1.75 in. (44.5 mm) tool (3 in., 76 mm nominal hole diameter) and 4,000 ft (1220 m) with the 5 in. (127 mm) tool (6.75 in., 171 mm nominal hole diameter).

In the case of rotary drilling there is a substantial discrepancy between what has been accomplished in horizontal drilling and what has been accomplished in vertical and directional drilling. The longest vertical holes have exceeded 30,000 ft (9144 m) while directional holes beyond 15,000 ft (4572 m) in length are not uncommon, whereas the longest horizontal hole appears to have been less than 6,000 ft (1829 m) in length. Probably the most significant factor in this discrepancy is that the market for vertical and directional (up to 70° from vertical) holes runs to 30,000 holes and $3.4 billion per year[6] while the market for long horizontal holes in rock is too small to be documented. On the technical side, the most significant impediments to horizontal rotary drilling are that (1) bit thrust must be provided by the surface drilling rig, rather than by weighting the drill string and (2) this requires that drilling be performed with the drill string in compression rather than tension. This in turn leads to buckling problems which exacerbate the already substantial problem of transmitting energy from the surface rig to the bit. Based upon the assumption that the Koken FS400 is an "available" piece of equipment, the penetration capability of state-of-the-art horizontal rotary drilling equipment is assessed as 5000 ft (1524 m) for a 6.75 in. (171 mm) hole, ranging to 0 ft for a 12 in. (305 mm) hole.

There is a class of equipment which has been developed for boring small utility tunnels beneath streets, highways, railways, and other structures where cut-and-cover techniques are not practical. A state-of-the-art study of the techniques involved concludes that they are suitable for boring holes in rock from 15-72 inches (381-1829 mm) in diameter to a length of 500 ft (152 m).[17]

The preceding discussion is a synopsis of the penetration capability of state-of-the-art horizontal drilling equipment procedures. The next section discusses what should be possible in horizontal drilling if the entire range of available drilling equipment and drilling procedures were to be applied to the horizontal drilling problem.

7.1.2 Near Term Capability

Estimates of present day performance and cost characteristics (Section 2.2) show that horizontal drilling is substantially cheaper than pilot tunneling for performing horizontal penetrations out to 5000 ft (1524 m). There is a strong indication that the penetration capability of horizontal drilling can be improved substantially while reducing the per foot cost of holes. The following discussion addresses the question of increasing the penetration capability of horizontal drilling.

Given the enormous marketing base for vertical and directional rotary drilling in the petroleum industry, it is likely that one of the most rewarding routes to improving the capabilities and economics of horizontal drilling lies in the direction of adapting procedures and equipment developed in the petroleum industry to horizontal drilling requirements. Fortunately, this appears to be a fertile field for development.

Rotary drilling has evolved as the preferred technique for petroleum drilling and is now also widely used in blast-hole drilling. Raise boring has evolved from petroleum drilling procedures to become a widely employed shaft drilling technique.[27] Raise boring machines offer great promise as horizontal rotary drilling machines and have in fact been proposed for this application.[16]

In general raise boring is performed at angles ranging from vertical to 45° from vertical and normal deviations are quoted at 0.25° per 100 ft (30.5 m) of depth.[27] This is equivalent to a deviation of $\pm$ 0.44 ft (0.13 m) per 100 ft (30.5 m) of depth. In 1970 a raise boring pilot hole 12.25 in. (311 mm) in diameter was drilled at an angle of 21.5° from horizontal and 405 ft (123 m) in length and was described as "right on target at the break-through."[16] Raise boring machines differ from petroleum drilling rigs in that they are capable of applying thrust to the bit. It is this characteristic of the raise boring machine which makes it suitable as a horizontal rotary drilling machine. Table 6.6 lists the performance specifications of a "small" raise boring machine. Larger units have thrust capacities approaching 500,000 lb (226,800 Kg) and torque capacities to 220,000 ft.lb (30,419 Kg·m).[36]

If raise boring machines can be modified to perform as horizontal rotary drilling rigs, and indications at this time are that they can, one of the major stumbling blocks to adapting rotary drilling procedures to long horizontal drilling can be overcome, that is, finding suitable surface rigs. Among the factors which make it attractive to adapt rotary drilling to the problem of horizontal drilling in rock, some of the more significant are the following:

(1) As the preferred technique for petroleum drilling, rotary drilling is by far the most well developed drilling method in terms of equipment and procedures.

(2) Rotary drilling methods are suitable for the entire range of formation strengths from very soft to very hard.

(3) Rotary drilling has proven to be the most economical method of drilling long holes in rock.

(4) The larger hole sizes which are compatible with rotary drilling equipment are more conducive to maintaining a straight hole. The reason for this is that the ability of the drill string assembly to drill straight increases with its stiffness, and the stiffness of the string is proportional to the fourth power of its diameter.

With the proper surface rigs, and employing roller or non-rotating stabilizers spaced along the entire drill string, to prevent buckling and reduce friction between the drill string and hole wall, rotary drilling methods should be capable of penetrations well beyond present limits. Holes to 10,000 ft (3048 m) and beyond and diameters from 7 - 15 inches (178 - 381 mm) do not seem unreasonable.

With larger surface rigs, diamond full-hole and core bits developed for the petroleum industry could be used for horizontal drilling. This would allow diamond wireline coring up to 12.25 in. (311 mm) in diameter with cores to 5.25 in. (133 mm) in diameter and full hole diamond drilling to 12.5 in. (318 mm) in diameter. The reduced thrust and torque requirements for diamond bits (relative to equal outside diameter rolling cutter bits) should allow longer penetration capabilities, for a given hole size, with diamond bits. However, bit costs per foot would be greater than for rolling cutter bits.

Down-hole motor drilling is not an economical method of straight hole drilling in most circumstances in petroleum drilling, and it does not seem likely that the economics of down-hole motor drilling will be more attractive in horizontal straight hole drilling. However, the down-hole motor is a strong candidate for extending penetration capabilities beyond what is achievable with techniques which require that the drill string be turned. The technique has been projected as suitable for distances to 15,000 ft (4572 m) by some sources.[20]

Down-hole percussive drilling should be applicable out to 1,000 ft (305 m) for the range of available equipment. This would allow hole diameters to 12 inches (305 mm).

The projected horizontal penetration capabilities for systems which would adapt available equipment and procedures to horizontal drilling are presented in Figure 7.2.

7.2 Chip Removal

It is highly unlikely that anything other than drilling mud will be used as a flushing fluid in a developed procedure for long horizontal drilling. (For distances beyond 1,000 ft, 305 m) The ability of drilling mud to control lost circulation, stabilize the hole, and lubricate the drill string to hole wall interface is essential to a successful horizontal drilling operation.

In future programs, double tube reverse circulation may be used in certain circumstances to control lost circulation.

