SCHOOL OF
CIVIL ENGINEERING

INDIANA
DEPARTMENT OF HIGHWAYS

JOINT HIGHWAY RESEARCH PROJECT

Final Report

JHRP-89/8

CONSTRUCTION SPECIFICATIONS
FOR HIGHWAY PROJECTS REQUIRING
HORIZONTAL EARTH BORING AND/OR
PIPE JACKING TECHNIQUES

Donn E. Hancher
Thomas D. White
D. Thomas Iseley

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ENGINEERING AND
MANAGEMENT

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TO: H. L. Michael, Director
Joint Highway Research Project

July 7, 1989

FROM: T. D. White, Research Engineer
Joint Highway Research Project

Project: C-36-672
File: 9-11-26

Attached is the Final Report for the above referenced project. The study was conducted and the report authored by Dr. D.T. Iseley, Graduate Research Assistant, under the direction of Professors T.D. White and D.E. Hancher.

The major objective of this study was to evaluate the various horizontal earth boring and pipe jacking techniques used by highway agencies for placing drainage structures and utilities under highways and railroads. Background information on all known methods, materials, and equipment are provided in the report. Current design procedures are reviewed and summarized. Recommended modifications to existing guidelines and specifications are presented.

This Final Report is forwarded for review and acceptance by all sponsors as fulfilling the objectives of the study.

Sincerely,

Thomas D. White
Research Engineer

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CONSTRUCTION SPECIFICATIONS FOR
HIGHWAY PROJECTS REQUIRING
HORIZONTAL EARTH BORING
and/or
PIPE JACKING TECHNIQUES

Joint Highway Research Project
Project No. : C-36-672
File No. : 9-11-26

Conducted For :
Indiana Department of Highways

Prepared By :
D. E. Hancher, Research Engineer
T. D. White, Research Engineer
D. T. Iseley, Research Assistant

This research was carried out by the Joint Highway Research Project, Purdue University, under the direction of the first author as the principal investigator. The contents do not necessarily reflect the official views or policies of the Indiana Department of Highways.

PURDUE UNIVERSITY
School of Civil Engineering
West Lafayette, Indiana

July, 1989

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HIGHLIGHT SUMMARY

On the basis of a preliminary evaluation, it was determined that a high degree of variation in specifications for horizontal earth boring, pipe jacking, and utility tunneling projects exists across the United States. It was also recognized that many designers and highway department representatives were not familiar with current methods, materials, and equipment being utilized. Since the contract documents, detailed plans, and specifications are the primary instruments of communication for the contractor, then it is understandable why "incomplete, inaccurate, and faulty construction specifications often result in a large number of field problems " [55]. Designers and highway departments have a professional responsibility to insure that their specifications are accurate and complete.

This report is a result of in-depth research into the development of specifications for the rapidly evolving area of trenchless excavation construction (TEC). A summary description of the various methods, equipment, and materials commonly utilized in the United States is provided. The design principles and practices for various conditions and materials are presented. Recommended guidelines and specifications have been developed and are presented in this report.

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CHAPTER 1 - INTRODUCTION

1.1 General Description Of The Industry And Problem

Increased demand for higher environmental standards and quality of life have resulted in transportation, communication, and utility networks growing in size and complexity. These network systems include tunnels, subways, pipelines, and cables installed below ground with highways, railways, and waterways installed above ground. As these networks grow, the frequency for two or more systems to occupy a common right-of-way or intersect one another continues to increase resulting in construction, maintenance, and operational problems [1]. This point of intersection is critical and should be given special design consideration.

Trenchless excavation construction (TEC) methods for the placement of underground utility systems are becoming popular due to their inherent advantages. TEC methods are divided into three basic categories: (1) horizontal earth boring, (2) pipe jacking, and (3) utility tunneling.

There exists a natural industry division

between traditional tunneling contractors and those that specialize in trenchless excavation construction. This division has resulted from typical project characteristics. Traditional tunneling projects tend to be major undertakings due to their diameter and length; and are classified as high profile because they normally attract international attention. Such projects require a high degree of engineering design, geotechnical evaluation, and construction tunneling skill. Due to the dollar value involved, the traditional tunneling contractor is a large firm that will be the prime contractor. Historically, excellent records have been maintained, and this segment of the industry is well organized. For example, in 1972 the first Rapid Excavation and Tunneling Conference (RETC) was conducted. In 1987, the eighth conference was held at which eighty technical papers were presented describing research and projects in 15 countries. In addition, many technical articles and books have been published on practically all aspects of tunneling.

TEC contractors (i.e., horizontal earth boring, pipe jacking, and utility tunneling) are usually subcontractors with the trenchless phase being a small segment of a total project. Thus, these projects do not get the same degree of emphasis as larger tunnel projects. Very few case studies and written documentation exist.

Only a limited amount of research has been conducted with most being conducted by equipment manufacturers. Until approximately 10 years ago, the industry was disorganized with members having little association with each other professionally. However, during the past decade TEC contractors have realized that they must share their knowledge and experience if the industry is to grow and provide a benefit to the fullest extent possible.

This research endeavor concentrated in its entirety on the TEC industry. While this industry primarily is concerned with trenchless excavation for the placement of utilities, these techniques are utilized in the larger sizes for the placement of major drainage structures. The diameter size range that was investigated varies from 2-inch to 12-feet.

The intersection of two or more networks involves many safety, installation, maintenance, operational, and legal concerns by each owner. This intersection phase of a project may seem like an insignificant portion of the project when compared to the total project cost. However, due to its critical nature, degree of risks, and uncertainties, it may be the most critical and significant component of the project. Utilities intersecting with highways is the most common type of intersection encountered.

Figures 1-1 and 1-2 illustrate typical plan, profile, and standard details associated with the trenchless placement of utilities. The obvious intent is to install the watermain without damaging any of the existing utilities or the roadway. This represents an extremely complex operation, technically and politically. Each of the existing lines indicated in Figure 1-1 has an owner which means that the TEC must be co-ordinated with several entities.

The following quote illustrates the common lines of responsibility and the importance of standard guidelines and specifications :

"Each highway agency has the responsibility to maintain the right-of-way of highways under its jurisdiction as necessary to preserve the operational safety, integrity, and function of the highway facility. Since the manner in which utilities cross or otherwise occupy highway right-of-way can materially affect the safe operation, maintenance, and appearance of the highway, it is necessary that such use and occupancy be authorized and reasonably regulated. The highway agencies have various degrees of authority to regulate the use of utilities on highways, generally through their authority

BORED HIGHWAY CROSSING NO.3

INSTALL 105 LF. OF 36" X. 0.531"
STEEL CASING PIPE AND 115 LF. OF 20",
CLASS 51, RESTRAINED JOINT D. I. PIPE..

Figure 1-1. Typical Plan and Profile Detail for a Trenchless Excavation Construction (TEC) Project.

Figure 1-2. Typical Standard Detail for Trenchless Excavation Construction (TEC)

to designate and to control the use made of right-of-way acquired for public highway purposes. Their authorities depend upon state laws or regulations, which differ between states. A state also may have local, city, or county government laws and regulation which differ from those applicable state-wide for highways.

Utilities also have various degrees of authority to install their lines and facilities on the right-of-way of public roads and streets. Like highway agencies, their authorities depend upon state laws and regulations which differ between states. They also depend upon franchises, local laws, and ordinances which differ in the several political subdivisions within a state.

Aside from the necessary differences imposed by state and local laws, regulations, franchises, governmental and industry codes, climate, and geography, there can be and should be reasonable uniformity in the engineering requirements employed by highway agencies for regulating utility use of highway right-of-way. In this respect,

guidelines outlining safe rational practices for accommodating utilities within highway right-of-way are of valuable assistance to the highway agencies." [1]

However, even with this emphasis on standardization, existing policies relating to TEC among utility and transportation facility owners, regulatory agencies, consulting engineers vary considerably. Many organizations have developed guidelines, policies, and specifications independent of each other and from differing backgrounds. As a result of not being updated for many years, the validity of many such policies is not clear and cannot be substantiated in many cases. Therefore, since no comprehensive uniform guidelines exist for the various trenchless methods currently available, much confusion has resulted concerning what is acceptable.

As a result of the lack of comprehensive guidelines and design criteria, design engineers will often limit options by specifying oversized, thick walled casing pipe, coating inside and / or outside, and both ends bulkheaded and vented to the ground surface. Other options that may be specified include filling the space between the carrier pipe and casing pipe with sand or grout, and that the annular space between the outside of the casing

and the bore hole be grouted. Although a particular installation may require most or all of these options, other installations may not. Overdesign is a waste while underdesign involves inherent dangers and liabilities. Continuing to pay the high price tag for overdesign as a standard practice because of lack of experience in the industry does not have to continue.

The demand for trenchless placement of utilities is growing at an increasing rate. As designers become cognizant of the capabilities that exist, and as the unit prices continue to become more competitive; these methods will become specified for entire systems rather than just a method of getting pipes under roadways. The problem of overdesign or underdesign can be mitigated with comprehensive design and construction guidelines for trenchless underground excavation founded on state-of-the-art technology. At the present time, industry information is fragmented; and there is no single source of information which compiles data on materials, methods, and equipment for trenchless construction. The NATIONAL UTILITY CONTRACTORS ASSOCIATION (NUCA) has published the most comprehensive guidelines available in the industry in their Horizontal Earth Boring and Pipe Jacking Manuals No. 1 & 2 which

are a product of the Horizontal Earth Boring and Pipe Jacking Committee. This committee is composed of TEC contractors, equipment manufacturers, and material suppliers involved in the industry.

The major objective of this research project was to develop model guidelines and specifications for the TEC industry. This thesis will be useful to design engineers, regulatory agencies, and others that need specific information on horizontal earth boring, pipe jacking, and utility tunneling techniques. It will provide specific information on the various methods, materials, design criteria, and existing specifications.

A description of the TEC industry must acknowledge its current status of technological revolution. This worldwide technological revolution is a result of the rapidly increasing demand for trenchless techniques. The incentives for utilizing these techniques include :

- * A reduction in the total (direct, indirect, social, etc.) cost of utility installation.
- * Reduction or elimination of restoration costs.
- * Labor cost reduction.
- * Urban operation simplification.
- * Improvement of customer relations.
- * Easier access to new utility customers. [11]

In situations where trenching techniques are being

compared with trenchless techniques, the feasibility evaluation should consider the following quotes :

"Even when backfilling and street reinstatement are of high quality, long term settlements and water migration under the repaired pavement can result in uneven surfaces, cracks and separations. Although all forms of trenchless construction require some open excavation, the trenching is reduced typically to less than 10% of that needed by conventional methods." [18]

"With trenches, substantially more volume than that of the pipeline must be removed. The surface is disrupted and large areas of the excavation are exposed to ground loss." [18]

"Studies have shown that, under unfavorable circumstances, the indirect costs can be as high as ten times the amount paid for engineering and construction services." [18]

Indirect social costs that should be considered:

- * Traffic delays
- * Damage to services and structures
- * Disruption of business
- * Loss of environmental quality
- * Damage to detour routes when not designed for the heavy loads.

1.2 Justification For Research On Trenchless Placement Of Utilities

The trenchless excavation construction (TEC) industry has been in existence for over 40 years. The greatest growth, developments, and innovations have evolved the last 10 years with tremendous intensity in the past 5 years. The magnitude of this technological revolution has been such that those involved in the industry on a continuous basis cannot keep abreast of the innovations and developments. This revolution is not limited to the United States. Significant efforts have been made outside the United States to organize the industry and inform all segments of the industry regarding the capabilities of modern methods, equipment, and materials.

In April 1985, the first international conference (NO-DIG 85) was held in London. The goal of the conference was to obtain a global view of the state-of-the-art of the TEC industry. The conference success was indicative of the interest level. Approximately 400 delegates attended with over 100 delegates being from 26 different countries. This conference emphasized the fact that extensive research and development was being concentrated in this area. However, it is clear that the U.S. is lagging behind in methods that required a high degree of sophistication, such as micro-tunneling.

In April 1987, the second international conference concerning TEC for utilities was conducted in London. The success was a repeat of NO-DIG 85. It was recognized that technological advancements were taking place at such a rapid rate that the third conference should be conducted sooner than a two year interval. Therefore, the third international conference was conducted in October, 1988 in Washington, D.C.

This dynamic advancement of the TEC technology has compounded the problems already experienced concerning communications between the designers, regulatory agencies, and those responsible for executing the work. The major source of communications are the guidelines and specifications. However, before effective specifications can be developed, a comprehensive, unbiased, thorough research program must be conducted to evaluate the status of the industry.

Based on the data collected on the industry, the following tasks have been accomplished :

- * Developed a knowledge base of the available equipment and provided procedure descriptions for methods that utilize various types of equipment.
- * Presented an overview of current regulations and specifications to illustrate the degree of variation that exists in the industry.

- * Developed model guidelines and specifications.
- * Reviewed current design criteria and made necessary modifications which reflect the state-of-the-art.
- * Developed decision making guidelines to assist design engineers and contractors in selecting proper materials, methods, and equipment for specific project applications.
- * Illustrated how computer simulation utilizing the powerful SLAM II software is applicable to the trenchless excavation industry. [54]

The following list illustrates the multitude of factors that should be taken into consideration during the design process. These major concern areas were investigated in depth as part of this research endeavor.

- * When should a casing pipe be required.
- * Minimum size casing pipe determination.
- * Minimum casing pipe wall thickness determination.
- * Establishing the casing pipe material and standard of quality.
- * Determination of casing pipe coating requirements.
- * Establishing the carrier pipe material and standard of quality.
- * Determination of safe distance pits and the

end of the casing pipe should be located from the edge of roadway pavement.

- * Should ends of casing pipe be capped or bulkheaded, if so, how.
- * Should void space between carrier and casing be filled, if so, with what and how.
- * Should casing pipe be vented, if so, how.
- * Selection of proper methods and equipment.
- * Should the annular space between casing pipe and borehole be filled, if so, how.
- * Determination of the required accuracy.

The justification for this research was to evaluate specification variation to determine the feasibility of standardization. Standard specifications would benefit the total TEC industry. The designer could be assured that the specification was adequate in providing the necessary information for contractors to develop responsible bids. Standard specifications would assist the contractor by allowing him to know what will be expected from project to project. As it currently exists, the contractor must comply with different guidelines from one project to another. Because of a lack of understanding concerning TEC methods, many specifications contain restrictions that prevent safe, modern methods from being utilized.

1.3 Description Of The Research Methodology

A preliminary investigation indicated that existing industry related published literature was minimum and appeared to be fragmented, confusing, and biased. Therefore, the initial phase of this research required the development of an in-depth knowledge base on TEC. The knowledge base for the objectives of this research endeavor were obtained was developed from conducting the following activities over a two year period :

- * Conducted a HRIS literature search on the topics of auger boring, boring, jacking, or casing from 1980 to the present time. Obtained and reviewed copies of applicable articles.
- * Solicited active participation and involvement from the (NUCA) National Utility Contractors Association's special task force which was appointed by the Horizontal Earth Boring and Pipe Jacking Committee.
- * Visited 35 jobsites in 10 states to observe various methods, equipment, and materials, collected data, and interviewed TEC field personnel.
- * Solicited input from 17 major equipment manufacturers. Visited five manufacturing facilities of different types of TEC equipment in different sections of the United States.

Conducted many personal and phone interviews in an effort to obtain the latest developments and future forecasts concerning equipment.

- * Collected and reviewed over 100 sets of currently used specifications from state highway departments, private consulting engineers, municipalities, utility owners, and railroad organizations.
- * Corresponded with over 130 state highway department divisions in 50 states to obtain an understanding of standard practices and problems encountered across the United States.
- * Attended and participated in several seminars, workshops, and conferences throughout the United States to learn more about the technical aspects associated with TEC, and to inform others of the research objectives of this project to encourage participation and input. Presented a technical paper at the ASCE Pipeline Infrastructure Conference in Boston, MA. Received a "Certificate Of Achievement" for attending the American Augers, Inc. 5-day Horizontal Earth Boring Seminar. Attended the Third International Conference and Exhibition on the Achievements in Trenchless Methods.

1.4 Description Of Research Limitations

This research endeavor was limited to evaluating the industry in sufficient detail to develop effective guidelines and specifications. Therefore, it was beyond the scope of this project to develop any type of economic analysis, detailed equipment evaluations, computer design models, or actual field comparisons.

CHAPTER 2 - EVALUATION OF TRENCHLESS EXCAVATION METHODS

This chapter evaluates the various trenchless excavation construction (TEC) methods that are being practiced in the United States. It is not the intent of this chapter to select specific methods as being preferred, but rather to present an unbiased description to aid individuals in understanding the mechanics and background involved. The template used to evaluate these methods is:

* Method Description	* Major Advantages
* Main Characteristics	* Major Disadvantages

All methods evaluated are classified into one of the three following categories : (1) Horizontal Earth Boring, (2) Pipe Jacking, and (3) Utility Tunneling. Figure 2-1 illustrates the classification system which was developed to provide continuity for this research.

2.1 Horizontal Earth Boring

This category includes methods in which the borehole excavation is accomplished through mechanical means without workers being inside the borehole.

Figure 2-1. Classification Flow Chart for Typical Trenchless Excavation Construction (TEC) Techniques.

2.1.1 Auger Horizontal Earth Boring

2.1.1.1 Method Description

The Auger Horizontal Earth Boring (HEB) method utilizes the process of simultaneously jacking casing through the earth while removing the spoil inside the encasement by means of a continuous rotating flight auger. [2] The auger is a flighted drive tube having couplings at each end that transmits torque to the cutting head from the power source located in the bore pit and transfers spoil back to the machine. Table 2-1 illustrates auger physical characteristics. [14]

The auger HEB method is traditionally classified as : (1) Track - Type or (2) Cradle - Type.

Major components of track-type methods include the track system, machine, casing pipe, cutting head, and augers. In addition to these major (necessary) components, many optional components are available which include a bentonite lubrication system, a steerable (grade control) head, a casing leading edge band, and a ditch water level indicator.

Two factors that impact auger boring are attempting to minimize torque and thrust. The torque is created by the power source which can be pneumatic, hydraulic, or an internal combustion engine (diesel or gas) through a mechanical gearbox. [15] The torque

Table 2-1. Physical Characteristics of Horizontal Boring Augers [13]

NOMINAL SIZE	ACTUAL O.D.	HEX CONNECTION	WEIGHT PER FOOT ²
3"	3"	1"	4.50 LBS.
4"	3¾"	1⅜"	6.50 LBS.
4"	4"	1⅞"	5.50 LBS.
4"	4"	1⅜"	7.50 LBS.
6"	5"	1⅜"	9.00 LBS.
6"	5"	1⅝"	10.80 LBS.
8"	7"	1⅝"	15.00 LBS.
8"	7"	2¼"	18.50 LBS.
10"	9"	1⅝"	18.00 LBS.
10"	9"	2¼"	18.75 LBS.
12"	11"	1⅝"	21.75 LBS.
12"	11"	2¼"	25.75 LBS.
12"	11"	3"	39.00 LBS.
14"	13"	1⅝"	24.00 LBS.
14"	13"	2¼"	27.50 LBS.
14"	13"	3"	43.00 LBS.
16"	15"	1⅝"	22.75 LBS.
16"	15"	2¼"	29.75 LBS.
16"	15"	3"	46.00 LBS.
18"	17"	2¼"	35.00 LBS.
18"	17"	3"	51.00 LBS.
20"	19"	2¼"	37.00 LBS.
20"	19"	3"	53.00 LBS.
22"	21"	2¼"	40.00 LBS.
22"	21"	3"	56.00 LBS.
24"	23"	2¼"	49.00 LBS.
24"	23"	3"	58.00 LBS.
30"	29"	3"	65.00 LBS.
36"	35"	3"	82.50 LBS.

rotates the auger and cutting head. The casing remains stationary by being temporarily attached to the boring machine. The thrust is created by one or more hydraulic thrust rams (cylinders) located at the rear of the machine. One end of the rams is attached to the machine, and the other end is attached to lugs (ears) that lock into the track system.

In the event that torque or thrust required exceeds machine capacity then all forward advancement is halted. Actual excavation conditions to be encountered are never known or visible; therefore, every effort should be made to minimize torque and thrust. Both should be closely monitored throughout the operation. When torque or thrust demand increases or decreases beyond reasonable limits, then this is an indication of problems developing.

Soil test borings, soil classification, and groundwater level determination should be provided for all significant projects. The contractor should excavate test pits prior to bidding; however, this does not preclude that changed conditions and/or obstacles may be encountered during the execution of the boring operation. All reasonable efforts should be made to insure that unexpected conditions can be handled safely.

Basic procedures associated with any project are:

- * Jobsite preparation.

- * Bore pit and receiving pit excavation and preparation for the boring equipment.
- * Set boring machine track system in prepared pit and adjust for line and grade.
- * Place boring machine on the track system.
- * Attach cutting head on leading end of auger.
- * Install casing/auger unit on supports located on the track system and attach to machine.
- * Begin forward advancement and auger rotation.
- * Begin embankment penetration (collaring).
- * Continue forward advancement until casing is completely installed.
- * Retract machine.
- * Place casing/auger unit on track system.
- * Attach auger at both ends.
- * Weld leading edge of new casing to previous casing, and attach trailing end to machine.
- * Begin forward advancement and continue cycles until desired casing length is installed.
- * Remove augers, machine, and tracks.

The jobsite characteristics must be taken into consideration during the planning stage to insure compatibility with the proposed operation strategy. Enough room must be provided to safely load and unload equipment and materials as well as for spoil removal. Accidents are less likely to occur on sites that are

open and kept clear of debris. [13] Jobsite drainage and bore pit dewatering must be taken into consideration. Since the major boring equipment will be located in the pit during the boring operation, all surface water should be routed away from the pit and water entering the pit should be routed to a sump for expulsion by an adequate pumping system.

The operation strategy is a function of the site. The most common (industry standard) casing length is 20-LF segments; however, in congested areas 10-LF segments may be used. Where conditions permit, 40-LF or even 100-LF casing lengths can be used.

The pit size is a function of machine size and casing length to be utilized. Table 2-2 illustrates recommended pit dimensions for standard 20-LF casing lengths for various size boring machines. The model (series) number indicated in the table correlates with the largest diameter bore the machine was designed for. The depth of the bore is a function of the carrier pipe design. Dimension "H" in Table 2-2 is the machine height, and is important in providing proper clearance for existing utilities that may cross the bore pit or pit sheeting cross struts.

The bore pit must be constructed in accordance with the rules set forth in the Occupational Safety and Health Administration's Code of Federal Regulations 29.

Table 2-2.. Boring Pit Dimensions for Track - Type
of Auger Horizontal Earth Boring [13]

PIT DIMENSIONS (English)

MODEL	CL	S	L	W	H
16, 20	13½	6	32	9	3
24	14½	6	32	9	3
30	19½	7	32	10	5-6
36	22	7	32	10	5-6
42	25	7	32	10	6
48	28	8	32	12	6
60	35	9	34	14	8
SERIES	in	feet			

NOTE : (1) The model number indicates the largest outside diameter to be bored with the particular series machine. (2) All dimensions are based on using standard 20-LF casing lengths.

Since the pit will remain open for an extended period of time, housing men and equipment, it is important that it be safe and be protected during the operation. It is beyond the scope of this project to discuss in detail the recommended mechanics associated with trench or pit excavation protection. However, it is the responsibility of all parties associated with the operation (prime contractor, owner, engineer, sub contractor, regulatory agencies, etc.) to prohibit the use of any pit not constructed in accordance with the regulations promulgated by OSHA (Department of Labor).

The proposed grade (slope) of the carrier pipe, allowable tolerance, and depth are parameters established by the system design engineer. These parameters have an exponential impact on the cost of the proposed crossing. Generally speaking, for pressure lines such as petroleum products, water, etc. alignment and grade are not critical unless located in highly congested areas. However, for sanitary or storm sewer (gravity) flows, the alignment and grade are critical.

Boring preparation work (setting up) is crucial; however, the more critical the required alignment and grade, then the more crucial the preparation work. Pit construction involves the excavation, side protection, subbase grading, track foundation system, and thrust reaction support. Since auger boring is basically using

a cutting head that is unintelligent and unguided, the probability of success depends to a great extent on the quality of the original set up. The vertical direction of the cutting head can be steered to some degree by the installation of a steering (grade control) head which will be discussed in detail later; and horizontal alignment can be corrected to a small degree on larger casing by pulling the augers and having a man crawl through the casing to the leading edge, then manually excavate on the appropriate side and use wedges.

Even though grade and alignment modifications can be made, these are considered primarily as corrective measures. The line and grade of the completed bore depends on original machine alignment and grade.

The necessary effort, time, and money must be expended to insure that the foundation is secure. This will be a function of the nature of the bore and the site material. For short, shallow, ungraded, non critical alignment in stable conditions, the foundation may be undisturbed soil of the pit. For unstable conditions, a concrete slab may be a necessity as illustrated in Figure 2-2. However, the most common foundation construction is of crushed stone.

The maximum horizontal thrust created during the jacking operation of the auger bore procedure is a function of the hydraulic rams. It typically varies

Figure 2-2. Track - Type Auger Horizontal Earth Boring [13]

from 14,000-lbs. to as high as 1,000,000-lbs. for 60-inch series machines. This thrust is transmitted to the track system by the rams then transmitted through the track system to a thrust reaction structure. The thrust reactor (backstop) must be designed securely. The industry accepted design safety factor is 1.5 to 2.0 times the maximum possible thrust that could be created by the machine to be used. It may vary from hardwood piling to large, heavy steel plates and/or concrete structures.

Adequately designed and constructed track system foundation and thrust reaction structure are essential for all auger bores. Many problems that occur during the operation can be traced back to these elements. If a bore is unusable (not within allowable tolerance) then it must be abandoned. An abandoned bore benefits no one, and normally results in project delays, disputes, and claims which add even additional expense to the project. If a boring machine and track system are being supported by a soft foundation and/or pushing against an unstable thrust reaction, it is highly probable that the bore will be abandoned.

Once the pit has been prepared properly, the track system can be positioned. The master track section is the segment designed to fit at the rear of the pit and transfer thrust from track to backstop. The

master track section must be placed first, and the remaining sections are placed as required. Track segments are bolted to each other. Alignment and grade must be carefully monitored during the installation process with a final check to insure correctness.

The boring machine is then placed on the track system. The machine may be solid frame (one piece) or it may be split frame to decrease the lifting load requirement. If a split frame machine is being used, then the machine base is placed in one operation; and the engine part of the machine is installed separate, then secured to the base by lock down devices (dogs).

Prior to casing and auger installation, much consideration must be given to the measures to be taken to minimize torque and thrust; and to insure specified line and grade tolerances are obtained. Proper casing preparation eliminates blind risk. The use of the optional components described previously must be determined before the casing is placed in the bore pit. In most cases the boring contractor will perform all work necessary on the lead casing at the shop prior to transport to the jobsite. However, whether accomplished at the shop or in the field, skill is required for the preparation of the lead casing. Table 2-3 illustrates what options are recommended for specific soil conditions.

Table 2-3. . Ground Conditions Chart for Track - Type Auger Boring Procedures [13]

GROUND CONDITIONS CHART RECOMMENDATIONS AND SUGGESTIONS FOR CASED BORES

SOIL CONDITION	Augar Speed	Rate of Penetr.	Head	Wing Cutters	Head Position	Bent-on/le Inside	Band	Bore Continuous	Clean Pipe		Backstop
									Section	Pit Base	
Wet Runny Sand	S	H	HTD	NO	INSIDE	YES	NO	YES	YES	PACK	CONC
Wet Stable Sand	F	H	HTD	NO	INSIDE	YES	NO	YES	YES	PACK	CONC
Dry Sand	S	H	HTD	NO	INSIDE	YES	NO	YES	YES	PACK	CONC
Dry Clay	F	H	HTD	NO	FLUSH	YES	YES	YES	OPT	CLEAN	PLATE
Wet Clay	M	H	HTD	NO	FLUSH	YES	YES	YES	OPT	CLEAN	STONE
Small Gravel	M	H	HTR	YES	OUTSIDE	YES	YES	YES	OPT	CLEAN	STONE
Hard Pan	S	M	HTR	YES	OUTSIDE	NO	YES	YES	OPT	CLEAN	PLATE
Large Gravel	S	L	HTR	YES	OUTSIDE	NO	NO	YES	OPT	CLEAN	PLATE
	S	L	HTR	YES	OUTSIDE	NO	YES	OPT	OPT	CLEAN	STONE
Small Boulders	S	L	HTR	YES	OUTSIDE	NO	NO	YES	OPT	CLEAN	STONE
Soft Solid Rock	S	L	HTR	YES	OUTSIDE	NO	NO	YES	OPT	CLEAN	CONC
Hard Solid Rock	S	L	SDRC	—	—	NO	YES	—	OPT	CLEAN	CONC

EXTREMELY DIFFICULT

Large Boulders	HAND TUNNEL				NO	YES	—	CONC	CONC
	C	L	HTR	YES					
Land Fill	C	L	HTR	YES	OUTSIDE	YES	OPT	CLEAN	OPT
Railroad Fill	C	L	HTR	YES	OUTSIDE	YES	OPT	CLEAN	OPT
River Crossings	C	L	SOIL	SOIL	SOIL	SOIL	YES	CLEAN	CONC

S-Slow, F-Fast, M-Medium, H-High, L-Low, C-Cautious, OPT-Optional, CONC-Concrete, PLATE-Steel Plate.

Normally, the lead casing will arrive at the jobsite with the auger inside and the cutting head attached to the leading end of the auger. All other casing will be delivered with the appropriate auger. In stable conditions, it is standard practice to operate with the cutting head leading the casing by several inches and using cutting head wing cutters to over excavate approximately 1 to 2-inches to minimize casing skin friction and thus minimizing jacking thrust. The boring contractor must know at all times where the cutting head is located with respect to the leading end of the casing. If the cutting head is not out far enough then it is probable that the wing cutters could contact the casing, creating a bind, and thus increasing torque and probable equipment failure. If the cutting head is leading the casing too far, then too great of a void is created before the casing is jacked into position. If the stand up time is less than the time the void is left exposed, then the borehole crown will be lost.

Knowing the exact location of the cutting head is accomplished by keeping a written record of the casing length and auger length. The only way to maintain a specified clearance between the rear of the cutting head and the leading edge of the casing is to insure that the casing length is the same as the auger length being used. For example, should a contractor decide to design

his operation based on 20-LF casing segments, then the casing should be inspected to verify that they are all even 20-LF lengths (referred to as dead twenties). This is a critical element. Major problems and failures (caved-in roadways) have developed due to the contractor not knowing the cutting head location, allowing it to lead too far in advance of the casing, creating a void, losing the borehole crown and eventually the roadway.

The auger used should be sized based on the casing size. Table 2-1 illustrates the actual outside diameter of the auger versus the nominal size. For auger sizes equal to or greater than 6-inch, the actual auger O.D. is 1-inch less than the nominal. This 1-inch clearance allows the auger to rotate freely inside the casing. All bores should be executed with a complete string of full size auger sections. However, under ideal soil conditions where the auger loading will be light and the spoil moves easily in the casing, lead sections of full size auger can be followed with smaller auger diameter sections. The smaller diameter auger should never be used in the lead section of the casing. The smallest backup auger used should not be less than 75% of the casing diameter. [13]

Contractors may attempt to use a smaller diameter auger instead of a full size auger to utilize his own rather than renting or purchasing sufficient length of

full size auger. This practice decreases the efficiency because all of the spoil is not being removed from the casing where the small diameter auger is being used. The auger must rotate more revolutions to remove the volume of soil being excavated at the face. This results in rotation of the auger without forward advancement.

The undersized auger creates other undesirable stresses such as bending stresses and sometimes binding stresses in the auger stem. Also, a windup effect is created by the smaller auger. Obviously, the smaller auger will have more windup from the same amount of torque loading than the full size (properly designed) auger. The torque windup pulls the cutting head back toward the casing and could cause the wingcutters to contact the casing, further increasing the torque requirements and causing even more damage and problems.

Use of bentonite applied near the leading edge of the casing has proven to be an effective method to reduce skin friction minimizing thrust requirements. Bentonite is an expansive, montmorillonite, colloidal clay material, when mixed with water becomes an excellent lubricant and sealant. In unstable conditions the use of bentonite aids in restricting sloughing and caving.

The consistency of the bentonite slurry can be modified by increasing or decreasing the bentonite concentration. Typically, a 5% gel concentration is desirable. The complete bentonite system consists of a mixing, pumping, and distribution system. The bentonite is transferred to a point of application near the leading end of the casing through a 0.5 to 1.5-inch steel pipe tack-welded to the outside top of the casing.

When the bentonite system is used in conjunction with a band attached to the leading edge of the casing, then the bentonite distribution line is flattened just behind the band and a small piece of flat metal bridged over the gap for support. This allows bentonite to be evenly distributed on top of the casing.