7.3 Hole Stabilization

The stabilization procedures presented in Section 6.3 are capable of controlling most hole stabilization problems. However, based on the experience of drilling contractors, there will be instances where casing will have to be employed or the hole will have to be abandoned.

With the application of equipment which would allow larger hole sizes, the procedure of inserting plastic or fiberglass pipe inside the drill string (see Figure 6.27) becomes increasingly viable as a non-metallic casing technique, in that the resulting final hole diameter assumes more useful proportions.

7.4 Guidance

7.4.1 State-of-the-Art

State-of-the-art survey tools are limited to magnetic single shot and multi-shot devices. Steering techniques which are

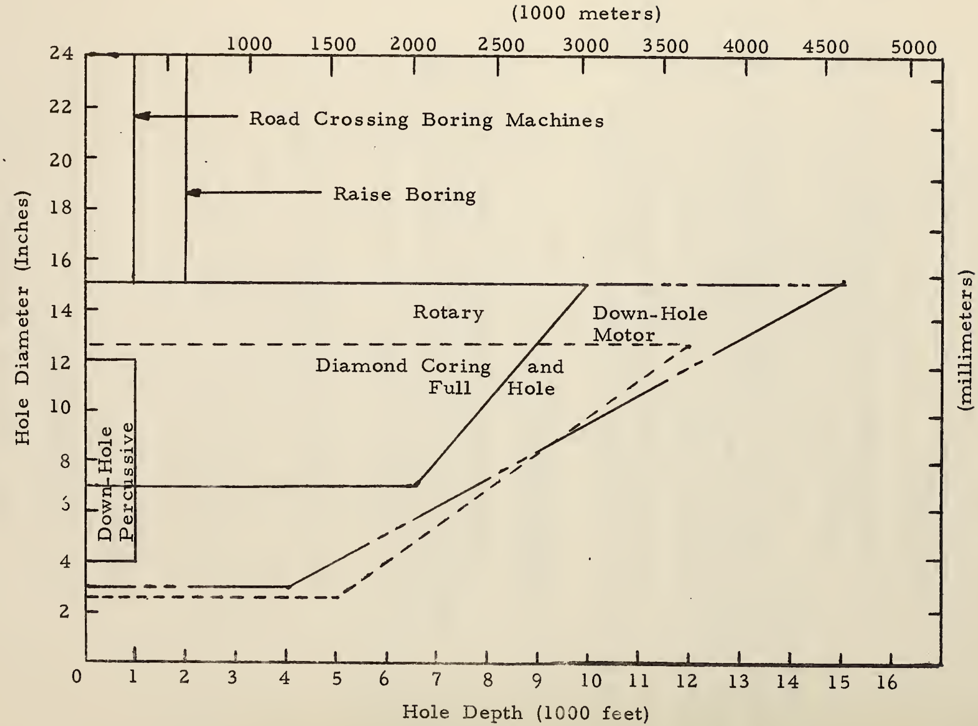


Figure 7.2 - Projected Horizontal Penetration Capability of Available Adaptable (Near Term) Equipment and Procedures

effective in drilling rock are limited to (1) techniques employing the fulcrum principal, (2) whip stocking and (3) the Dyna-Drill. The best estimate of the guidance capabilities of this combination of techniques is portrayed graphically in Figure 7.3.

One factor which adds greatly to the expense and time involved in horizontal guided drilling is the necessity for frequent corrections of the drilling trajectory. Instances have been reported where whipstocking was employed at 10 ft (3.05 m) intervals to maintain a trajectory within 15 degrees of the desired trajectory.[14] By contrast, the procedures employed in directional drilling for the petroleum industry most often involve (1) employment of a down-hole motor to achieve an initial deviation from vertical, (2) buildup of the deflection through use of the fulcrum principal, and (3) drilling to completion in a straight line with a drilling assembly employing a high degree of stabilization.[32] The final straight hole leg can be up to 70 degrees from the vertical. The factor which allows the directional driller to hold a reasonably straight course is the stiffness of the drill string immediately behind the bit. The smaller diameter (B size) equipment employed in most state-of-the-art long horizontal drilling does not have the stiffness required to resist hole deflecting factors.

A second significant state-of-the-art limitation is the lack of high angle survey steering tools. In petroleum drilling, the availability of the survey steering tool has made the down-hole motor the most frequently used deflection tool. With this instrument the driller can correct for the drill string torque reaction, and achieve the exact angular orientation required for the down-hole motor. The horizontal driller must drill a length of hole with the down-hole motor and then run a survey instrument down the hole and retrieve it, to determine if he made proper allowance for the drill string torque reaction.

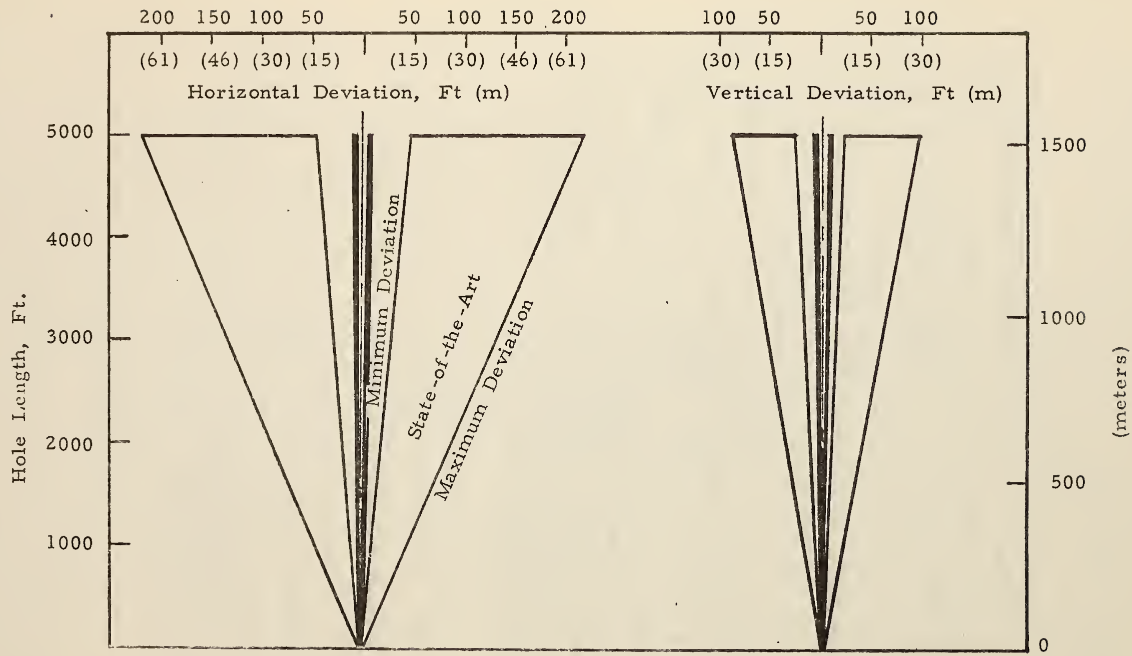


Figure 7.3 State-of-the-Art and Projected Near Term Guidance Capability

7.4.2 Near Term Capability

Available custom gyroscopic survey equipment will improve survey accuracy by about one order of magnitude. The availability of high angle survey steering tools will make the down-hole motor the preferred deflection tool for horizontal drilling. This in turn, will reduce the time required to make direction changes. The net result of applying this equipment horizontal drilling should improve guidance capability to $\pm$ 1 ft (0.3 m) per 1,000 ft (305 m) drilled in terms of survey accuracy, with a steering capability of $\pm$ 5 ft (1.5 m). This capability is illustrated graphically in Figure 7.3.