When the bentonite system is used in conjunction with a steering (grade control) head, then the steering adjustment rod is housed in a 1.5-inch steel pipe which also serves as the bentonite distribution pipe. With bentonite being pumped through this line, it insures that the steering head mechanical linkage will remain free of soil caking around the rod.

Figure 2-3 illustrates a process referred to as banding the casing. The use of the partial band located at the leading end of the casing has proven to be effective in most soil conditions for compacting the soil in the borehole, decreasing the skin friction.

BANDING THE CASING

Figure 2-3. Casing Leading Edge Band Detail for Auger Horizontal Earth Boring [13]

In most soils, there is a natural tendency with the rotating auger to drift down and to the right; however, the design of the partial band develops a counterbalancing lift. The banding process is most effectively utilized in unstable soil conditions where wingcutters are not used. In this case, the casing is pushed forward without the borehole being over excavated. The soil compacting effect is more pronounced as it relieves the pressure on the following casing sections. In addition, it is beneficial in rock because it strengthens the leading edge of the casing. [14]

Wing cutters are devices which are attached to the cutting head which open and close. When the cutting head is rotating in a clockwise direction, when viewed from the operator's position, the wing cutters open up to provide over excavation of the borehole. Over excavation results when the borehole is excavated larger than the casing O.D. Over excavation is a common procedure used to minimize casing skin friction. The wing cutters are adjustable to control the amount of over excavation. Standard over excavation is 1-inch greater than the casing pipe O.D.

When the cutting head rotates counterclockwise, the wing cutters close up so that the cutting head can slide back inside the casing for auger removal purposes.

The wing cutters must be set so as not to over excavate at the bottom of the casing. This practice will cause the bore to drift in a downward direction. Over excavation at the bottom can be prevented by using new or built up auger sections in the lead section of the casing. This practice maintains the proper centerline of the head. A worn auger in the lead section will allow the head too much freedom, and the wing cutter pattern will be erratic. [13]

Figure 2-4 illustrates typical types of cutting heads used in the industry. The cutting head type selected for a particular project should be compatible with anticipated soil conditions. In general, the following categories would apply :

<u>SOIL TYPE</u>	<u>HEAD TYPE</u>
Sand, Light Dirt	AAD / HTD
Clay, Heavy Dirt	BHD / HTD
Shale, Soft Rock	AAR / HTR
Rock To 6000 psi	HTR

A "Dutch Level" is a simple device that permits the monitoring of grade by using a water level sensing head attached to the top of the leading edge of the casing. The sensing head functions as an inverted "P" trap in a plumbing system. It must be securely welded to the casing. Water is transferred from a storage tank located at ground elevation at the pit to the control/

CUTTING HEADS

Figure 2-4. Typical Cutting Heads for Auger Horizontal Earth Boring [13]

indicator panel located in the pit, then to a 0.5-inch steel pipe that extends the full length of the casing to the sensing head. The steel pipe is attached to the casing pipe with welded straps. It should not be directly welded due to possibly creating a pinhole leak. However, if it is to be utilized, the sensing head must be welded to the casing prior to starting the bore.

Figure 2-5 illustrates the steering (grade control) head. It is useful in making minor corrective adjustments in the grade. The proposed line and grade are established with the above machine in the bore pit; however, with the aid of the dutch level, actual grade can be monitored and the necessary adjustments can be made with the steering head. It can only be used to make vertical corrections. If a steering head is to be utilized then the leading end of the casing must be properly prepared.

In some types of soil, it is advantageous to inject water into the casing to facilitate spoil removal. The point of injection is located behind the steering head a safe distance to prevent the water from contacting the excavation face. Normally, this distance is approximately 24-inches from the leading edge of the casing. This simply requires a 0.5-inch steel pipe tack-welded to the top of casing. The injection point is a 3-inch slot cut in the casing with

Figure 2-5. Mechanical Steering (Grade Control) Head for Track - Type Auger Horizontal Earth Boring.

the steel pipe beveled and bent so that it can be welded over the slot allowing water to enter the casing. This steel pipe is connected to a source of water.

When the lead casing section has been properly prepared, then it is placed in the bore pit with the proper size and length auger securely placed inside so that it will not slide out. The leading end of the casing is placed in a cradle. At the machine end, the auger is attached to the hex shank of the bore machine and the casing is securely attached to the bore machine frame to prevent rotation, and provide additional stabilization as the bore is being executed. After all of the necessary fabrication and hook ups have been made then the boring operation can begin.

Collaring is the first operation in beginning a bore. The objective of collaring is to get the cutting head started into the embankment without allowing the casing to be lifted out of the temporary casing support saddle. When the rotating cutting head first comes in contact with the resistance of the ground, there is a natural tendency for the leading end of the casing to climb upward. Should this occur, then the line and grade established previously will be affected. Collaring is accomplished by rotating the cutting head at low RPM's and using a slow thrust advance. When approximately 4-feet of the casing has entered the ground, the engine

is stopped, the temporary casing support saddle is removed, and the line and grade of the casing is checked. If the casing is not true, then the process is repeated. To a large extent, the success of the bore depends upon the line and grade established on the first section of the casing. [13]

The casing is installed by a sequence of cyclic operations. The thrust rams begin at the rear of the bore pit in the retracted position. As the cutting head/auger are being rotated, forward advancement is made by extending the hydraulic cylinder of the thrust rams to the limit of their stroke. The lugs which fit into prefabricated slots in the track system are retracted and then the hydraulic rams are retracted until the lugs can lock into slots nearest the machine. The cyclic operation is repeated until the entire casing has been installed.

In stable ground conditions, the augers are rotated several revolutions to clean the spoil out of the casing. Disconnect the auger at the machine. Next, the torque plates which are used to secure the casing pipe to the boring machine should be unbolted and removed. Move machine to the rear of the track so that another casing/auger unit can be placed into position. Hold and align the casing/auger unit until the auger-to-auger connection is "timed" (a continuous flight-

to-flight match). When the auger-to-auger connection is made, the two casings are welded together, the auger-to-machine connection is made, the casing-to-machine connection is made, and the auger rotation is begun along with the jacking operation.

This process is repeated as necessary until the desired length of casing has been placed. Next, the augers are removed from the casing, and the casing cleaned out as required. A final check is made of the line and grade of the installed casing.

Cradle-type auger horizontal earth boring (HEB) is suitable for projects that provide adequate room. The bore pit size is a function of the bore diameter and the desired length of the bore. This method is commonly used on petroleum products pipeline projects where large rights-of-way are essential. The cradle-type method is not as common for water and wastewater projects because these lines typically run parallel to the roadways, and then at some specific point turn to make a crossing.

The bore pit design and construction is not as critical a factor in the cradle-type boring operation as it is with the track-type method because the boring machine and the complete casing/auger system is held in suspension by construction equipment (pipelayers, excavators, and/or cranes) as the boring process is

executed. Thus the cradle-type method is often referred to as a "side boom" or "swinging" method.

This method offers the advantage that all preparatory work can be performed at ground level rather in the bore pit. The bore pit is excavated on line at a depth several feet deeper than the invert of the casing pipe. This extra depth allows space for spoil and water (ground and/or surface) collection as the bore is made. No foundation or thrust reaction structures are needed; however, a jacking lug (dead man) must be securely installed at the bore entrance embankment. Since all welding is completed prior to starting the boring operation, no one is required to get in the pit.

Figures 2-6 and 2-7 illustrate typical cradle-type auger bore equipment, setup, and procedures. All casing for the entire bore is welded together. The auger/cutting head unit placed in the casing. The cradle boring machine is attached to the trailing end of the casing, and the auger-to-machine connection is made. The total system is then suspended and moved into position in the bore pit. The operator's station is located on the machine which is secured to the end of the casing. The winch cable is attached to the deadman, and the cutting head properly positioned at the initial point of entry for the bore.

Source : Transportation Research Record 483

Figure 2-6. Direct Installation of Carrier Pipe with Cradle - Type Auger Horizontal Earth Boring [52]

Figure 2-7. Direct Installation of Casing Pipe with Cradle - Type Auger Horizontal Earth Boring [52]

By using appropriate survey equipment, the desired line and grade are established on the suspended casing by making necessary adjustments with the construction equipment suspending the boring equipment system. When the desired line and grade of the casing have been established, the boring process is initiated and is a continuous operation until completed.

Special design and construction consideration should be given to the foundation of the carrier pipe that is eventually installed through the casing. As a result of the extra depth excavation below the casing pipe invert required in the bore pit, this zone can be extremely unstable if it is not restored properly. Most casing/carrier failures which have been investigated have concluded that differential settlement is a major problem as illustrated in Figure 2-8. The cuttings which collect in the bore pit are often not removed and the area stabilized. The problem is not with the casing, but rather with the workmanship at the crossing. More emphasis needs to be placed on the importance of insuring that the pit areas are highly compacted to develop a firm pipeline foundation.

A steering (grade control) head and the water level sensing device, as described for the track-type auger bore method, are not appropriate for this method. The cradle-method is suitable for pressure systems.

POSSIBLE FAILURES IN CASED CROSSINGS

Source: Transportation Research Record 483

Figure 2-8. Differential Settlement Between Casing and Carrier Pipe [52]

2.1.1.2 Main Characteristics

Auger horizontal earth boring can be accomplished either cased or uncased (free bore); however, the industry has taken a negative position on promoting free boring due to the safety aspect relating to an unprotected rotating auger. Most manufacturers have modified their equipment to prevent free boring.

The standard casing material used with auger boring is steel. At the present time, most railroad and highway specifications require the use of steel casings. The standard casing diameters that the auger horizontal earth boring method utilizes range from 4-inch to 60-inch. The most common size range is from 8-inch to 36-inch. For sizes less than 8-inch, there exists alternative TEC techniques that are suitable especially for projects where line and grade are not critical. Also, for sizes greater than 36-inch there exists several alternatives that can ensure greater accuracy than the auger bore method (i.e.: the bores head, pipe jacking with a steering shield, small tunnel boring machines). In most of the cases, for the larger diameters, the line and grade are much more critical; therefore, these techniques become more attractive.

The maximum span obtainable continues to increase since the auger method was developed. Initially, it was

thought that the objective would be to cross under a two lane paved roadway with a average length of 40-LF and a maximum length of 60-LF. As innovations have developed in the equipment capability, an average bore is between 150 to 200-LF with the maximum bore being around 400-LF.

In stable conditions, the cutting head will be extended several inches beyond the leading edge of the casing and the wing cutters will over excavate 1-inch greater than the outside diameter of the casing pipe. This disturbance will not result in surface subsidence. In unstable conditions, the wing cutters are removed and the head is retracted back in the casing to reduce the inflow of groundwater. However, should over excavation occur, the void between the casing O.D. and the borehole should be pressure grouted. This can be accomplished with ports fabricated through the casing wall for sizes equal to or greater than 30", but must be accomplished with vertical holes drilled from the ground surface for sizes equal to or less than 30".

The ideal site should allow adequate room for a boring pit excavation plus the subsequent stockpiling of excavated material or if the material is to be removed from the jobsite then adequate room must be provided for loading and hauling spoil. Space must also be provided for loading, unloading, storage of materials

and equipment, and operation of equipment (i.e., crane, boom truck, excavator, etc.) to place materials and equipment in the bore pit. [2]

Due to unique characteristics of the auger bore method, operator skill is more critical than some of the other techniques. For alternative techniques utilized on the smaller diameter bores (i.e.: 2-inch to 6-inch), the accuracy is normally not critical. Should the bore be unusable then the operator simply makes necessary corrections and repeats the boring process until the borehole is acceptable. Since the borehole is of such small diameter, the impact to the ground surface is insignificant when several attempts are made.

For the larger diameter boreholes (i.e., 36-inch to 60-inch) in questionable ground conditions, the alternatives available permit the operator to be on the inside so that he can see what is being excavated. However, with the auger TEC method, the operator cannot see the excavated face. Therefore, the operator must be skilled in constructing bore pits and setting the equipment up. Only a skilled operator understands the significance of knowing at all times the location of the cutting head with respect to the end of the casing, when conditions change or unforeseen obstacles are encountered, and what corrective action should be taken. A skilled operator realizes how often alignment should be checked, and any necessary corrective procedures.

The specified accuracy (tolerance) concerns every trenchless excavation contractor. It is directly correlated with the cost associated with the bore. The tighter the tolerance then the higher the cost. On many projects an unreasonable tolerance is specified without the designer being cognizant of its impact. For example, on projects which require a tight tolerance (± 1 -inch), the contractor may bid the project using oversize casing to provide maneuvering room inside the casing with the carrier pipe to obtain the specified tolerance or the contractor may decide to utilize another more costly technique that increases the probability of obtaining the specified tolerance.

In situations where tolerances must be tight to accomplish the end results of the project then these additional costs are justified; however, the specified tolerance should be a function of the specific project and not standardized for all projects.

A reasonable tolerance for line and grade for the auger bore technique is $\pm 1.0\%$ of the length. In cases where this tolerance is not acceptable then the designer should inform all bidders that they must submit information prior to beginning the work that explains their method to obtain required line and grade. This will require the designer to be familiar with the capability of specific methods.

2.1.1.3 Major Advantages

The auger bore method offers the primary advantage of being able to install the casing as the borehole is being excavated. Therefore, no uncased hole will exist which could result in a cave-in and eventual ground surface subsidence. The amount of excavation can be controlled. Many options are available to permit the handling of a wide variation of ground conditions. These options include the capability of being able to monitor the grade throughout the boring operation and to make grade control adjustments. The cuttings are discharged from the machine so that the volume can be determined readily.

2.1.1.4 Major Disadvantages

The auger bore method requires a substantial investment in bore pit construction and the initial set up. The size of boulder or other obstacle that can be removed by the augers is limited to approximately one third the nominal casing diameter due to the physical characteristics of the auger. Separate cutting heads and auger size are required for each size casing thus requiring a substantial investment in augers. Systems currently in use offer no alignment control.

2.1.2 Compaction Method

The compaction/expansion method's distinguishing characteristic is that it forms the borehole by means of compressing the earth that immediately surrounds the compacting device. Therefore, no spoil is removed. It is compacted and left in place by thrust displacement of the in-situ soils. This method is restricted to relatively small diameter lines (i.e., 2-inch to 6-inch) in compressible soil conditions. The compaction method is divided into three sub-classifications : the push rod method, the rotary method, or the percussion (impact) method. All of which are classified as an expansive installation technique which means the volume of the installed pipe exceeds the volume of the excavated soil; therefore, the earth surrounding the borehole will be displaced by the expanding effect. [16]

2.1.2.1 Method Description

A rod pusher is a machine that will push or pull a solid rod or pipe through the earth to produce a hole by means of compaction (soil displacement) without rotation or impact. The principles and procedures associated with the push rod TEC technique are among the simplest. The name is self explanatory. A compaction bit is literally

pushed through the earth by means of rods being powered by some mechanical device. Should the desired hole need to be larger than the compaction bit, then the compaction bit hole acts as a pilot hole for a reamer to be pulled back through by the push rods.

The power source by which the rods are pushed through the earth varies. The crudest and least accurate source is utilizing the bucket of a backhoe. This method has been used with success on numerous occasions, but is limited to relatively short crossings and where a large tolerance exists for acceptance. This method is not recommended for most projects.

There are several manufacturers of commercial rod pushing machines. The most popular principle of operation consist of a large hydraulic cylinder, a reaction plate, and a rod gripping device. If the operation requires reaming, then the reaction plate must be installed to resist forces in both directions. The recommended practice is to construct a "T" slot for the bore pit. The reaction plate will be placed in the branches of the "T", and the body of the "T" will house the cylinder, rod gripping device, and provide operator working room. The hydraulic cylinder can be powered by the hydraulic manifold system of a backhoe, trencher, etc., or a separate hydraulic power unit. The rods are usually 4-feet in length and 1.375-inch to 1.75-inch in diameter. These rods are solid

and are thrust through the ground without rotation. Figure 2-9 illustrates a typical push rod machine.

The procedures consist of excavating an appropriate bore and receiving pit, placing the machine in the bore pit and connecting a power source, placing the compaction bit on the push rod, attach the rod to the machine, make final line and grade adjustments, and begin the bore cycle. Each bore cycle consists of several independent pushes per rod length which are a function of the cylinder stroke length. The cylinder stroke length will vary from machine to machine but will normally be approximately 9-inches in length. Should a 4-foot rod be used, then five separate push cycles will be required per rod.

Accuracy is a function of the initial set-up and soil conditions.

The rotary method combines the advantages of a rotating drill rod and the compaction effect developed from utilizing a compaction bit. The power source varies from an adapter kit that can be attached to a backhoe, trencher, etc., above ground to standard horizontal earth boring units similar to those described for the auger bore operation with the exception that these use solid drill stem rather than a cutting head and augers.

By back reaming, the pilot hole can be enlarged to 12-inches; however, this depends greatly on the soil characteristics. Care must be exercised so as not to

TOP VIEW

SIDE VIEW

DIMENSIONAL:

U.S.

L ² . Length, T-Bar installed, cylinder retracted.....	41.5 in.
W ² . Width, T-Bar	72 in.
H ³ . Height, w/o handle	16.25 in.
Push rod diameter	1.75 in.

Figure 2-9. Push Rod Machine for Compaction
Horizontal Earth Boring [19]

cause damage due to a heaving action. It is recommended that this method be limited to small bores (i.e., less than 6-inches)

The basic procedures involved are a function of the equipment selected for the operation. For relatively short bore lengths where accuracy is not critical, then there exists many types of bore units that can be selected. However, if length and accuracy are important then the track type unit set up in a bore pit and utilizing rigid, solid drill stem should be selected. Figure 2-10 illustrates several types of rotary bore equipment.

An appropriate bore and receiving pit must be excavated. If above ground equipment is to be utilized, then the bore pit will consist of only a bore slot; however, if a track machine is to be utilized, then the same degree of care must be exercised as described for the track auger bore machine. The compactor bit is thrust through the ground by a power source which also has the capability of developing torque in the drill stem.

The percussion method utilizes an underground piercing tool that is self-propelled by a pneumatic or hydraulic power source. The diameter and length of the tool vary from manufacturer to manufacturer, but they are all streamlined into a bullet or missile shape. Compressed air or hydraulic fluid is transmitted to the tool through flexible hoses, and imparts energy

Figure 2-10. Rotary Machines for Compaction
Horizontal Earth Boring [14]

at a blow frequency of 400 to 600 strokes per minute to a reciprocating piston located inside the nose of the tool. This action results in the tool propelling itself through the ground. These tools are effective in most ground conditions from loose sand to firm clay. [20]

The soil around the tool applies friction to the body holding it in place while the piston returns on its back stroke; thus, the friction is necessary for the proper operation of the tool. Without this friction, for example in very wet unstable soils, the tool will vibrate but not move forward. [20]

Percussion tools vary in O.D. from 1.75-inches to 7-inches. While all manufacturers claim a relatively high degree of accuracy, some of the more recently developed small diameter units seem to be more accurate. This has been credited to a properly designed diameter-to-length ratio and weight distribution. [20]

Percussion tools typically travel at a rate of from 3-inches per minute up to approximately 4-feet per minute with travel speed being a function of soil conditions and not a function of tool size. While the larger tools are more powerful, their speeds are not much different than the smaller sizes because they must displace larger volumes of soil. [20]

Most of the percussion tools have a reversal capability. This drastically enhances its capability.

Should conditions become non-negotiable or an obstacle is encountered, the unit can be backed out of the borehole. Whereas, before the feature was developed, the unit would have been lost or required open excavation.

The boring pit size, for the percussion operation, is a function of bore depth and size of tool selected. Pit sizes have varied from 6-inches wide, 3 to 5-feet long, and 18-inches deep to 10-feet wide, 30-feet long, and 15-feet deep.

If ground conditions are stable and accuracy is not critical, then the percussion tool can be placed in the bore pit and collared into the embankment by one man for the smaller units. However, when accuracy is critical a launching platform should be utilized. This platform provides a support for the tool so that it can be aligned as required. A sighting device is normally used to insure alignment is satisfactory. Some manufacturers provide adjustable bearing stands as a part of the platform so that vertical adjustments can readily be made. After proper alignment is obtained by using the launching platform, the tool is collared into the embankment, power is applied, and the operation is monitored until the tool exits in the receiving pit. The tool is then removed, and the desired utility such as a power cable can be attached to the end of the air hose so that it can be inserted directly into the borehole. When rigid pipe is being

installed, the tool and the air hose is removed and the pipe is then pushed through the open borehole.

In most soil conditions the compaction effect is sufficient to develop a borehole with sufficient stand-up time to perform the necessary pipe insertion. However, overall performance and accuracy of the unit are functions of the type of ground and soil conditions. The factors that need to be taken into consideration are: (i) soil type and degree of homogeneity; (ii) soil compactness; (iii) moisture content and ability to be deformed and displaced; (iv) the critical depth defined as the minimum point of entry and the line of travel below the surface; (v) ground contour; (vi) obstructions. [21]

2.1.2.2 Main Characteristics

Any type of small diameter utility line can be installed in the borehole since the line insertion process is independent of the boring process. These methods are extremely popular for installation of electric, telephone or T.V. cables, gas pipe, sprinkler irrigation systems, and service lines for water systems.

When no sensing or guiding system is being utilized with the compaction method, the span length should be limited to 60-feet with 40-feet being the optimum. However, 200-foot bores have been made successfully.

The limiting factor is not the ability to move through the ground. The limiting factor controlling bore span is accuracy. Since the boring mechanism is of small diameter, then the longer the bore the more difficult it is to control.

Recently guiding systems have been developed for the push rod method and the percussion tool method. [11, 19] By utilizing an electronic sensing device which allows the operator to know, at all times, the alignment and depth, and by utilizing a guiding system, the risk of producing a non-usable borehole has been eliminated.

Disturbance to the ground is a critical factor that must be taken into consideration. The two major problems that can result are a heaving action or a settlement. Since the compaction/expansion method creates extra volume, then heaving would be anticipated; however, in cases where a percussion tool has been utilized in a loose cohesionless sand, the vibration created appreciable consolidation to the point where volume loss exceeded the amount of expansion. The compressibility of the soil can have a dramatic effect on the degree of disturbance. [16]

A rule-of-thumb that has been applied states that the depth of cover should be 1-foot for each inch of diameter. According to several manufacturer's recommendations, this is a conservative guideline; however, it has been field tested and found it is reliable.

Bore pit sizes range from as small as 6-inches wide, 3 to 5-feet long, and 18-inches deep to as large as 10-feet wide, 30-feet long, and 15-feet deep.

The surface area required is minimum because the amount of equipment required is minimum. In most cases, the only equipment required is the tool and an average size air compressor (i.e., 160 CFM) for the power source.

Since the principles and procedures are simple, no special operator skills are required. Should problems develop the borehole can be abandoned without serious consequences.

When no sensing and guiding systems are utilized, the accuracy is a function of ground conditions, length of drive, and experience of the operator. A tolerance of 1.0% of the borehole length is normally the objective; however, for the small diameter lines, it is normally accepted where it exits if at all possible. When sensing and guiding systems are utilized, then a reasonable tolerance is 1.0% with a maximum variation of ± 2 -feet of the desired point for long bores.

2.1.2.3 Major Advantages

The compaction method of horizontal earth boring is a rapid, economic, and effective method of installing the smaller diameter utility lines. The capitol

investment in equipment is minimum, and several of the pieces are multi-functional. For example, the hydraulic power source used to power the rod pusher can be used for any purpose that requires hydraulic power; and the air compressor that powers the percussion tool can be used for many purposes. Any type of pipe can be installed in the borehole.

In most cohesive soils, the stability of the soil is increased by the compacting action as an earthen encasement is formed. However, in some types of soils (i.e., saturated silts) the compacting action will increase pore pressures resulting in a weakened soil structure. In saturated clays, soil displacement is a result of elastic deformation rather than densification.

2.1.2.4 Major Disadvantages

Compaction methods are limited in their length by the reliability because the present systems are basically unintelligent, unguided tools that tend to bury themselves, surface in the middle of the road, or damage nearby existing utility lines. [11]

The use of sensing and guiding systems with compaction methods have recently been developed, field tested, and are commercially available. Such systems will have a significant effect on their reliability.

2.1.3 Slurry Horizontal Rotary Drilling Method (SRD)

2.1.3.1 Method Description

This process is distinguished from horizontal auger boring in that it utilizes drill bits and drill tubing in lieu of augers and cutting heads. A drilling fluid, such as: a bentonite slurry, water, or air, is used to facilitate the drilling process by keeping the bit clean and aiding in spoil removal. Because of this latter characteristic, it is often confused with the jetting method; however, unlike the jetting method, the SRD method does not use the drill fluid to cut the face or to wash out a hole. The face is cut mechanically by the bit. Wash-outs are prevented by controlling the drill fluid rate of flow and pressure.

The process can be executed from above ground or from a pit. The power unit can be hydraulic, gas, air, or diesel driven mounted on tracks, rubber tires, or hand held. The fluid is introduced into the tubing through a water swivel tee which allows the drill tubing to rotate. The fluid is then transferred to the cutting bit through the drill tubing. Drill bits which are compatible with the soil conditions, are used to mechanically cut the borehole face.

A bentonite slurry drill fluid is used in unconsolidated, noncohesive soils. Bentonite consistency will vary with soil type encountered. Bentonite is an expansive, montmorillonite, colloidal material when mixed with water becomes a slurry or drill mud. This slurry is then mixed with the borehole cuttings by the drill bit. While some cuttings are removed from the borehole during the bore operation, the majority remain. This bentonite slurry/ borehole cuttings mixture aids in preventing borehole collapse by exerting a counter balance earth pressure on borehole walls. The colloidal characteristic of the bentonite develops an impermeable seal on the borehole walls reducing water infiltration as it facilitates spoil removal.

In cohesive, consolidated soils the addition of bentonite is not needed. The water will mix directly with in situ materials by the drill bit mixing action to form the necessary consistency to develop the same behavior previously described in the borehole.

The basic slurry rotary drill procedures are :

1. Construct bore and receiving pit.
2. Drilling a pilot hole. Diameters for pilot holes range from 2 to 5 inches with the most common being either a 2 or 4-inch hole.
3. Determine line and grade accuracy of the pilot hole.
4. Ream pilot hole to desired borehole diameter.

5. Pull cleanout swab through the borehole.
6. Insert casing in borehole.
7. Grout void between casing and borehole as required.
8. Insert desired carrier pipe.
9. Construct Casing Pipe Bulkheads.
10. Backfill and restore pit areas.

These steps are illustrated in Figure 2-11.

The following are several specialized variations of these basic procedures : (1) The Melsheimer Slurry Horizontal Earth Boring Method [8], (2) The Horner Slurry Horizontal Earth Boring Method [2], (3) The Turner Slurry Horizontal Earth Boring Method [2].

The Melsheimer Method is often referred to as "Cut and Bore", "Gopher Bore", or "Spud-In Bore". Equipment utilized in this process are above ground, rubber tired machines; therefore, no bore pit is required. This manually guided system has the capability of making small diameter bores in excess of 1,000-LF. It utilizes a narrow, shallow, starting pit (spud-in-hole) and access pits (pot holes) which will be spaced at 25-LF to 50-LF centers depending on soil conditions and existing subsurface obstructions.

The starting pit is excavated at the desired entry angle. The first access pit is located at a point that will permit the flexible drill tubing to be manually guided to the desired line and grade. A sighting

Figure 2-11. Typical Procedures for the Slurry Horizontal Rotary Drilling Method in Cohesive Stable Soil Conditions. [2]

instrument and target device is used to insure proper guiding. Access pits are excavated deeper than the anticipated pilot hole to provide a sump for the accumulation of excess slurry and spoil.

After rotation of the drill tubing is initiated, forward feed (advancement) is made in the starting pit. After the cutting bit and drill tubing are guided to the first access pit, forward feed is resumed until the bit arrives in the first access pit. By using proper guiding tools, adjustments are made to line and grade as required; and then this process is repeated.

At the termination point, the drill bit is replaced with a back reamer, swivel, cleanout swab, and either casing or carrier pipe. The leading end of casing or carrier pipe should be equipped with a nose cone (bullet) to provide a streamline effect. Casing or carrier pipe may be connected to the swab with a breakaway cable which is designed to break at a specified tensile force.

The reamer, swivel, swab, and pipe are pulled through in one operation. The pipe should be inspected at each access pit for any obvious damage.

Sludge is removed from all access pits prior to backfill and compaction followed by restoration as required. Figure 2-12 illustrates the Melsheimer Method.

Figure 2-12. Typical Procedures for The Melsheimer Slurry Horizontal Rotary Drilling Method. [8]

The Horner Slurry HEB Method [2] is illustrated in Figure 2-12 and summarized as follows :

1. Install 2" or 4" pilot hole to the desired line and grade tolerance.
2. Retract drill stem.
3. Forward ream pilot hole to the desired size. The reamer is guided by a lead bar which follows the pilot hole path.
4. Advance reamer approximately one yard.
5. Retract reamer while continuing to rotate to form a compressed plug of slurry cuttings near the bore hole opening.
6. Advance reamer approximately one additional yard.
7. Retract reamer while continuing to rotate to form a second compressed plug of slurry cuttings. A drilling fluid seal is formed in the void between the two compressed plugs of slurry cuttings.
8. The drill fluid seal prevents the escape of air.
9. Compressed air is applied to the reamer through the drill stem creating a positive pressure in the cutting zone which supports the bore hole and retards ground water infiltration. The compressed air and reamer action will displace the necessary volume of cuttings through the original pilot hole.
10. Pull the swab (cleaning plug) through followed immediately by casing insertion.

Figure 2-13. The Horner Slurry Horizontal Rotary Drilling Method for Unstable Soil Conditions. [2]

This method is recommended for unstable ground conditions.

The Turner Slurry Horizontal Earth Boring Method is illustrated in Figure 2-14. It was developed to accommodate various types of unstable ground. Variations on the process are identified as Method A and Method B described as follows:

METHOD "A" (Forward Reaming)

1. Construct earthen containment berm between boring machine and borehole entrance to a height greater than crown of the borehole to keep the drill fluid in the hole and create a positive pressure.
2. Penetrate berm with drill stem to minimize leakage through berm.
3. Install 2 or 4- inch pilot hole to desired line and grade tolerance.
4. Retract drill stem.
5. Plug pilot hole located in the exit pit to prevent drill fluid loss and create a positive pressure.
6. Forward ream pilot hole to the desired size. The reamer is guided by a lead bar in the pilot hole.
7. In granular unstable soils, use a bentonite slurry drilling fluid with a consistency of one pound of bentonite to five gallons of water.
8. Use slusher (mixer) bit immediately behind the reamer to mix the drill fluid with cuttings to

Figure 2-14. Typical Procedures for The Turner Slurry Horizontal Rotary Drilling Method for Unstable Soil Conditions. [2]

produce a solution with a thick slurry consistency. A thin cake of this thick slurry material will be deposited on the borehole walls to provide a seal and minimize ground water infiltration.

9. Construct second earthen containment berm around borehole in exit pit.
10. Attach swivel to reamer when it enters the exit pit.
11. Attach cable end to swivel. This cable will be utilized to pull casing pipe in place.
12. Retract drill stem with reamer rotating to enhance the mixing action creating a well mixed solution.
13. Attach cable to casing pipe. The leading end of casing pipe should be capped or formed into a cone or bullet shape.
14. Casing pipe is inserted into borehole.
15. The insertion force develops a compacting action to the borehole solution of bentonite slurry and borehole cuttings as the casing is forced through the hole. The remainder of this thick consistency solution is displaced out of the hole.

METHOD "B" (Reverse Reamer)

1. Install pilot hole to desired line / grade tolerance.
2. Construct earthen containment berm around borehole in exit pit to sufficient height to create a positive hydro - static counter balance pressure in the borehole

3. Remove pilot bit and replace with reverse reamer, swivel, and leading end of cable.
4. Construct earthen berm around borehole in the pit to provide containment of the slurry.
5. Reverse ream pilot hole to the desired diameter.
6. Use slusher (mixing) bit placed immediately behind the reamer to mix the drill fluid with cuttings to produce a solution with a thick slurry consistency. A thin cake of slurry material will be deposited on the borehole walls to provide a seal and minimize ground water infiltration.
7. Attach cable to casing pipe.
8. Casing pipe is inserted into borehole.
9. The borehole solution of bentonite slurry and borehole cuttings is compacted as the casing is forced through the hole. Excess solution is displaced out of the borehole.

2.1.3.2 Main Characteristics

Since the casing and/or carrier pipe installation procedures are independent of the boring operation, any currently available pipe material or cable may be installed. Types of pipe commonly installed include steel, concrete, fiber glass, all types of plastic, corrugated metal pipe, and ductile iron.