The use of rotary and diamond drilling equipment in large diameters will allow more effective stabilization of the drill string behind the bit. This should increase the interval required between corrections in hole trajectory.

8. Planning and Estimating Horizontal Drilling

8.1 Selecting a Drilling Technique

In contemplating the use of horizontal drilling as a technique for exploring along proposed tunnel alignments, the options available, in terms of state-of-the-art equipment, are quite limited. If coring is required along the entire alignment, then diamond wireline coring is the only technique available. If intermittent coring is acceptable, then rotary drilling, down-hole motor drilling, and down-hole percussive drilling are candidate techniques. Requirements in terms of hole diameter and hole length further restrict the available techniques as indicated in Figure 7.1. Down-hole percussive techniques are limited to competent formations of medium to hard rock with minimal ground water. A logic diagram for determining the available options in selecting a drilling technique is presented in Figure 8.1. It should be noted that if rotary drilling is to be employed, a modified raise borer, road boring machine, or blasthole rig will probably have to be used as a surface rig.

8.2 Horizontal Drilling as a Development Program

If the horizontal drilling customer is willing to fund developmental work on a horizontal drilling program, significant areas for investigation should include:

(1) Complete instrumentation of the drilling system to record thrust, torque, rotational speed, penetration rate etc.

(2) Development of a rotary drilling surface rig to allow the application of the complete range of rotary drilling techniques to horizontal drilling.

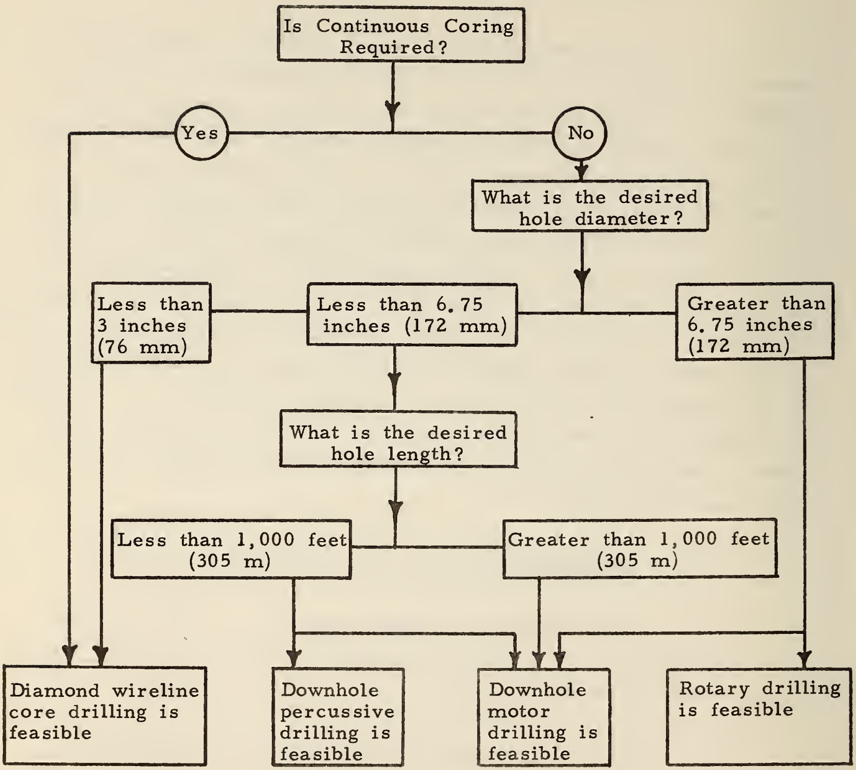


Figure 8.1 - Drilling Method Selection Process

(3) Evaluation of available custom order high angle survey steering tools.

(4) Evaluation of available custom order gyroscopic survey tools.

(5) Development of automated rod handling systems.

(6) In conjunction with (2), evaluation of drill string stabilization techniques.

8.3 Costing Model

Volume II of this report is a Long Hole Horizontal Drilling Cost and Time Requirements Estimating Manual. The manual presents a method for determining the time and cost required to drill a horizontal hole by any of four methods:

(1) Diamond Wireline Core Drilling

(2) Rotary Drilling

(3) Down-Hole Motor Drilling

(4) Down-Hole Percussive Drilling

Relationships were developed for determining the time required for each drilling activity. These relationships include all variables which affect the total time required. Values for these variables were determined from (a) analytical techniques, where such techniques were available, (b) consultation with drilling contractors, (c) empirical data, where available. The technique or combination of techniques employed to determine the value of variables or rules-of-thumb to be employed are indicated in the model.

The primary value of this model is to establish logical techniques for defining the governing parameters in horizontal drilling. The accuracy of the model as a method of predicting drilling costs will improve as the quality of available data improves. Diamond wireline core drilling is the only technique for which there is any sort of data base in horizontal applications. For this technique, the model predictions correlate well with contractor field data and estimates.

APPENDIX A

EQUIPMENT MANUFACTURERS AND CONTRACTORS

This appendix lists representative manufacturers of drilling equipment and experienced horizontal drilling contractors. The numbers refer to the alphabetical company listing contained in Appendix B. This is not intended to be an exhaustive listing. Further listing of equipment manufacturers and drilling contractors may be obtained from:

Composite Catalog of Oil Field Equipment and Services, Gulf Publishing Company, Houston, Texas.

Petroleum Industry Yellow Pages, Whico/General Telephone Directory Co., Houston, Texas.