The SRD method is most effective for smaller diameter boreholes which range from 2 to 12-inches; however, in stable soil conditions 48-inch bores have been completed successfully. The most common spans negotiated with the SRD method range from 40 to 75-LF. Since this method is not directionally controlled, the risk of obtaining an unacceptable pilot hole increases greatly with bore distances.

When cohesive soil conditions and the proper installation procedures are adhered to, no disturbance to the ground should occur with the exception of that required for the boring, guiding, and receiving pits. However, a cognizant operator will be aware of the fact that, with any type of TEC method, conditions can change drastically very quickly. The operator must be prepared to take necessary corrective action. The types of disturbance that could occur are : subsidence, heaving, and the drill bit exiting prematurely. Of these three, subsidence is the most common, and usually results when the volume excavated exceeds the volume of the conduit inserted. However, heaving can result from two major causes : (1) when the bore is installed in highly expansive clay material and the borehole is left saturated for long time periods, (2) when grout is pumped in to fill the casing/bore hole void and the grout pressure is too great.

Subsidence can occur with any TEC method. In this case, it occurs when excessive soil is removed from the borehole. The operator/inspector must be cognizant of the expected volume versus the actual volume displaced. For example, a 4-inch hole that is 100-LF will require the displacement of only 8.73 cubic feet of soil. This determination is more difficult than with a dry bore method because the spoil is removed in the form of a slurry.

Since the drill bit is unguided, it will seek the path of least resistance. While many bores in excess of 200-feet have been installed at remarkable accuracies, this success depends to a great extent on the subsurface conditions. Should the drill bit come in contact with an obstacle, it will be deflected in some direction possibly without operator awareness. If the direction of deflection is upward, then the drill bit will exit prematurely. A competent operator will terminate the boring operation when an obstacle is encountered until its nature has been investigated. The obstacle could be a stump, boulder, existing utility, etc.

The bore pit size is a function of the equipment and materials utilized. Bore pits are used for track mounted machines. Hydraulic powered machines require smaller pits than gas or diesel powered units. For example, when 5-foot long drill rods are used with a hydraulic powered unit the pit need only be 10-feet long

and approximately 18-inches wide. If 10-foot drill rods are used then the pit will be 15-feet long and 18-inches wide. However, increasing the pit width to 24-inches is recommended when possible to provide additional work space.

The actual mechanics involved in SRD horizontal earth boring are simple and can be learned quickly. However, the success and accuracy of a bore depend largely on the skill of the operator. The operator learns to feel his way through ground and he can tell when conditions are changing, or when he has encountered an obstacle and many times can determine the nature of the obstacle. The operator must know what bits, reamers, and packers to use with the type of ground conditions he is confronted with.

The accuracy is dependent to a large degree on the operator skill in setting the bore up. In stable, homogeneous material for average length (30 to 60-feet) bores the accuracy can be within a 6-inch radius. However, the operator must allow for anticipated right pull and drop. The drop allowance is a function of soil conditions. For example, in unstable sand the drop allowance should be 3 to 4-inches per 10-foot bore length when using a thick concentration of bentonite drilling mud. In stable clay, the drop allowance should be 1 to 2-inches per 10-foot bore length when

utilizing only water as drilling fluid. Normally, required tolerances are eventually obtained through a trial and error process. That is, a pilot hole is produced, and if it is out of tolerance then adjustments are made until a suitable pilot hole is obtained.

The Horizontal Earth Boring and Pipe Jacking Manual [2] describe in detail procedural modifications that can be utilized to adapt the SRD methods to various soil conditions, such as: sugar sand, sandy loam, clay, hard gumbo clay, loose river gravel, decomposed granite, hardpan, and sandstone.

2.1.3.3 Major Advantages

The SRD methods have the distinct advantage of being quick and easy to set up. They have the flexibility of being able to be set up in a pit or operated from above the ground. Regardless of how large the desired diameter, the pilot hole is installed first. Therefore, the alignment can be confirmed prior to the reaming of the final bore. Since the pilot hole is small diameter, it can be installed quickly; and if it is out of tolerance then it can be reinstalled. For multiple size bores, only proper size reamers are necessary. Various types of casing material can be utilized. For example, these methods are often used for

the installation of bores for rural water systems; and where permitted PVC casings are used which reduce the crossing cost. This method requires less equipment than some alternative methods which reduces cost.

2.1.3.4 Major Disadvantages

The fact that a drilling fluid is used increases the risk that a jetting action can take place which indicates a lack of control for the borehole diameter. Special care must be exercised by experienced operators to preclude a jetting action. It is important that the face be cut through mechanical action of the drill bit. In all equipment surveyed by the researcher, the drill stem rotates in an unprotected environment (i.e., while the borehole is being drilled and reamed, it is uncased). Accidents have occurred where workers' clothing have gotten tangled with the drill stem. While the borehole is being drilled and reamed, it is uncased. Many state highway specifications forbid the use of any method that results in an uncased borehole at any time. As the diameter of the bore increases, the volume of drilling fluid increases which creates a greater disposal problem. If the operation is not properly planned, slurry may collect in the bore causing hazardous working conditions for the crew.

2.1.4 Water Jetting Method

2.1.4.1 Method Description

By definition, a jetting action occurs when soil is placed into a quick condition which means it has taken on the properties of a liquid. That is, it has been liquified; or it is being washed. This action develops a hole; thus, it can be used as a horizontal boring method.

Jetting requires a source of pressurized water, a flexible hose to transmit water from the source to the probe. The probe is normally a rigid small diameter pipe that is used to direct the water as it cuts or washes out a borehole. Often, the probe rod is fitted with a nozzle to increase the water velocity which aids in the jetting process. The length of the bore is controlled by adding extensions on to the probe rod.

This method has been used extensively to place water lines under roadways. Usually a source of water is readily available. However, it has been banned by all state highway department agencies for many years as a TEC technique because of the lack of directional control and subsidence problems. Nevertheless, it is still utilized by owners of water systems with their own crews in isolated situations. During the course of the field investigation

phase of this research, the researchers witnessed crews for a major municipality utilizing this method to make road bores for the replacement of water service lines. It should be noted that these methods were not permitted for contractors to use. It was observed that a borehole at least 18-inches in diameter had been washed out in the middle of the road for the installation of a 0.75-inch copper service line. The bore hole was approximately 2-feet deep.

The water jetting method uses water pressure to perform all of the cutting action, and it uses the flow to wash the cuttings out of the borehole. There is no way to control the amount of excavation. Over excavation is inevitable. Normally, with time, surface settlement will occur causing the same problems and dangers that were to be avoided by performing a bore.

2.1.4.2 Main Characteristics

Since the pipe insertion process is independent of the boring process, the type of pipe is unrestricted.

Theoretically, the size of pipe is limited to the size of hole that can be washed out successfully. However, from a practical point of view, this method should be limited to only small diameter lines $\leq$ 4-inch.

The span should be limited to a 25-LF maximum.

Unless strict control and ideal ground conditions are present during the boring operation, ground settlement is highly probable due to the required overexcavation that must be washed out in order to obtain a usable borehole.

Since the operation is basic and simple, no special operator skill is required.

The degree of accuracy is excellent with the water jetting method because the washout effect can be continued until the borehole is large enough to allow the line to be installed as desired.

The water jetting method functions best in a sandy cohesionless soil condition because of the ease of developing a quick condition.

2.1.4.3 Major Advantages

The water jetting process is simple and the capital expenditure in equipment is minimum. It requires no special operator skill.

2.1.4.4 Major Disadvantages

There is no way to control the amount of overcut. The principle of operation depends on a washout effect. The process results in large quantities of water and muck that must be disposed of.

2.1.5 Pipe Ramming Method

Pipe ramming is an innovative use of the percussion tool described in Section 2.1.2 of this chapter. For pipe ramming, the tool does not create a borehole; rather, it is used as a pipe driving hammer.

2.1.5.1 Method Description

Up to approximately 8-inches in O.D., depending on soil conditions, the leading end of the steel pipe can be closed into a streamline shape. However, in most cases if the line is larger than 6-inches in diameter it will be driven with the face open. A band is installed around the leading edge of the pipe for reinforcement and to decrease the amount of friction on the following pipe sections.

When the closed face technique is selected, then the boring operation takes on the properties of the compaction method previously described in Section 2.1.2.

If room is available, the bore pit will be constructed so that the pipe can be driven in one piece. This offers the advantage that all of the welding can be accomplished above ground and at one time. Otherwise, the pipe is installed in segments of varying size depending on room. The pipe is then lowered into the pit. If alignment

and grade are not critical then the pipe can be supported by traditional heavy construction equipment such as backhoes, cranes, pipelaying sideboom tractors, etc. In cases where alignment and grade are critical or the pipe is being driven in segments then the pipe will be supported by adjustable bearing stands in the launch cradle or platform.

The next step involves mating the percussion tool to the pipe. This is accomplished by utilizing special adapters for each size of pipe. Figure 2-15 illustrates this arrangement. The tool is rigidly connected to the pipe that is being driven by lugs welded onto the casing and a pushing plate that is fitted to the rear of the tool.

The power source is normally compressed air supplied from a portable compressor; however, as with any of the percussion tools, the source could be hydraulic.

After the power is connected to the tool and alignment and grade checked, the pipe is then collared into the embankment; and the ramming operation is begun.

The leading edge of the open face pipe cuts a borehole only the size of the pipe O.D. The spoil enters the pipe and is compacted as it is forced to the rear of the pipe. In the bore pit, a spoil ejection port is cut in the end of the pipe being rammed. The spoil can be extruded or washed from this opening. On long bores utilizing large diameter pipe, it is common practice to

Figure 2-15. A Typical Pipe Ramming Project Profile Detail with an Exploded Detail of the Percussion Tool Being Adapted to the End of the Casing Pipe.

weld a 0.75-inch water line on top of the casing being jacked to a point approximately 2-LF from the end of the casing, and then water is injected into the casing at rates which vary from 10 to 40-GPM to facilitate the spoil being washed to the spoil ejection port.

In addition, depending on soil conditions, either water or a bentonite slurry can be applied to the outside of the casing pipe to provide lubrication. This is accomplished as described previously for the auger bore method.

After the pipe has been rammed in place, the tool is removed, and the pipe is cleaned out. This cleaning process can be accomplished by several methods; such as, a high pressure or a pipe cleaning pig can be placed inside one end of the pipe followed by a plug that is properly braced so that air or water pressure can be applied which will force the pig through the pipe.

2.1.5.2 Main Characteristics

Due to the cyclic impact associated with the pipe ramming method, the type of pipe is limited to steel.

Pipe ramming has been used on steel pipe that range from 2-inch to 55-inches in diameter; however, the most common sizes with the equipment currently available range from 4-inches to 42-inches. [17]

The bore length is a function of the conditions.

Many bores over 200-LF have been installed successfully.

When applied properly, no ground disturbance should occur because the leading edge of the casing is performing the actual cutting. There should also be no over excavation. This method has been successful in unstable soil conditions because it compacts an earthen plug at the leading edge of the casing which creates a positive pressure at the cutting face to prevent losing excessive soil in unstable conditions.

As with the percussion tool, the impact (vibration) of the tool in sandy cohesionless soil conditions may create appreciable consolidation to the point that a loss in volume could result in surface settlement.

The length of the casing to be installed and the percussion tool size selected determines the length of pit required. The depth is a function of the project design.

A substantial amount of operator skill is required for the pipe ramming method as compared to techniques that are designed primarily for the small diameter pipe sizes such as the compaction methods. The operator must select the closed or open face technique depending on size and soil conditions. Options available for the open face method include various spoil removal schemes, banding the leading edge of the casing, how many pieces to ram at a time, how to obtain line and grade, to use bentonite or water to lubricate the outside of the casing, etc.

2.1.5.3 Major Advantages

It is an economic and effective method for installing medium size casings. It allows many options which means it can be adapted to jobsite more readily. For instance, the casing can be placed in one piece or in segments. Also, the casing does not have to be a specific length. One percussion tool and air compressor can be used to drive a wide variety of casing size and length. In addition, the compressor and tool are multi-functional. For example, the tool can be adapted for use as a small pile driver. No horizontal thrust reaction structure is required since the thrust of the impact is absorbed within the tool directly. Since there is no requirement for other equipment inside the casing, larger obstacles, such as boulders, can be accommodated.

2.1.5.3 Major Disadvantages

There is no control of line and grade. Since the spoil removal process depends on a washing action and the forward movement of the casing, then should the driving be stopped unintentionally it usually becomes very difficult and time consuming to clean the spoil out of the casing in order to inspect the cutting face.

2.1.6 Directional Drilling Method

The directionally controlled horizontal drilling process used as a horizontal boring technique for crossing under natural or manmade obstacles is an outgrowth of the technology and methods developed for the directional drilling of oil wells. The directional drilling method was developed in the United States, and has revolutionized complicated pipeline river crossings. It has, also, been utilized to install numerous roadway/railway crossings.

2.1.6.1 Method Description

The horizontal directional drilling method, in most cases, is a two stage process. The first stage consists of drilling a small diameter pilot hole along the desired centerline of the proposed pipeline. The second stage involves enlarging the pilot hole to the desired diameter in order to accommodate the pipeline. The pilot hole is drilled with a specially built drill rig that allows the drill string to enter the ground at an angle of entry which can vary from 5 to 30 degrees; however, the optimum entry angle is 12-degrees. This drill rig pushes the drill string into the ground while a bentonite drilling mud is pumped through the drill stem to a down hole drill motor located just behind the bit. [25]

The drill mud operates the down hole motor, functions as a coolant, and facilitates spoil removal by washing the cuttings to the surface where they settle out in a reception pit. The drill stem is approximately 3-inches in diameter, nonrotating, and contains a slightly bent section which is called a bent housing. The bent housing (typically from 0.5 to 1.5 degrees) is used to create a steering bias. A curved or a straight profile is achieved by steering the drill rod as it is being pushed into the ground. The steering is controlled by the positioning of the bent housing. [24]

The pilot hole path is monitored by a down hole survey system located behind the bent housing and provides data on the inclination, orientation, and azimuth of the leading end. This data is transmitted to the surface where it is then interpreted and plotted. Normally, position readings are taken on every pipe segment which is about every 30-feet. Should the pilot hole get off of alignment then the drill stem is pulled back and a new course is cut. [25]

During the drilling operation, a 5-inch diameter steel washover pipe is rotated over the pilot drill stem. The washover pipe relieves the friction and resisting pressure caused by the cuttings mixed with the drill mud. In addition, the washover pipe provides rigidity to the pilot drill stem. Bentonite slurry is pumped between the

washover pipe and the pilot drill stem. The rotation of the washover pipe allows the diameter of the borehole to be increased to approximately 11-inches.

After the pilot hole has been constructed then the pilot drill stem is withdrawn through the washover pipe. Reaming devices are then attached to the washover pipe, and pulled back through the pilot hole enlarging it to the desired diameter suitable to accept the designed pipeline. For a project where the designed pipeline is equal to or less than 20-inches, then the pipeline can be attached directly behind the reamer with a swivel device so that the total assembly can be pulled through in one pass. However, if the designed pipeline is greater than 20-inches the borehole will probably require pre-reaming in order to obtain the desired diameter. The pull sections of the design pipe are fabricated in one continuous length to avoid shutdown periods during pullback, and they are supported during the installation in such a way that the axial loads imposed on the line as it is pulled through are minimum. [25]

Figure 2-16 illustrates the typical drilling procedure and the typical pullback operation. It shows how the drill bit and a section of drill stem lead the washover pipe. Figure 2-17 illustrates a detail of the bottom hole assembly.

Figure 2-16. Typical Directional Drilling and Pullback Procedure. [57]

Figure 2-17. Typical Detail of the Bottom Hole Assembly for Directional Drilling Method. [57]

2.1.6.2 Main Characteristics

The type of pipe installed is limited to being able to be joined together so that it can accept sufficient axial tensile force to permit it to be pulled through the borehole. For example, steel pipe is the most common pipe used at the present time; however, high density PE pipe could be used.

The sizes range from 3-inch up to 40-inch; however, it is not uncommon for multiple lines to be installed in a single pull. The most significant multiple line crossing to date was 2,800-LF of five separate lines that range in size from 6-inches to 16-inches. The bore span ranges from approximately 400-LF to 6,000-LF.

Disturbance to the ground must be taken into consideration in the design and construction of a directional drilled crossing. Significant forces are created by the flowrate and pressures at which the bentonite slurry drilling mud is circulated through the drill stem to operate the down hole mud motors, and then to wash the cuttings from the borehole. The flows and pressures must be monitored to prevent mud migration problems. Much of this problem is eliminated in the design by making sure that adequate depth is obtained and that a compatible strata exists for the process to function properly. Therefore, subsurface conditions are

critical to the success of the directional drilled crossing.

The rig working area should be reasonably level, firm, and suitable for the movement of rubber tired vehicles. Normally, it should measure approximately 400-LF in length and 200-LF in width. A suitable access road should be provided. At the receiving area, enough room will be required so that the complete string of design pipeline can be fitted together and stored on pipe racks. The site must accommodate : (1) the drill rig which will be approximately 50-feet long and 9-feet wide, (2) two skid power packs, (3) drilling fluid (bentonite) tank, control cab, and (4) storage facilities.

The directional drilling equipment is sophisticated and requires a skilled operator. The operator must be knowledgeable concerning down hole drilling, impact of drilling in various geological formations, sensing and recording instrumentation, and interpreting computer printout data.

Clay is considered to be the ideal material for the directional drilling method. Drillability of rock is dependent on its strength and hardness. Cohesionless silt and sand will generally behave in a fluid manner, and will be able to stay in suspension in the drill fluid for a sufficient period of time in order to be washed out of the borehole. [25]

2.1.6.3 Major Advantages

Directional drilling can accomplish long and complicated crossings quickly and economically with minimum environmental impact. Obtaining sufficient depth to eliminate ground surface damage potential is of no consequence. This process does not require bore or receiving pits.

2.1.6.4 Major Disadvantages

As has been made clear directional drilling is specialized, and has not been utilized to any large extent outside the petroleum industry. The cutting and washing action that takes place down hole is not clearly understood. Specialized equipment and highly skilled operators are required. Installation costs are high; therefore, the bore length must be substantial to be economically feasible. The type of borehole is not suitable for graded bores. Until recently, the equipment and technology were closely held, and the equipment was not for sale. Only the services could be purchased. At the present time, American Augers, Inc., which is located Wooster, Ohio is the only firm that has developed a smaller size directional drilling rig that can be purchased.

2.1.7 FlowMole Guidedril Method

The FlowMole Guidedril Method is a proprietary system that was researched, designed, developed, and operated by the FlowMole Corporation located in Kent, Washington. The method involves a unique steerable tunneling system specifically designed for small diameter lines that need to be installed at depths up to 30 feet and up to 400 LF in length. A low-flow, high-pressure bentonite slurry cutting fluid is used to bore stable, long-distance, small-diameter boreholes. This process is referred to as the SoftBor™ process. The soil is actually cut by the small-diameter, high pressure jets of the liquified clay (bentonite slurry) just ahead of the boring tool. The bentonite slurry drill mud impregnates the soil immediately around the tool and lines the borehole wall stabilizing inherently unstable soils, such as fine sand, etc. The lubricating characteristics of the bentonite slurry greatly reduce the frictional drag when utility lines are being inserted in the borehole.

2.1.7.1 Method Description

The patented SoftBor process is characterized by a low-flow (1 to 2 GPM), high-pressure (1,000 to 4,000 PSI) soil-cutting system. While the fluid performs the cutting

action, it is differentiated from the water jetting (see section 2.1.4) and the slurry bore (see section 2.1.3) methods because of the pressures and flowrates used for cutting. Soil erosion and overcutting do not occur with the FlowMole system because the small-diameter jets that produce the type of flow required are designed so that the cutting fluid's energy is dissipated rapidly. This prevents the cutting fluid from being able to cut through existing utility lines. [26]

The most significant feature of the SoftBor process is its remote steering capability. The remote steering is accomplished through directing cutting jets at the nose of the bore tool. The tool can be made to change directions as it is thrust through the ground. In addition, a computerized electronic locating system provides exact information for steering commands to guide the tool. This system keeps the tool on course and provides detailed data on the exact position of the tunnel so that bores of over 400-LF in length can be made on a controlled path. The position of the tool can be determined within ± 1 inch both laterally and vertically. [26]

The basic operating procedures are as follows:

- (1) The trailer, or self-propelled dolly, housing the Guidedril system is properly positioned.
- (2) The drill head and first drill pipe are loaded onto the thrust frame.

- (3) The proper cutting fluid pressure is set on the field power unit. The pressure is a function of the soil conditions.
- (4) The tool is advanced and steered level at the proper depth using the locator to sense the tool position.
- (5) More drill pipe is added as the tool advances.
- (6) After each new drill pipe is advanced into the ground, the tool is located and a steering command is made for the next length of drill pipe to keep the tool on course.
- (7) Steps 5 and 6 are repeated until the tool advances to the end of the run.
- (8) At the end of the run, the drilling head is removed and a reamer is attached to enlarge (if necessary) the borehole for a utility.
- (9) The utility is attached to the reamer swivel.
- (10) The drill stem is used to pull the utility back through the borehole.
- (11) The appropriate utility connections are made.
- (12) All disturbed areas are restored. [26]

Figure 2-18 illustrates the pilot hole boring process (microtunneling process), typical steering head and reaming tools, and the reaming and utility installation process.

Microtunneling process

Steering head and reaming tools

Reaming and utility installation process

Figure 2-18. Pilot Hole Boring Process, Steering and Reaming Tools, and the Reaming and Utility Installation Process for the Flowmole Guidedril Method. [26]

The system is available throughout all major developed countries; however, the distribution network as currently set up does not sell the equipment. FlowMole Corporation is a construction company which sells services. This aids in protecting the technology involved with the process. In addition, it insures that the operators are properly trained.

2.1.7.2 Main Characteristics

Any type of cable or small-diameter pipeline that can be joined so as to accept the necessary tensile forces that are required to pull the line through the borehole, such as high-density PE, PVC, steel, cables, copper, etc. Pipe sizes compatible with this process range from 1.5 inches to approximately 6 inches, and successful bores have been made up to 830 LF within specified tolerance.

There have been no reported adverse effect on the ground conditions. This technique is only used for small diameters, and the small void between the utility and the borehole is filled with cuttings and bentonite; therefore, no void is left under the roadway.

A typical crew consists of three men. The operator must have a high degree of skill in order to know how to handle the various situations that develop in the field. He must be able to operate the high-technology, computer-

sensing device, and be able to interpret the results so that the necessary adjustments can be made in the guiding system. The operator must select a drill head compatible with soil conditions. He must know how to insure all equipment is properly grounded electrically and safely.

The steering accuracy is rated at ± 6 inches which is adequate for most small-diameter utility lines for distances up to 400 LF. The accuracy tolerance can be increased to ± 3 inches by reducing the locating interval.

Suitable soils range from hard clay to soft sand.

2.1.7.3 Major Advantages

Some of the major advantages include the fact that the system can be located and is directionally controllable. The SoftBor process will not damage existing underground utilities; and the drill stem can be guided around obstacles should they be encountered. The system is constructed with significant safety systems and alarms. No bore pits are required.

2.1.7.4 Major Disadvantages

It can only accommodate the small-diameter lines at the present time.

2.1.8 Micro - Tunneling Method

The term micro - tunneling is used to describe methods of horizontal earth boring which are highly sophisticated, laser guided, remote controlled, and permit accurate monitoring and adjusting of the alignment and grade as the work proceeds so that pipe can be installed on precise line and grade. These methods are for lines that are $\leq$ 36-inches. Basically, they are manless tunnel boring machines (TBM s).

2.1.8.1. Method Description

It is beyond the scope of this report to describe in detail all of the basic variations and capabilities that have been developed for micro-tunneling machines throughout the world. However, it is considered important to describe the three most common machines that have been widely used in the United States. These are the Iseki, the Soltau, and the American Augers machines.

Iseki Poly-Tech, Inc. manufactures a wide variety of long distance pipe jacking and tunneling systems. These systems possess the state-of-the-art in technology to install small diameter pipelines in soft, unstable, water bearing soils. This is accomplished by automatically and continually counter balancing earth pressures by mechanically coordinating excavation speed,

cutting face pressure, and thrust force. This unique mechanical earth pressure counter balance (M.E.P.C.B.) system utilizes a slurry pumping system to balance the ground water pressures in the soil as well as to transport the excavated material from the cutting face to the disposal process. The M.E.P.C.B. system results in a tunneling system which can operate in water saturated sands, silts, clays, and gravels without dewatering or compressed air. All systems are electronically monitored and controlled from a single operation panel. [29]

Figure 2-19 illustrates the Iseki Unclemole system which is one of their latest developments. It has the capability of installing pipes from 15-inch O.D. upward and crushing boulders up to 30% of the shield diameter. Other machines manufactured by Iseki include the large M.E.P.C.B. slurry tunneling machine, Telehole, Crunchingmole, Mighty John, Molemiester. The Unclemole system has been selected for description because of its size range capability and popularity.

The basic Iseki process involves the pipe being hydraulically jacked in place following the micro-tunnel boring machine from a bore pit. The bore pit must be structurally stable because of the degree of precision required and the length of time the pit is in use.

UNCLEMOLE SYSTEM For pipe ID 10in to ID 20in.

Figure 2-19. Iseki Poly-Tech, Inc. Slurry Shield Micro-tunneling Machine for Varying Soil Conditions [29]

All systems (jacking, steering, M.E.P.C.B., slurry, etc.) are controlled at the operations board which is normally located in a job trailer at the surface of the bore pit. Also, located at the surface near the bore pit are the power pack and the slurry separation equipment tank. The power pack is an electrical generator unit which provides electrical power to the motors located in the machine near the cutting head, and a hydraulic pumping unit which provides power to the thrust rams and steering jacks. [29]

The slurry charging pump is designed to take the supernatant from the separation tank and pump it to the cutting head of the machine through small diameter supply and discharge lines. The cutting head is designed to mix the cuttings with the slurry so that the spoil can be removed by pumping through the discharge lines into the slurry separation tank. The pumping pit by-pass unit permits flow and pressure control of the slurry system.

A pipelaying laser is used for alignment and grade control. The laser is set up in the bore pit and the beam travels through the pipe to a target located in the indicator panel at the rear of the machine. The indicator panel houses numerous pressure gauges as well as the laser target. This panel is continuously monitored by the remote TV camera. The operator controls the process by the readings from the indicator panel.

Typical operating procedures include the following :

- (1) Bore and receiving pits are constructed.
- (2) Pipe jacks and jacking frame are accurately placed in the pit.
- (3) The machine is placed in the jacking frame.
- (4) The first joint of pipe is placed in the bore pit so that the leading end is fitted into the machine so that it is water tight.
- (5) All electrical, instrumentation, hydraulic, and slurry lines are properly connected.
- (6) The thrust jacks are energized so that they begin the push.
- (7) The cutting head is collared into the ground.
- (8) The drive is initiated for the length of the pipe.
- (9) The jacks are retracted.
- (10) All lines are disconnected.
- (11) The pipe segment is placed into the bore pit.
- (12) The push cycle is repeated.
- (13) Steps 8 through 12. are repeated.
- (14) The machine is removed from the receiving pit.
- (15) Remove thrust jacks and jacking frame.

The earth pressure counter balance machanism prevents the ground from collapsing. Slit plates automatically resist the excavated earth pressure.

Slurry pressure at the chamber prevents ground water from running into the shield machine. The automatic slit opening system is synchronized with the changeable earth pressure at the cutter head. The cutter head rotates with the crushing rotor on a drive axis. Cobbles coming in the slits are instantly crushed for slurry transportation through the slurry chamber.

The cutting head is specially designed so that it can be controlled while the thrust pressure is kept higher than the active earth pressure of the ground to prevent the risk of subsidence or a collapse of the face. It is also kept below the prevailing passive earth pressure avoiding the possibility of heaving or bulging of the ground. [29]

At the same time the volume of soil removed by the cutting head is automatically controlled and correlated to the advance speed of the machine. [29]

The Soltau machines are similar in principle to the Iseki machine described in the previous section. They are sophisticated, automatic, micro - tunneling machines that can be continually monitored and adjusted to provide the high degree of accuracy required for critical alignment and grade of sanitary gravity sewers. Figure 2-20 illustrates the basic components of the Soltau machine.

System layout

- ① Jacking shaft
- ② Guide rails
- ③ Jacks
- ④ Auger drive
- ⑤ Back pressure plate
- ⑥ Steering head
- ⑦ Equipment housing
- ⑧ Steering jack
- ⑨ Product pipe
- ⑩ Auger flight
- ⑪ Auger casing
- ⑫ Lazer target
- ⑬ Lazer
- ⑭ Lazer beam

Figure 2-20. Dr. Ing. G. Soltau GMBH RVS 100 Micro-Tunneling Machine Layout Detail [56]

The pipe is hydraulically jacked in place following the micro-tunneling machine by means of large thrust rams located in the bore pit. A bentonite slurry is injected at the cutting head, and the excavated material is removed in a slurry solution by means of augers located inside a casing to a holding tank which is located beneath the machine in the bore pit. Therefore, this spoil removing slurry does not need to be of the same consistancy as the Iseki machine because with the Iseki machine the slurry is pumped out. The Soltau machine relies on a mechanical removable process. The slurry retention vault located in the bore pit should be sized to store spoil generated from one joint of pipe. Therefore, on each cycle the vault must be mechanically removed from the pit by a crane, excavator, etc. and emptied into a water tight dump truck bed for removal from the jobsite. When a dump truck cannot be assigned to the jobsite then the spoil must be stored in a separate holding tank located at the surface of the bore.

The power source for operating the cutting head and augers originate from hydraulic motors located in the bore pit. The hydraulic reservoir and pumps are located at the surface of the bore site. The cutting head is specially designed to function in a closed area, the counter balance earth pressure is created by the slurry pumped into the cutter head compartment and the rate

of feed generated by the thrust rams.

A pipelaying laser is used for controlling the alignment and grade. The laser beam travels through the pipe to a target located at the rear of the machine, and monitored by a closed circuit TV camera. The laser is located in the bore pit.

The basic process is the same as with the Iseki machine previously described with the exception that the spoil must be handled on each cycle and an auger and casing segment must be placed inside the casing.

The American Augers machine is manufactured by American Augers, Inc., Wooster, Ohio. Currently, American Augers, Inc. is only manufacturers of micro-tunneling equipment in the United States. It is laser guided with articulated steering and remote control. This machine involves an innovative adaptation of the standard 36-inch horizontal earth boring machine. It was researched and developed in 1986, field tested in 1987, and introduced to the market on a rental or purchase basis in 1988. future developments will concentrate on sizes from 18 to 36-inches.

The cutting head is powered by a hydraulic drive motor and steered by four electrically activated hydraulic cylinders. The cutting head is in a closed section which can create necessary earth pressure counter balance by controlling auger speed and thrust.

The thrust and spoil removal auger are powered by the horizontal earth boring machine. It was field tested on 20-foot segments of standard steel casing pipe.

In the past several years, many manufacturers have entered the micro-tunneling equipment industry. Over thirty manufacturers exist worldwide; therefore, this equipment and methods are readily available.

2.1.8.2 Main Characteristics

Micro - tunneling machines have been used with reinforced concrete pipe, vitrified clay pipe, glass reinforced plastic pipe, Hobas (fiberglass) pipe, steel pipe, ductile iron pipe, and asbestos cement pipe. The typical pipe sizes for micro - tunneling equipment range from 10 to 36-inches.

Micro-tunneling equipment are used primarily for areas requiring critical alignment and grade as for sanitary sewer lines. The bore spans typically required for these projects are approximately 400-LF. However, the equipment has the capability of exceeding these lengths depending on ground conditions.

The majority of the micro-tunneling equipment was designed to operate in wet, unstable soil conditions. Control problems have occurred with both the Iseki and Soltau in tight hard clay ground conditions.

2.1.8.3 Major Advantages

The micro - tunneling equipment was specifically designed to meet the needs of the sewer line installation industry. They can install the mainline sewer pipe direct to extremely accurate line and grade tolerance. It has the capability of performing in very difficult ground conditions without expensive dewatering systems and/or compressed air. These methods have the capability of installing lines from manhole to manhole. Lines can be more readily installed at deeper depths without such a drastic impact on cost. The depth factor becomes increasingly more important as congestion is increased. Safety is enhanced as men are not required to enter trenches, just protected bore pits that can be constructed safely.

2.1.8.4 Major Disadvantages

The capital cost in equipment is high. However, on projects where these methods have been competitively bid against other tunneling methods, the unit price costs have been in line. Most of the major manufacturers are foreign firms with no strong sales and maintenance network in the United States. This condition is improving rapidly.