A. Manufacturers - Drill Rigs

1. Diamond:
   1, 6, 8, 10, 26, 30, 47, 48, 49

2. Rotary:
   28

3. Down-Hole Motors:
   13, 15, 16, 18

4. Down-Hole Percussive Drills:
   1, 25, 34, 37

5. Raise Boring Machines:
   25, 33, 40

6. Road Crossing Boring Machines:
   35, 39

B. Manufacturers - Drill Bits

1. Diamond:
   1, 6, 9, 10, 30, 47, 51

2. Rolling Cutter:
   1, 20, 30, 33, 36, 42, 51, 56

3. Percussive:
   1, 20, 37, 51

C. Contractors - Drilling
5, 7, 8, 30, 38, 41, 44, 47

D. Manufacturers and Service Companies - Drilling Mud
4, 11, 32

E. Manufacturers and Service Companies - Grouting
11, 19

F. Manufacturers and Service Companies - Hole Surveying
16, 23, 29, 43, 46

G. Manufacturers - Stabilizers, etc.
2, 12, 14, 16, 21, 24

H. Manufacturers - Steering Tools
2, 15, 16

I. Manufacturers and Service Companies - Fishing
2, 11, 20, 21, 24, 27, 30, 50, 52, 53, 54, 55

J. <u>Manufacturers and Service Companies - Core Sampling</u>

1. Core Barrels, etc.

   1, 5, 9, 30

2. Oriented Core.

   9, 16, 41

K. <u>Manufacturers - Soil Sampling</u>

17, 24, 30, 45, 47

L. <u>Manufacturers - Water Pressure and Permeability Measuring Components</u>

3, 17, 29, 31

APPENDIX B

ADDRESS LISTING

This appendix lists alphabetically the names and addresses of the companies referred to in Appendix A. The numbers refer to the equipment and contractor categories used in Appendix A.

1. Acker Drill Company, Inc.
   Box 830
   Scranton, Pennsylvania 18501
   Phone: 717-586-2061
   A1, A4, B1, B2, B3, J1, K

2. A-Z International Tool Co.
   3317 West 11th Street
   Houston, Texas 77008
   Phone: 713-869-6451
   G, H, I

3. Baker Division
   Baker Oil Tools, Inc.
   7400 E. Slauson Avenue
   P.O. Box 2274
   Los Angeles, California 90051
   Phone: 213-724-5400
   L

4. Baroid Division, NL Industries, Inc.
   P.O. Box 1675
   2402 Southwest Freeway
   Houston, Texas 77001
   D

5. Boyles Bros. Drilling Company
   P.O. Box 58
   1624 Pioneer Road
   Salt Lake City, Utah 84110
   Phone: 801-487-3671
   C, J1

6. Boyles Operations, Dresser Industrial Products Ltd.
   256 Hughes Road
   Box 460
   Orillia, Ontario L3V6K3, Canada
   Phone: 705-325-6131
   A1, B1

7. Calvert Western Exploration
Box 2920
Grand Junction, Colorado 81501
Phone: 303-242-4124
C

8. Canadian Mine Services
745 Clark Drive
Vancouver, British Columbia V5L3J3, Canada
A1, C

9 Christensen Diamond Products Company
1937 South 300 West
P.O. Box 387
Salt Lake City, Utah 84110
Phone: 801-487-5371
B1, J1, J2

10. Craelius S.A.
F-06
Carros Industries, France
Phone: (93) 08.13.21.
A1, B1

11. Dowell Schlumberger
909 Americana Building
Houston, Texas 77002
Phone: 713-224-1313
D, E, I

12 Drilco Division of Smith International, Inc.
P.O. Box 3135
Midland, Texas 79701
Phone: 915-683-5431
G

13. Drilling Tool Division of Cook Testing Co.
2552 Cherry Avenue
P.O. Box 6127
Long Beach, California 90806
Phone: 213-426-3031
A3

14. Driltrol
1361 East Hill Street
Long Beach, California 90806
Phone: 213-424-0461

15. Dyna-Drill Co., Division of Smith, International, Inc.
P.O. Box 327
Long Beach, California 90801
Phone: 213-426-7186
A3, H

16. Eastman Whipstock Inc.
P.O. Box 14609
Houston, Texas 77021
Phone: 713-748-2350
A3, F, G, H, J2

17. Gearhart-Owen Industries, Inc.
P.O. Box 1936
Fort Worth, Texas 76101
Phone: 817-293-1300
K, L

18. Grant Oil Tool Company
(Neyrpic turbodrills)
2042 East Vernon Avenue
Los Angeles, California 90058
Phone: 213-232-8167
A3

19. Halliburton Services
Drawer 1431
Duncan, Oklahoma 73533
Phone: 405-255-3760
E

20. Hendershot Tool Company
1006-12 S.E. 29th Street
P.O. Box 94444
Oklahoma City, Oklahoma 73109
Phone: 405-677-3386
I

21. Homco International, Inc.
P.O. Box 2442
Houston, Texas 77001
Phone: 713-734-0281
G, I

22. Hughes Tool Company
Oil Tool Division
P.O. Box 2539
Houston, Texas 77001
Phone: 713-926-3101
B2, B3

23. Humphrey Inc.
2805 Canon Street
San Diego, California 92106
Phone: 714-223-1654
F

24. Hunt Tool Company
P.O. Box 1436
Houston, Texas 77001
Phone: 713-223-7131
G, I, K

25. Ingersoll-Rand Co.
Woodcliff Lake, New Jersey 07675
Phone: 201-887-1212

or

Memorial Parkway
Philipsburgh, New Jersey
A4, A5

26. Joy Manufacturing Co.
Claremont, New Hampshire 03743
A1

27. Joy Oil Tools
Baash-Ross Division
P.O. Box 1348
Houston, Texas
Phone: 713-672-1721
I

28. Koken Boring Co., Ltd.
Taira-cho 2-20-13, Meguro-ku
Tokyo, Japan
Phone: 717-1141
A2

29. Kuster Company
2900 East 29th Street
Long Beach, California 90806
Phone: 213-426-9311
F, L

30. Longyear Company
925 Delaware Street S.E.
Minneapolis, Minnesota 55414
Phone: 612-331-1331
A1, B1, B2, C, I, J1, K

31. Lynes, Inc.
7042 Long Drive
P.O. Box 12486
Houston, Texas 77017
Phone: 713-643-4393
L

32. Magcobar Operations
Oil Products Division of Dresser Industries, Inc.
P.O. Box 6504
Houston, Texas 77005
D

33. Mining Equipment Operation
Mining Services and Equipment Division of Dresser Industries, Inc.
P.O. Box 24647
Dallas, Texas 75224
A5, B2

34. Mission Manufacturing Co.
P.O. Box 40402
Houston, Texas 77040
A4

35. PCM Division of Koehring Co.
Port Washington, Wisconsin 53074
A6

36. Reed Tool Co.
Drilling Equipment Division
P.O. Box 2119
Houston, Texas 77001
B2

37. Reed Tool Co.
Rotary Percussion Equipment Division
P.O. Box 3641
San Angelo, Texas 76901
A4, B3

38. Reynolds Electrical and Engineering Co., Inc.
P.O. Box 14400
Las Vegas, Nevada 89114
Phone: 702-734-3011
C

39. Richmond Manufacturing Co.
P.O. Box 588
Ashland, Ohio 44805
Phone: 419-869-7107
A6

40. James S. Robbins and Associates, Inc.
500 Wall Street
Seattle, Washington 98121
Phone: 206-767-7150
A5

41. Charles S. Robinson & Assoc.
622 Gardenia Court
Golden, Colorado 80401
Phone: 303-279-0028
C, J2

42. Rucker Hycalog
P.O. Box 15372
Houston, Texas 77020
Phone: 713-675-8221
B2

43. Scientific Drilling Controls, Inc.
4040 Campus Drive
Newport Beach, California 92660
Phone: 714-557-9051
F

44. Soil Sampling Service, Inc.
5815 North Meridian
Puyallup, Washington 98371
Phone: 206-927-3173
C

45. Soiltest, Inc.
2205 Lee Street
Evanston, Illinois 60602
Phone: 312-869-5500
K

46. Sperry-Sun
P.O. Box 36363
Houston, Texas 77036
Phone: 713-494-3021
F

47. Sprague and Henwood, Inc.
221 West Olive Street
Scranton, Pennsylvania 18501
Phone: 717-344-8506
A1, B1, C, K

48. Tigre Tierra, Inc.
5815 North Meridian
Puyallup, Washington 98371
Phone: 206-927-7411

49. Tone Boring Machine Mfg. Co.
Tokyo, Japan
A1

50. Tri-State Oil Tool Industries, Inc.
P.O. Box 5757
Bossier City, Louisiana 71010
Phone: 318-746-3800
I

51. Varel Manufacturing Co.
9230 Denton Drive
P.O. Box 20156
Dallas, Texas 75220
Phone: 214-351-6487
B1, B2, B3

52. Wilson Industries, Inc.
P.O. Box 1492
Houston, Texas 77001
Phone: 713-225-4071
I

53. Bowen Tools, Inc.
P.O. Box 3186
2429 Crockett Street
Houston, Texas 77001
Phone: 713-869-6711
H, I

54. The Dia-Log Company
Box 14103
Houston, Texas 77021
I

55. Houston Engineers, Inc.
P.O. Box 567
1710 Burnett Street
Houston, Texas 77001
Phone: 713-227-4188
I

56. Smith Tool Co.
Division of Smith International, Inc.
P.O. Box 4549
Compton, California 90224
Phone: 213-324-4977
B2

APPENDIX C

GROUTING

The following material was prepared by Jacobs Associates of San Francisco, California. Included is a detailed discussion of grouting and an assessment of the impact of grouting procedures on hole cost. The economic data was based on the "Estimating Manual for Time and Cost Requirements" which constitutes VolumeII of this report.

C.1. Drill Hole Stabilization

Other than steel casing, which is not recommended for this study, grouting appears to be the most promising method of horizontal drill hole stabilization. Particular drilling parameters, such as hole diameter and drilling fluid, may be dictated by the method of stabilization selected.

Where grouting is employed as a stabilization medium it would be preferable to use water, rather than mud, as a drilling fluid. The use of mud may create additional grouting trips and a resultant time delay. Drilling mud forms an impervious layer on the hole walls, which may interfere with a grouting operation. Figure C.1. (a) shows the cross section of a hypothetical drill hole with an impervious mud layer on the walls and a failure, due to high groundwater pressure, at the top of the hole. Figure C.1. (b) shows the same section after a grouting operation. The grout was unable to penetrate the impervious mud layer which resulted in a partial grouted section around the hole. High water pressure then collapsed another portion of the hole which required an additional grouting operation. The same hole section drilled with water as a drilling fluid is shown in Figure C.1. (c). Absence of a layer of impervious mud permitted a full grouted section in one grouting operation.

Hole size is another important consideration when hole stabilization activities are required. Small diameter holes are generally more self supporting than large holes and they require less grout when grouting is necessary.

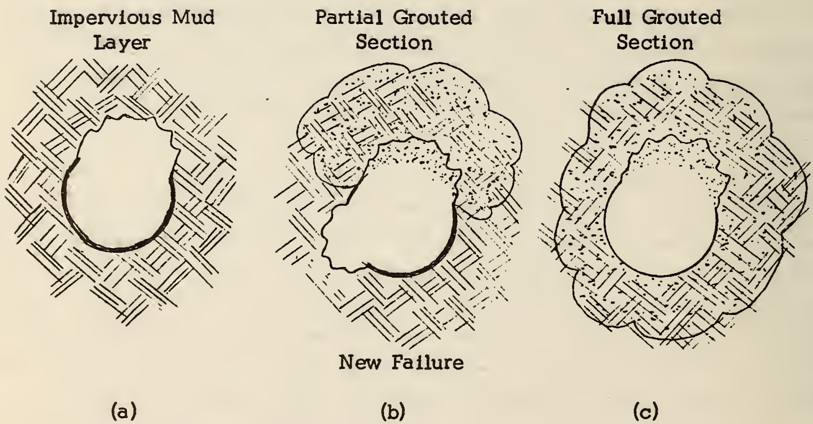


Figure C.1 - Effect of Drilling Fluid on Grouting Activities

The typical method of grouting drill holes is with a cement water grout. This grout usually has a 6 to 1 water to cement ratio and is pumped to a resistance pressure as high as 3000 psi. This method may require great volumes of grout to be pumped into a formation before a cement filter plug is acquired. A cement filter plug will occur in fissures of 0.25 mm. or less. Grout may be pumped great distances before meeting this condition.

Other disadvantages to neat cement grout are set volume reduction and the time required to attain adequate strength to continue drilling. Grout with a 6 to 1 water to cement ratio may have a set volume reduction up to 75%. This condition, in conjunction with high water pressures may cause cement plugs to be forced out of the fissures and a resulting drill hole collapse. Forty eight hours or more may be required for cement grout to attain adequate strength for drilling to continue. Delays of this nature can be very costly, particularly when frequent grouting operations are required.

C.2. Characteristics and Conditions for Grouting Drill Holes

For successful, economical, drill hole grouting the following characteristics and conditions must be met.

a) Grout must have a predictable, controllable, set time. The set time should be controllable from a few seconds to several minutes.

b) Full volume set is required and a small amount of set expansion is desirable.

c) The material must have adequate strength for prevailing conditions.

d) It must have the ability to penetrate the voids and fissures encountered.

e) Grout chemistry must be compatible with the formation.

f) Temperature changes in the formation must be monitored to assure accuracy of set times.

All of the above conditions can be met by one or more of the available grouting materials provided there is adequate confining pressure in the formation. It may not be possible to grout drill holes, in soil, close to the surface. If more than 15% of the material passes a 200 mesh and 100% passes a 1/4 mesh the formation will probably not offer adequate confining pressure.