2.2 Pipe Jacking

Pipe jacking is a method of trenchless excavation construction (TEC) technique which requires men working inside the pipe. The pipe are prefabricated and jacked into position from a jacking pit. The excavation can be either mechanical or manual. The previous methods, described in section 2.1, involves techniques that do not require men to enter the pipe during the normal operation. While horizontal earth boring techniques can be utilized on pipes as large as 60-inch, the excavation and spoil removal is completely mechanical.

The excavation method varies from the very basic process of men digging the face with pick and shovels to the highly sophisticated tunneling boring machines (TBM). However, regardless of the excavation method, it is accomplished inside an articulated shield. This shield is guidable with individually controlled hydraulic steering jacks. This shield is designed to provide a safe working environment for the men, and allow the bore to stay open in order for the pipe to be jacked in place.

2.2.1 Method Description

The basic steps involved with a pipe jacking method are illustrated in Figure 2-21. This process

Pits are excavated on each side. The jacks will bear against the back of the left pit so a steel or wood abutment is added for reinforcement. A simple track is added to guide the concrete pipe sections. The jack(s) are positioned in place on supports.

A section of concrete pipe is lowered into the pit

The jack(s) are operated pushing the pipe section forward.

The jack ram(s) are retracted and a "spacer" is added between the jack(s) and pipe.

The jack(s) are operated and the pipe is pushed forward again.

It may be necessary to repeat the above steps four and five several times until the pipe is pushed forward enough to allow room for the next section of pipe. It is extremely important, therefore, that the stroke of the jacks be as long as possible to reduce the number of spacers required and thereby reduce the amount of time and cost. The ideal situation would be to have the jack stroke longer than the pipe to completely eliminate the need for spacers.

The next section of pipe is lowered into the pit and the above steps repeated. The entire process above is repeated until the operation is complete.

Figure 2-21. Steps for Jacking Reinforced Concrete Pipe. [34]

requires a simple, cyclic procedure of utilizing the thrust power of the hydraulic jacks (rams) to force the pipe forward. The face is excavated simultaneously with the jacking operation to minimize the amount of over excavation and risk of face collapse. In stable ground conditions, excavation may proceed the jacking process if necessary. The spoil is removed through the inside of the pipe to the jacking pit. After a joint of pipe has been installed the rams are retracted, and another joint is placed into position so that the thrust operation can be started again.

It is recommended, when possible, to select jacks with stroke length greater than the pipe length. This permits a smooth and continuous forward thrust for the full length of the pipe. Otherwise, the jacks are extended to full stroke capability then retracted so that a spacer can be installed and forward thrust reapplied. This process would have to be repeated as necessary to get the full pipe joint in place. Short stroke jacks are required in congested areas where the size of the jacking pit is restricted.

Due to the jacking forces required to push large diameter pipe through the ground, the jacking pit design and construction are critical. Safety precautions and safety factors should be used generously. The pit embankment supports should be properly designed and

constructed in accordance with the Code of Federal Regulations 29 (C.F.R.) 1926.650 - 1926.653. The pit floor (foundation) and thrust reaction structure must be designed to handle the repeated process of supporting extremely heavy joints of pipe as the jacking operation is being executed. Since pipe jacking procedures are typically utilized on pipe that will function as the finish carrier pipe, alignment and grade control are critical. Alignment and grade control are not possible with an inadequate foundation; therefore, in most cases it is advisable to construct a concrete slab foundation on a gravel base. A gravel foundation bed has been used with success particularly on the smaller diameter pipes for short distances in fairly stable ground conditions.

Figure 2-22 illustrates the components of a typical pipe jacking operation. The guide rails are positioned on proper line and grade so that when the jacking pipe is placed on the guide rail it will be properly positioned. It should be remembered that even though the jacking shield is equipped with steering jacks, these are for corrective action only and not to establish the line and grade. It is critical that the guiding frame be properly supported so as not to move during the operation. Much of the success in a pipe jacking operation is insuring proper alignment. Proper alignment reduces the probability of developing deflections that result in high

Figure 2-22. Components of a Typical Concrete Pipe Jacking Project With a Shield [2]

pressure point loadings, and reduces the amount of thrust required.

The anticipated jacking (thrust) force should be calculated based on the job conditions. This force will include the penetration resistance, friction resistance force between pipe and the earth, and friction resistance force due to the dead weight of the pipe. [35] "One practioner suggested that an estimate be made of the total thrust required, then use four to six times that requirement in jacking power. Jack thrust available often exceeds pipe compressive strength. This requires careful attention to applied thrust." [33] The required thrust is applied utilizing one, two, four, or six jacks with the thrust being applied as required; but should be balanced about the pipe centerline. It is standard practice to use at least two jacks placing one on each side of the centerline. It is common to see jacking forces increase from 20 to 50% after as little as an 8 hour delay.

The thrust wall (reaction block) is typically constructed of concrete. It transfers the jacking force from the jacks into the ground. Therefore, the thrust wall should be designed as a footing for the allowable compressive stress of the given soil. It should be

analyzed for shear resistance. The thrust wall must be constructed perpendicular to the designed jacking axis. Otherwise, problems will be inevitable in attempting to obtain line and grade as well as problems developing from the uneven force distribution. [33]

One of the major factors that concern pipe jacking contractors is the development of the required jacking power. The application of a bentonite slurry to the outside skin of the pipe has been effective in reducing frictional forces. It is common for jacking forces to be reduced in excess of 50% as a result of the use of bentonite. There are many techniques used in this process which vary from manual application before the pipe penetrates the ground to bentonite being pumped from the inside of the pipe through small diameter pipe nipples that have been prefabricated in the pipe. Another common method for controlling the amount of required jacking force is to operate on a continuous 24 hour basis. This decreases the risk of getting stuck due to delays. If a continuous operating basis is not feasible then it is recommended that the operation be manned so that jacking pressure can be applied pre-determined intervals to prevent a freeze-up.

The use of intermediate jacking stations (IJS) are common to control or increase the amount of jacking force. An IJS is illustrated in Figure 2-22. There is

no limit to the number of IJS that can be installed in a line. Many pipe jacking contractors install the shell of the IJS at regular intervals as a safety factor. If they are needed then the jacks can be placed in the shell providing the additional power. If not needed then the investment is considered as insurance. The IJS simply permit the pipe to be thrust forward in an inch-worm approach rather than the total force being delivered from the jacking pit. The IJS typically contain four or six jacks evenly spaced around the circumference.

The excavation process takes place inside the shield. Many contractors throughout the country still maintain craftsmen skilled in manual excavation utilizing either pneumatic tool or simply picks and shovels; however, most prefer mechanical moles (tunnel boring machines). This mechanical excavation can be with a full-face cutting head which is similar to those used in the auger horizontal earth boring method or it can be with a hydraulic backhoe mounted inside the shield. In either of these common techniques, the operator is located near the face so that he can see what is going on.

The spoil is commonly removed by small carts which are manually operated, powered by a winch cable, or battery power; or spoil is removed by a conveyor belt system; or by small diameter augers.

Packing material must be placed between the pipe

joints to provide cushioning and flexibility. The most commonly used material is .5 to .75-inch plywood; however, other suitable materials include .5 to 1-inch manila rope, jute, oakum, etc.

2.2.2 Main Characteristics

Primarily, this method has been utilized to install reinforced concrete pipe; however, it is appropriate for steel pipe, Hobas (fiberglass) pipe, ductile iron pipe, corrugated metal pipe, etc. depending on the project conditions.

The pipe jacking method has been limited, by definition, to projects that utilize men inside to perform the excavation. This has been accomplished on sizes as small as 30 - inch I.D.; however, from a practical standpoint it should be limited to a minimum of 36-inches. Even at 36-inches I.D., it becomes very difficult for a man to function efficiently. If the proposed lines are lengthy then it is recommended that the minimum size be 48-inches. The method has been utilized on pipes as large as 132-inches. [34]

Theoretically, there is no limit to the span capability due to the fact that there is no limit to the number of intermediate jacking stations that can be

installed. Spans in excess of 1,600-LF were reported without the use of any IJS; however, bentonite was used generously.

In stable ground conditions, negligible subsidence will occur. In unstable ground or where stability is questionable, then geotechnical stabilization techniques should be utilized. These stabilization techniques can vary from lowering the ground water table with wellpoints or deepwells to the use of cementitious or chemical grouts. It is important that the subsurface conditions be properly evaluated by the design engineer during the planning and design phase, and not left completely up to the contractor. [36]

The jacking pit size is a function of shield dimensions, length of pipe to be jacked, jack size, thrust wall design, pressure rings or plates to be utilized, and the guide rail system. Naturally, the selection of each of these components must be compatible with the available space allowed by the jobsite conditions. If adequate space is available, the jacking pits will vary from 25 to 30-feet in length or diameter. However, in congested areas pits 10 to 13-feet in length or diameter are commonly used. A common practice in pipe jacking is to sink a vertical shaft to work out of. The reaction block can be constructed by excavating into the embankment opposite the jacking direction.

2.2.3 Major Advantages

The pipe jacked into position can function as the carrier. This procedure results in an accurate installation. The operator is located at the face, and can see what is taking place to take corrective measures for any changing subsurface conditions. When unforeseen obstacles are encountered, they are identified and removed without removing augers, etc. The face can be readily inspected by the foreman and/or regulatory representative either personally or by use of a video camera. Many options are available for handling varying conditions. Over-excavation can be determined directly. Pipe jacking can be executed expeditiously with a relative small crew. By utilizing bentonite as a lubricant on the outside surface of the pipe and intermediate jacking stations, relatively long drives are obtainable.

2.2.4 Major Disadvantages

"Pipe jacking is a specialty, if you will, an art. It requires much coordination and "feel." A first-time contractor on the pipe-jacking job will usually encounter difficulties." [33] While pipe can be jacked on a radius, it is highly recommended that all direction changes be made at shafts.

2.3 Utility Tunneling

Utility tunnels are differentiated from the major tunneling industry by virtue of the tunnels typical size and use. These tunnels are used primarily as conduits for utilities rather than as passageways for pedestrian and/or vehicular traffic. Further, while methods of excavation for the pipe jacking and utility tunneling may be identical, the differentiation is in the lining. With the pipe jacking technique, the pipe is the lining; whereas, in utility tunneling either tunnel liner plates or rib and lagging become the lining. The linings for utility tunnels are considered to be temporary structures providing support until the utility is installed and the annular void between the utility and tunnel lining is filled with an adequate filler material.

2.3.1 Method Description

In most soil conditions, it is recommended that excavation take place inside of a specially designed tunneling shield. Figure 2-23 illustrates the details of a tunneling shield. Excavation can be either manual or mechanical. The lining is actually constructed in place in the tail section of the shield. This provides protection to the men assembling the lining system.

Tunnel liner plates are prefabricated modular units that are utilized to construct a temporary circular lining for the purpose of encasing a utility. The liner plates are typically made of steel or pre-cast concrete; however, steel tunnel liner plates are predominantly used for utility tunnels. The pre-cast concrete liner plates have become cost effective and are used for the larger tunnels. Therefore, it is beyond the scope of this research project to evaluate the pre-cast concrete units.

The liner plate is a pre-fabricated steel plate that has been coldformed so that all edges are flanged to provide an integrated tunnel system. The plates are relatively thin, and curved longitudinally to provide the desired tunnel diameter when the liner plates are bolted together. The flanges of the liner plate project inward, and they are pre-punched with oversized bolt holes to facilitate the placing and fastening operation. The back of the plates are deformed with corrugations to provide a higher degree of stiffening. Also, plates can be pre-punched to provide grout holes economically. [37]

The width of a steel liner plate is that dimension which is parallel to the tunnel axis and perpendicular to the plate curvature. The length of the plate is defined as the dimension from end to end as measured around the periphery of the tunnel. The radius of curvature is measured from the tunnel centerline to the back of the

plate and corresponds with the outside dimension for the tunnel. The standard size for steel tunnel liner plates are 16-inches in width and $37-11/16$ inches in length. The odd size length corresponds to a length of 12-inches times 3.1416 which results in the number of liner plates to make a complete segment as the diameter of the tunnel in feet. [37]

The principles behind the design of the steel liner plates were to develop a unit that could be handled comfortably by one man in congested areas such as commonly encountered at the heading of a tunnel or in the tail section of a shield.

The typical operating procedures require that excavation be conducted at the face with the spoil being removed by carts, conveyors, augers, etc. or a combination of these systems. The tunneling shield is hydraulically jacked forward as excavation is being conducted. The amount of excavation that can occur before jacking is a function of the standup time of the ground conditions. The jacks of the shield thrust against the previously installed liner plates. After the shield has been pushed forward far enough so that one or more courses can be placed, the jacking operation ceases; and the jacks are retracted so the men can install the plates in the tail section of the shield. The cyclic operation begins again.

Steel ribs and wood lagging tunnel liner systems are commonly utilized for utility tunnels because of simplicity, higher forward advancement rates, and economics. Steel liner plates offered many advantages over rib and lagging in unstable ground with short duration stand up times when utilizing the traditional hand-mining procedures. However, when shields are being utilized this is no longer a serious factor; and rib and lagging systems offer many inherent advantages.

The lagging material is usually wood boards which can vary in length up to 48-inches; however, other lagging materials have consisted of steel liner plates, standard steel channels, or corrugated lagging material. Only wood lagging systems will be discussed in this project since it represents the predominate material used for utility tunnels.

The wood lags create a bridging action transmitting the ground loads to the steel ribs. In addition, they must be designed to transmit axial compressive loads created by the jacking forces as the shield is propelled forward. The minimum size thickness for wood lagging is 3-inches with the most common nominal size being 3-by-6-inches; however, the size selection should be based on engineering design principles.

The steel ribs are typically standard ASTM A36 H-beams which have been coldformed to meet the curvature

requirements of the tunnel design. The minimum size H-beams used are normally 4-inch with at least a minimum weight of 10 pounds per foot.

The typical procedures involved in a rib and lagging tunnel system include the excavation of the tunnel face at the leading edge of the shield. The shield is jacked forward utilizing the previously erected rib as the thrust reaction structure. After the shield has been pushed forward a sufficient distance, the jacks are retracted to permit rib and lagging erection. The steel rib is erected in sections to form a complete ring placed at 90-degrees to the tunnel centerline axis and at a distance equal to the width of one course. The wood lags are placed in such a manner to form a tight enclosure in the tail section of the shield or tunnel boring machine. As the shield is pushed forward and the rib and lagging system is exposed to the tunnel excavation, the ribs are immediately expanded outward and upward to produce continuous contact with the supporting ground.

2.3.2 Main Characteristics

The rib and lagging systems are constructed of steel H-beams coldformed to the desired curvature to function as the ribs; and wood boards, steel liner plates, standard steel channels, or corrugated metal to

function as the lagging. Since wood lagging is predominantly used as lagging material for utility tunnels, it was the only type investigated.

These systems usually are considered practical at a minimum size of 4-feet in diameter with theoretically no upper limit. However, this investigation assumed that the upper limit for utility tunnels would be approximately 12-feet in diameter.

There is no limit to the span because the liner system is not pushed through the ground as in other jacking system.

The tunnel shaft can be of minimum size since it primarily serves as access to the tunnel. It must be of sufficient size to accommodate spoil removal equipment and air handling equipment; however, it does not have to accommodate large track systems, hydraulic jacks, etc. Further, it does not have to accommodate the construction of a thrust reaction structure.

2.3.3 Major Advantages

A high degree of accuracy can be obtained with a minimum amount of skilled labor. Changed ground conditions can be recognized and corrective action taken immediately. The liner is constructed in the safety of the tail section of the shield as the tunnel is being

constructed. Large sections of prefabricated pipe do not have to be handled or stored. Only a jacking force sufficient to drive the shield must be developed.

2.3.4 Major Disadvantages

The liner systems are classified as temporary structures; therefore, a carrier pipe or utility must be inserted through the tunnel liner and the void between the carrier and the tunnel liner filled to provide adequate support.

CHAPTER 3 - EVALUATION OF MATERIALS UTILIZED FOR TRENCHLESS EXCAVATION

This chapter summarizes the significant data that relates to the design and selection of materials utilized with various trenchless excavation construction (TEC) techniques. The emphasis of this chapter will be to assist those responsible for the approval of materials to obtain background information concerning the impact on the process or the end product.