C.3. Grouting Materials

Grouting materials available for stabilizing drill holes may be classified as particulate and chemical grouts. Particulate grouts have particles in suspension. The most commonly used particles are cements, bentonite and flyash. Chemical grouts are solutions and they contain no particles.

These grouts have wide variations in gel times, viscosites, strengths and costs. Any one of the grouts may have advantageous properties for a particular application. Table C.1 lists some particulate and chemical grouts that are commercially available.

High viscosity grouts, generally, have a higher unconfined compressive strength than low viscosity grouts. However, fine fissures and voids may not always be penetrated by high viscosity grouts. Cement grouts have unconfined compressive strengths up to 75,000 psf. Bentonite may be added to cement grout to increase viscosity and provide for a full volume set. The addition of bentonite retards the set and therefore, without a reagent, it is not very satisfactory for grouting drill holes. CemChem is a patented process which incorporates a reagent with cement bentonite grout. The added reagent makes the grout set time predictable and controllable.

TABLE C. 1

COMMERCIALLY AVAILABLE PARTICULATE AND CHEMICAL GROUTS

Particulate Grouts

a) Bentonite
b) Cement
c) Cement, Bentonite
d) Cement, Bentonite and Reagent (CemChem)
e) Chemical Grouts with Particulates Added
f) Asphaltic Emulsions

Chemical Grouts

a) Acrylic Resin
b) Chrome Lignin
c) Poly Phenol
d) Single Shot Silicates
e) Two Shot Silicates
f) Urea Resin
g) Epoxy Resin
h) Phenolic Resin
i) Polyester Resin

Most chemical grouts have lower viscosities than particulate grouts. Acrylic Resin is the lowest viscosity grout sold commercially. It has a viscosity of 1.2 centipoises. Chrome Lignin, Poly Phenol and Single Shot Silicates have viscosities ranging from 2 to 7 centipoises but they are generally used with viscosities of 4 to 5 centipoises. It is more desirable to use higher viscosity chemical grouts since they result in higher compressive strengths. Wetness of a chemical grout is a factor to be considered. Wetness may be increased by adding surfactants. This permits a high viscosity grout to be used, where a low viscosity would normally be used, with no apparent decrease in penetration. Urea Resin, Two Shot Silicates, Epoxies and Polyesters are generally used with viscosity ranges from 10 to 30 centipoises. All chemical grouts provide a full volume set.

C.4 Strength of Grouts

In general particulate grouts provide high strength for a comparatively low cost. Bentonite is an exception since it has insignificant compressive strength. Strengths of chemical grouts generally increase with increasing viscosity. Low viscosity chemical grouts (2 to 6 centipoises) have very low strength when gelled in a container. They are nothing more than a weak glue. However in a sand formation unconfined compressive strengths may reach 20,000 psf. High viscosity grouts (10 to 30 centipoises) have compressive strengths, in sand, of 20,000 to 75,000 psf. Table C.2 lists the unconfined compressive strengths of some grouts.

Time for grout to attain adequate strength, to permit drilling to resume, is an important economic factor. Grout cure times may vary anywhere from a few minutes to seven or eight days. If no groundwater pressure exists, neat cement grout may be drilled through within a few hours. However, there is a great danger of washing out the grout with drilling fluid and recreating lost circulation. On the other hand, if high groundwater pressure exists, it may be necessary to wait two to eight days before drilling through neat cement grout.

Two shot silicates acquire their full strength almost immediately.

TABLE C.2

UNCONFINED COMPRESSIVE STRENGTH OF GROUTS

Grout Type	Unconfined Compressive Strength in P.S.F.	Approximate Cost per Gallon $
Bentonite	Insignificant	
Cement	75,000	0.30
CemChem	20,000 to 30,000	0.45
Acrylic Resin Chrome Lignin Poly Phenol Single Shot Silicates	4,000 to 20,000	0.15 to 1.50
Two Shot Silicates Urea Resin Phenolic Resin	20,000 to 75,000	0.50 to 1.50
Epoxy Resin Polyester Resin		5.00 to 30.00

TABLE C.3

GROUT CURE TIME

Grout Type	Cure Time
Neat Cement	3 hours to 8 days
Cement Bentonite & Reagent	1/2 to 1 hour
Chemical Grouts	0 to 48 hours

Cement bentonite and reagent grout (CemChem) also has a very short cure time. Approximate ranges of cure times are shown in Table C.3.

C.5 Cost of Grouting Materials

Cement grouts and some chemical grouts have a relatively low cost. Several of the chemical grouts are very costly. Approximate costs of some grouting materials are shown in Table C. 2.

C.6 Grouting Equipment

Equipment required for a grouting activity varies with the type and method of grouting. In general two grout pumps, two mixing tanks and material storage tanks are required. The cost of the required equipment can vary from $10,000 to $25,000.

C.7 Selection of Grouts and Methods of Grouting

The most important factor in the selection of grouts is that they are capable of performing the required function. A secondary but important factor is low overall cost. In most drill hole applications there is very little knowledge of void ratios, fissures widths or groundwater pressure. Without the above knowledge a logical approach would be to estimate an amount of grout to provide a grouted radius of 2 to 5 feet around the hole.

Because of its low cost, moderate strength and short curing time, a cement bentonite and reagent grout would be a good first selection. The grouted section could be drilled through within an hour and its adequacy determined. In the event that adequate penetration was not accomplished the hole could then be grouted with a high viscosity chemical grout. This could be followed by an application of low viscosity grout, if adequate penetration was still not achieved.

C.8. Economic Considerations

To show the economic impact of various drill hole grouting selections, a sample hole is evaluated, using neat cement grout (classical grouting method), cement bentonite and reagent grout and a high viscosity chemical grout. The requirements, assumptions and estimates used for the sample hole are listed. Some additional estimates are also included.

(1) Hole lengths of 1,000 through 5,000 feet

(2) Method of drilling selected is NQ (approximately 3 inches diameter) wireline coring

(3) Maintain the hole within a $\pm$ 1% deviation

(4) An average geological profile is assumed

(5) An average bit life of 120 feet

(6) Penetration rates of 8, 18, and 30 feet per hour for hard, medium and soft rock respectively

(7) A direction change every 90 feet to maintain alignment

(8) A hole survey every 30 feet and three additional hole surveys every 90 feet for direction changes

(9) A fishing activity every 300 feet

(10) A hole stabilization activity every 200 feet and a length of 18 feet for each stabilization activity

(11) A job efficiency factor of (0.2) (time)

(12) Average drill rod trip velocity of 20 feet per minute.

Tables C. 4 and C. 5 show additional estimates for hole stabilization, assuming moderate to high groundwater pressure.

TABLE C. 4

GROUT CURE TIME AND COST ESTIMATE

Grout Type	Cure Time (Hours)*	Cost $ Per Gallon
Neat Cement	24	0.30
Cement, Bentonite and Reagent	1	0.45
Chemical Grout	1	1.00

*Time required to attain adequate strength for prevailing conditions.

TABLE C. 5

GROUT QUANTITY ESTIMATES

	Neat Cement Grout	Cement Bentonite & Reagent	Chemical Grout
Estimated Quantity of Grout Required Per Activity (gallons)*	10, 400	2, 600	2, 600
Grout cost per Activity($)	3, 120	1, 170	2, 600

*Based on providing a grouted radius of 5 feet around the drill hole in crushed rock with 25% voids. Since it is not possible to control the set time of neat cement grout, a conservative estimate is that four times the quantity would be required.

A summary of time estimates for hole lengths of 1, 000 through 5, 000 feet is shown in Table C. 6. This summary is based on procedures and formulas outlined in the Cost Model Volume of this study. A comparative summary of costs to drill the example hole is shown in Tables C.7, C.8, C.9 and C.10 and the results are plotted in Figure C.2. In this summary hole stabilization is accomplished using:

(a) Neat cement grout

(b) Chemical grout

(c) Cement, Bentonite and Reagent grout

(d) No hole stabilization required

This economic analysis is very approximate and is only as accurate as the idealized conditions are accurate in representing the actual conditions in the field. Despite these shortcoming, this analysis leads to two important conclusions:

The first is that hole stabilization can be the most important economic factor in drilling long horizontal holes. It can be seen from Figure C.2 if hole stabilization is required, the total cost to drill a hole can be more than doubled.

The second conclusion is that the cost can be nearly doubled if an incorrect assessment of conditions or a poor selection of grouting methods and materials is made.

TABLE C.6

SUMMARY OF TIME ESTIMATES - FOR HOLE LENGTHS OF 1000, 2000, 3000, 4000, AND 5000 FFET

	1) Neat Cement Front					1) Cement Bentonite & Reagent 2) Chemical Grout				
Length of Hole (feet)	1000	2000	3000	4000	5000	1000	2000	3000	4000	5000
Wireline Casing	108	247	447	690	960	108	247	447	690	960
Hole Survey										
1 Survey every 30 feet	9	21	40	64	94	9	21	40	64	94
3 Surveys every 90 feet	7	20	36	60	90	7	20	36	60	90
Direction of Change	49	170	364	630	970	49	170	364	630	970
Fishing for Tools	9	28	59	100	158	9	28	59	100	158
Hole Stabilization	156	321	495	678	870	19	48	85	131	186
Total Hours	338	807	1441	2222	3142	201	534	1031	1675	2458
Job Efficiency	68	161	288	444	628	40	107	206	335	492
*Total Job Time	406	968	1729	2666	3770	241	641	1237	2010	2950
Production (feet/hour)	2.47	2.07	1.73	1.50	1.33	4.15	3.12	2.42	1.99	1.70

*Total job time does not include mobilization and set-up time.

TABLE C.7

COST ESTIMATE FOR HOLE LENGTHS OF 1000, 2000, 3000, 4000 AND 5000 FEET

NEAT CEMENT GROUT USED FOR HOLE STABILIZATION

Length of Hole (feet)	1000	2000	3000	4000	5000
Equipment Operation	6,232	14,859	26,540	40,923	57,869
Materials	22,197	46,617	74,309	105,833	141,886
Crew (3 men)	14,616	34,848	62,244	95,976	135,720
Mobilization & Set-up	3,000	3,300	3,600	4,000	4,400
Total	46,045	99,624	166,693	246,732	339,875
Overhead 15%	6,907	14,944	25,004	37,010	50,981
Total	52,952	114,568	191,697	283,742	390,856
Profit 15%	7,943	17,185	28,755	42,561	58,628
Total Cost of Hole	60,895	131,753	220,451	326,303	449,484
Average Cost per Foot	60.89	65.88	73.48	81.58	89.90

TABLE C.8

COST ESTIMATE FOR HOLE LENGTHS OF 1000, 2000, 3000, 4000 AND 5000 FEET

CHEMICAL GROUT USED FOR HOLE STABILIZATION

Length of Hole (feet)	1000	2000	3000	4000	5000
Equipment Operation	3,699	9,839	18,988	30,853	45,282
Materials	18,680	39,141	62,386	89,018	119,710
Crew (3 men)	8,676	23,076	44,532	72,360	106,200
Mobilization & Set-up	3,000	3,300	3,600	4,000	4,400
Total	34,055	75,356	129,506	196,231	275,592
Overhead 15%	5,108	11,303	19,426	29,435	41,339
Total	39,163	86,659	148,932	225,666	316,931
Profit 15%	5,874	12,999	22,340	33,850	47,540
Total Cost of Hole	45,037	99,658	171,272	259,516	364,471
Average Cost per Foot	45.04	49.83	57.09	64.88	72.89

TABLE C.9

COST ESTIMATE FOR HOLE LENGTHS OF 1000, 2000, 3000, 4000 AND 5000 FEET

CEMENT, BENTONITE AND REAGENT USED FOR HOLE STABILIZATION

Length of Hole (feet)	1000	2000	3000	4000	5000
Equipment Operation	3,699	9,839	18,988	30,853	45,282
Materials	11,530	24,841	40,936	60,418	83,960
Crew (3 men)	8,676	23,076	44,532	72,360	106,200
Mobilization & Set-up	3,000	3,300	3,600	4,000	4,400
Total	26,905	61,056	108,056	167,631	239,842
Overhead 15%	4,036	9,158	16,208	25,145	35,976
Total	30,941	70,214	124,264	192,776	275,818
Profit 15%	4,641	10,532	18,640	28,916	41,373
Total Cost of Hole	35,582	80,746	142,904	221,692	317,191
Average Cost per Foot	35.58	40.37	47.63	55.42	63.44

TABLE C. 10

COST ESTIMATE FOR HOLE LENGTHS OF 1000, 2000, 3000, 4000 AND 5000 FEET

NO HOLE STABILIZATION REQUIRED

Length of Hole (feet)	1000	2000	3000	4000	5000
Equipment Operation	3,346	8,949	17,422	28,444	41,844
Materials	5,552	12,738	22,531	35,482	52,204
Crew (3 men)	7,848	20,988	40,860	66,708	98,136
Mobilization	3,000	3,300	3,600	4,000	4,400
Total	19,746	45,975	84,413	134,634	196,584
Overhead 15%	2,962	6,896	12,662	20,195	29,488
Total	22,708	52,871	97,075	154,829	226,072
Profit 15%	3,406	7,931	14,561	23,224	33,911
Total Cost of Hole	26,114	60,802	111,636	178,053	259,983
Average Cost per Foot	26.11	30.40	37.21	44.51	52.00

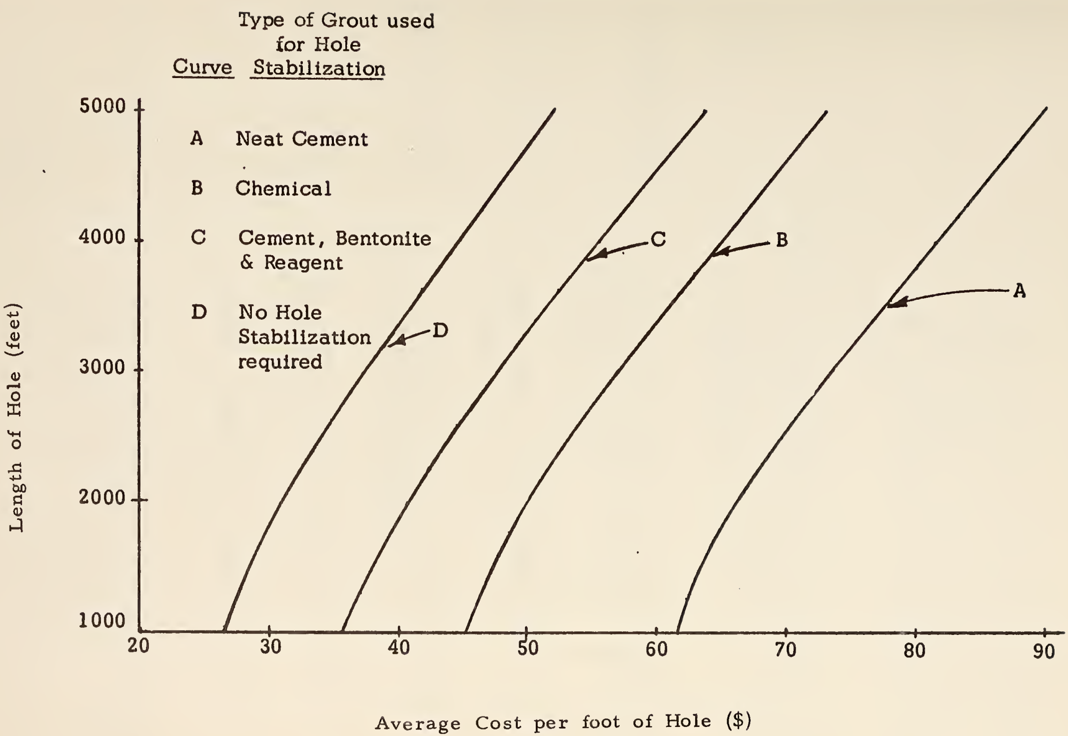


Figure C.2 - Average Cost per Foot for Hole Lengths of 1,000 Through 5,000 Feet

GLOSSARY OF TERMS

Bent sub:	(1) A short sub (section of drill rod) that has its upper thread cut concentric with the axis of the sub body, and its lower thread cut concentric with an axis at an angle (from $1/2^{o}$ to 3^{o}) in relation to the axis of the upper thread.
	(2) A short section of drill rod with a bend (usually of $1/2^{o}$ to 3^{o}) in it, used on an in-hole motor to change the direction in which the hole is being drilled.
Competent rock:	Rock which is able to maintain an underground opening or a steep slope at the surface without artificial support.
Core holes:	A hole which has been drilled using a core drilling technique.
Deflection tools:	Any instrument used in the hole to purposely change the direction of drilling.
Deviate the hole:	To cause a change in the direction that a hole is being drilled.
Dogleg:	A sharp, undesirable change in direction of the hole.
Drill string:	The sectionalized rod or pipe connecting the drill bit with the surface. Used for the transmission of force, torque, fluid, and control.

Fulcrum effect: A technique used to cause the drilling assembly to build angle (curve the drilling trajectory up) or lose angle (curve the drilling trajectory down) by establishing a pivot point on the drilling assembly (with a stabilizer or reamer, etc.) and adding weight either ahead of or behind the pivot point. (See Section 6.4.2)

Go-deviling: The process of transferring an object through a drill string (or pipe) by fluid flow.

Gouge: Crushed and comminuted rock formed by grinding action between moving adjacent walls of a fault.

Guidance: Combined actions of survey and steering to effect control of the borehole direction.

Incompetent rock: Rock which is not capable of remaining standing in an underground opening or a steep slope at the surface without artificial support.

Jet bits: A bit utilizing the principle of the hydraulic jet to deviate holes in soft ground. (Also called "one-eye" bit)

Kick sub: A hydraulically actuated bent sub used in hole deviation.

Knuckle joint: A tool used to deviate holes; basically a pilot reamer with a universal joint principle built into its connection with the drill stem.

Mud: Drilling fluid (it contains necessary solid particles and other additives to achieve desired results).

Mud pump:	The pump that injects the drilling fluid into the drill string at the desired rate and pressure.
Mule shoe:	A specially shaped cam which is designed to mate with a similar cam and remotely force survey instruments to rotate into proper angular alignment with respect to a reference point near the end of the drill string.
Overshot:	A wire line, self-engaging device which attaches itself to the head of any down-hole tool which has been equipped for that purpose.
Positive displacement motor:	A motor which converts the pressure of a fluid to shaft torque.
Raise boring:	A shaft drilling procedure in which a large drilling head is pulled back through a pilot drill hole.
Rat hole:	A section of hole which is purposely undersized (a pilot hole). Rat hole also refers to a hole of reduced size in the bottom of the regular well bore. Sometimes the driller "rat holes ahead" to facilitate the taking of a drill stem test when it appears that such tests will be desirable.
Reverse circulation:	A drilling fluid circulation technique in which the drilling fluid is pumped into the hole through an annular area, either outside the drill string or enclosed by a double tube configuration, and returns up the center of the drill string.
Spudding bit:	A spade shaped bit used to deviate holes in soft ground.

Steering: The mechanical process of directing a borehole along a desired path.

Slim-hole: A bore hole of small diameter which can be drilled with a very light-duty rig.

Stinger: The lower drilling assembly consisting of a bit and reamer.

Sub: A very short section of drill string.

Survey: The process of determining the path of a borehole relative to a fixed point in space by determination of attitudes in two dimensions and distance in the third at a sequence of stations. The line segments between stations are then connected to form a two-dimensional plot of the survey.

Tool: Any ancillary device used to assist in drilling operation.

Turbine: An engine or motor driven by the movement of water, steam, air, etc. past the vanes of a wheel or set of wheels fastened to a driving shaft. The turbine converts fluid velocity to shaft torque.

Whipstock: A wedge shaped tool used to change the direction of drilling.

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