3.1 Steel Casing Pipe

There exists mixed opinions concerning the purpose and need of encasement beneath railroad and highway facilities. It is standard practice with most railroad companies to require a casing pipe for all pipelines and cables that cross their facilities. The position of the American Association of State Highway and Transportation Officials (AASHTO) can be summarized in the following quote "definite guides for the encasement of pipelines cannot be fully resolved from present experience and knowledge. An arbitrary policy of requiring encasement for all highway crossings

may be too expensive, not only to the utility consumer but also to the highway user. However, it is not prudent to waive all encasement requirements. An intermediate policy should concede the highway agency's responsibility for safety of traffic and structural integrity of the roadway, placing the burden of proof on the utility if it contends for any particular location that encasement is unnecessary." However, as a matter of current practice, most federal, state, and local roadways require encasement.

The Gas Research Institute (GRI), Chicago, Illinois has sponsored research relating to the practices for pipeline crossings at railroads from 1985 to the present time. The principal investigator for this research is Professor T. D. O'Rourke, Department of Structural Engineering, Cornell University. The objective of this research is to identify and document the characteristics and behavior of pipelines and casings beneath railroads to assist in the development of alternative measures for providing the necessary protection required at such critical intersections. [12] [39]

In addition to the GRI research program, similar research is being conducted for encasement of pipelines through highway roadbeds. This research was initiated the early 1980's, and has been funded

by the National Cooperative Highway Research Program, Transportation Research Board, and the National Research Council. [40]

Both of these research projects are unanimous in recognizing that more effective pipeline protective measures are available than encasement.

The major reasons for requiring encasement are :

1. It permits the insertion, removal, replacement, and/or maintenance of the carrier pipe without requiring open cutting.
2. It provides structural protection for the carrier pipe from external loads and shocks either during or after construction.
3. It provides a means of conveying leaking fluids or gases away from the area directly beneath the travelled way to a point of venting at or near the right-of-way line or to a point of drainage. [1]

Several pipeline failure investigations have identified the following problems with casings :

1. Carrier pipe protective coating damage during the installation into the casing.
2. Infiltration of groundwater into the annular space between carrier pipes and the casings.
3. Establishing and documenting electrical isolation between carrier pipes and casings.

4. Decreases the corrosion control from cathodic protection systems.
5. Lack of atmospheric corrosion control by conventional cathodic protection systems.

Many of the specifications and guidelines in use were developed when the industry was young and before many advances were made in materials, equipment, and capability. Unfortunately, the specifications have not kept pace with technology resulting in additional cost and inefficiencies with no increase in benefit. The research conducted by the Cornell University researchers and funded by GRI concluded that alternative methods of pipeline protection include: [39]

1. Increased Carrier Pipe Wall Thickness.

"Conrail currently requires that carrier pipe within a casing be designed for railroad live loads as if they were not encased. Further, the AREA and ASME recommend and the Code of Federal Regulations dictate that increased wall thicknesses be used for uncased carrier pipes in some instances." [39] This indicates on some current crossings the wall thickness would be adequate to handle the additional railroad load.

2. Increased Depth of Burial.

"An obvious way of decreasing the effects of railroad live loads on an uncased carrier pipe is to increase its depth of burial." [39]

3. Hardened Protective Coatings.

Experience has shown that hardened resin epoxy coatings on carrier pipe performs well when installed by a slickboring process. It has, also, been documented that even with increased wall thickness and burial depth, coatings are necessary for an effective corrosive protection system. [39]

The proper casing size is a design decision that should be established for the project by the engineer. From a functional standpoint, common design practice requires a minimum of 6-inches between the O.D. of the largest component of the carrier pipe and the O.D. of the casing pipe. This criteria should serve as a minimum only, and the engineer should consider other specific project related factors which will impact the selection of casing size. Several of these factors are:

1. Casing size, cost, and availability.

Certain sizes are more readily available than others; therefore, specifying the next size larger may result in less cost with shorter deliveries.

2. Subsurface conditions.

Sufficient subsurface investigations should be conducted to ascertain the probability of encountering boulders or other obstacles. The casing size specified should be a

minimum of three times greater than the largest size boulder anticipated. It is recommended that, if boulders are anticipated, the minimum casing size specified be 36-inches so that personnel may enter and remove the obstructions if necessary.

3. Alignment and grade tolerance.
4. Bore length.
5. Future needs.

Larger casings provide greater stiffness ratios, and can be installed with greater accuracies.

Steel carrier pipelines installed without casings are generally petroleum pressure lines and must conform to ANSI/ASME B31.4-1979 and American Petroleum Institute (API) Recommended Practice 1102. The ANSI/ASME B31.4-1979 code contains pipeline material properties which determine the allowable circumferential stresses in the steel carrier pipes. The circumferential stress due to the internal pressure and external loads must be 72% of the pipeline minimum yield strength multiplied by a weld joint factor, and the weld joint factor varies from 0.6 to 1.0 according to the type of joint fabrication. While these codes do not specify that the crossings be cased or uncased, they do specify that where casings are used then a protective coating on the carrier pipe is required, electrical isolators are required between

carrier pipes and casings, and casing ends are required to be sealed. [39]

Steel casing pipe that is typically utilized has a minimum yield strength of 35,000 PSI. This strength is used in the loading calculations to determine the required wall thickness. From experience, it has been determined that structural steel pipe meeting ASTM specification A139 Grade B is adequate for use as casing pipe. Since casing pipe is not subjected to any internal pressure, there is no need to require the hydrostatic testing as discussed in this ASTM specification. Therefore, casing pipe is normally specified as ASTM A139 Grade B (No Hydro). Other factors of concern for casing pipe are the straightness and roundness of the pipe because they impact the accuracy of the bore. [2]

The possible certifications are : (1) A letter of compliance (2) Shop drawings (3) Independent laboratory test reports (4) Original mill test reports.

Each certification type represents a different degrees of security and cost; therefore, the designer should select the degree of security compatible with the application. For example, "in the case of auger boring or pipe jacking projects, the letter of compliance is sufficient provided all necessary information is given. On the other hand, if the steel pipe is used as a carrier with internal pressures,

the original mill test report or independent laboratory test reports should be required. If any fabrication is necessary, such as grout holes or weld bands, a shop drawing is usually helpful." [2]

Table 3-1 presents information on standard carbon steel pipe often used as casing pipe (conduit) for utilities when crossing under structures. It lists the nominal size, actual O.D., and weight per LF for a wide selection of pipe wall thicknesses. Table 3-2 lists recommended minimum nominal wall thicknesses typically specified for railroad and highway crossings for both bare and coated conditions. Typically, large variations have existed in minimum nominal wall thickness specifications from project to project. [38] However, the recommendations listed in this table are conservative and have been determined safe, provided a minimum of 4.5 feet of ground cover is available.

Experience has indicated that straight seam or seamless pipe functions better for auger boring than the spiral weld pipe; however, the job conditions should dictate its compatibility with the proposed method and conditions.

The quality of the casing is a major factor in the success and quality of the bore. Majority of the specifications reviewed required that all casing be new and unused and joined together with a circumference

Table 3-1. Steel Pipe Sizes With Weights Per LF for Various Wall Thicknesses [14]

NOMINAL SIZE	ACTUAL O.D.	W A L L T H I C K N E S S								
		.188"	.250"	.312"	.375"	.438"	.500"	.625"	.750"	1.00"
4"	4 1/4"	—	10.79 lbs.	14.98 lbs.	—	—	—	—	—	—
6"	6 5/8"	—	18.97 lbs.	—	—	26.57 lbs.	—	—	—	—
8"	8 3/4"	—	22.36 lbs.	28.55 lbs.	—	—	43.39 lbs.	—	—	—
10"	10 3/4"	21.21 lbs.	28.04 lbs.	—	40.48 lbs.	—	54.74 lbs.	—	—	—
12"	12 3/4"	25.22 lbs.	34.71 lbs.	—	49.56 lbs.	—	65.42 lbs.	—	—	—
14"	14"	—	36.71 lbs.	45.61 lbs.	54.57 lbs.	63.44 lbs.	72.09 lbs.	89.29 lbs.	106.1 lbs.	—
16"	16"	—	42.05 lbs.	52.28 lbs.	62.58 lbs.	72.80 lbs.	82.77 lbs.	102.61 lbs.	122.1 lbs.	—
18"	18"	—	47.39 lbs.	58.94 lbs.	70.59 lbs.	82.15 lbs.	93.45 lbs.	116.01 lbs.	134.2 lbs.	—
20"	20"	—	52.73 lbs.	65.60 lbs.	78.60 lbs.	91.51 lbs.	104.1 lbs.	129.3 lbs.	154.2 lbs.	—
24"	24"	—	63.41 lbs.	78.93 lbs.	94.62 lbs.	110.2 lbs.	125.5 lbs.	156.0 lbs.	186.2 lbs.	—
30"	30"	—	—	98.93 lbs.	118.6 lbs.	138.3 lbs.	157.5 lbs.	196.1 lbs.	234.3 lbs.	—
36"	36"	—	—	118.9 lbs.	142.7 lbs.	166.4 lbs.	189.6 lbs.	236.1 lbs.	282.4 lbs.	—
42"	42"	—	—	—	166.7 lbs.	194.4 lbs.	221.6 lbs.	276.2 lbs.	338.4 lbs.	—
48"	48"	—	—	—	190.7 lbs.	222.5 lbs.	253.6 lbs.	316.2 lbs.	390.5 lbs.	502.0 lbs.

Table 3-2. Available Steel Pipe Sizes and Recommended Wall Thicknesses [2]

Nominal Size	Actual O.D.	RAILROAD CROSSINGS		HIGHWAY CROSSINGS	
		Bare	Protective Coated	Bare	Protective Coated
8"	8 5/8"	.250	.188	.250	.188
10"	10 3/4"	.250	.188	.250	.188
12"	12 3/4"	.250	.188	.250	.188
14"	14"	.281	.219	.250	.219
16"	16"	.281	.219	.250	.219
18"	18"	.312	.250	.250	.250
20"	20"	.344	.281	.312	.250
24"	24"	.406	.344	.312	.250
30"	30"	.469	.406	.375	.375
36"	36"	.532	.469	.500	.438
42"	42"	.563	.500	.500	.500
48"	48"	.625	.563	.625	.563
54"	54"	.688	.625	.625	.625
60"	60"	.750	.688	.625	.625
66"	66"	.813	.750	.625	.625
72"	72"	.875	.813	.750	.750

provided a minimum of 4.5-feet of ground cover is available.

weld; however, it is not uncommon for used gasline pipe to be used. This selection is based on casing pipe cost only, with no consideration given to the possible negative impact likely to be imposed on the boring operation.

While used gas steel pipe may be structurally sound, it usually arrives to the jobsite with the exterior bitumastic coating in a ragged condition. When steel casing pipe is an integral part of the boring process (i.e.: auger horizontal earth boring, pipe ramming, pipe jacking, et.), the ragged exterior coating has created differential skin friction resulting in unsuitable accuracy. Therefore, if used gas pipe is to be used as a casing then special precautions should be implemented to ensure success of the bore.

Experience has proven that a sufficient circumferential weld can be developed as long as one end of the casing is beveled to 35 ± 2.5 degrees and the other end is cut square. This does not apply for pressurized carrier pipe installed without a casing.

When steel casing pipe is specified for the casing pipe, it is considered to be a part of the permanent casing/carrier pipe system. The casing pipe is expected to provide protection for the carrier pipe from external loads or shock, either during or after construction. It is expected to provide a permanent

vehicle whereby the carrier pipe can be removed, replaced, and maintained. In addition, it provides a means of conveying leaking fluids away from directly beneath the travelled way. [1]

Cathodic protection is provided for all pressurized petroleum products steel pipelines. The factors effecting this type of corrosion control are discussed in detail, particularly as they relate to carrier/casing pipe systems, in the research being conducted by Cornell University and funded by GRI. [39]

"Even though protective coatings are sometimes desirable for achieving longer life, designers should realize that the auger boring and pipe jacking methods of installation will usually damage even the best protective coating, whether they are applied on the inside or outside surfaces. It is almost always better to require that 0.063-inches be added to the desired nominal wall thickness and forget about using a protective coating." [2]

Types of coatings available are :

1. Hot applied coal	3. Hot applied petroleum waxes
tar enamel	4. Coal tar epoxies
2. Cold applied mastics	5. Reinforced concrete
bitumastics	6. Fusion bond epoxies

Durability is the most important characteristic of coatings, especially carrier pipe coatings. They should have minimum influence due to the installation

and operating conditions, environment, and time. Thermosetting powdered resins have proven to be tough and exhibit excellent resistance to soil stress, moisture adsorption, chemical exposure.

Design practice should anticipate defects in the coating. Coating improvements are certainly desirable, but should always be concerned about holidays and the corresponding need for supplemental protection.

Experience has proven that internally coated casings have practically no benefit, and may actually be detrimental for the protection of both casing and carrier. [39]

Modern electrical insulators constructed of high density polyethylene (PE) and fiberglass spaced at 8 to 10 feet on-centers have proven to be more than adequate to prevent casing-to-carrier contact under normal conditions for pressurized petroleum piping systems. Wood blocking attached to the pipe with metal bands have been used very effectively for other types of utilities. The objective with steel carrier/casing system is to prevent contact; and, with other utilities, the important thing is to provide carrier pipe support.

End seals vary from high quality, water tight, prefabricated items that are specified for pressurized petroleum systems to brick and mortar which are commonly specified for other utility piping systems.

3.2 Reinforced Concrete Pipe (RCP)

RCP is the most common pipe material used with the pipe jacking trenchless excavation construction (TEC) technique. RCP can serve as a casing (conduit) pipe; however, in most cases it serves directly as the carrier pipe (i.e., sanitary and storm sewer). It has been used effectively with the small micro-tunneling equipment as well as with the large traditional pipe jacking systems.

Due to the axial load which is applied during the jacking operation as well as the earth loading due to the overburden and live load, special design consideration should be given to : (1) Pipe strength, (2) Joint design and reinforcement, (3) Wall thickness, (4) Circumferential reinforcement.

Concrete pipe can be subdivided into nonreinforced and reinforced (RCP). ASTM C 14 applies to nonreinforced sewer and culvert pipe with bell and spigot joints; and ASTM C 76 applies to reinforced concrete culvert, storm drain and sewer pipe with both bell and spigot and tongue and groove joints. However, from a practical matter only tongue and groove joints are utilized with TEC methods of installation. RCP is specified by wall type and class.

ASTM C 76, presents the steel reinforcement required for wall types A, B, and C utilizing 4000,

5000, or 6000 PSI concrete strength for each of the five RCP classes of pipe. The D-load to produce a 0.01-inch crack and the ultimate load increases as the class of pipe varies from Class I to Class V. For example; 36-inch RCP, Class III, having a minimum compressive concrete strength of 4000 PSI can have a wall type of A, B, or C. The reinforcement can be either circular or elliptical as per ASTM C 76.

The wall type and class of RCP specified should be a function of the anticipated forces. Standard design principles and practices for vertical loads on circular pipe are described in detail in : (1) WPCF Manual of Practice, No. 9, Chapter 9, (2) ACPA Design Data 13, (3) ACPA Design Manual Chapter 4

These procedures are based on the pioneer work conducted by Professor Anson Marston of Iowa State College during the first two decades of this century. Marston combined soil type and their cohesive-ness, density, moisture content, and particle size gradation in one formula to determine the pounds per LF of trench. These concepts will be discussed in more detail in Chapter 4.

While Anson Marston's endeavors were primarily associated with trenched conditions, the principles apply as well for the forces encountered with TEC conditions. Thus, the practice of specifying a higher

class pipe because it is planned to be jacked in place is not warranted. The thrust capacity is related to the compressive strength of the concrete. Increasing the D-load strength or the class does not increase the thrust capacity unless the higher class of pipe results in an increase in the concrete compressive strength. [2]

Marston developed the Three-Edge Bearing Test and The Sand Bearing Test to test the strength of circular pipe. Both consisted of applying a vertical load to the top of the pipe for its full length behind the bell and spigot. In the three-edge bearing test, the pipe rested on two narrow parallel strips of wood placed about an inch apart as illustrated in Figure 3-1. This is the most severe loading to which a circular section may be subjected. The sand bearing test provided a sand cushion which more nearly approximated field conditions. However, with larger pipe and greater convenience of the three-edge test, the sand bearing test has largely been abandoned.

The three-edge bearing test subjects the pipe to much more severe loading conditions than the pipe would encounter under normal service. This test applies concentrated loads to the cross-section with no side support; whereas, under normal service the loads would be applied more uniformly and the surrounding earth would provide side support. Within narrow limits,

Figure 3-1. Detail of the Standard Three - Edge Bearing Test as Developed by Anson Marston.

concrete is an elastic material, but as loads are increased cracks rapidly appear in the crown and invert which permit the reinforcing steel to become effective in supporting the loads. As the loads are further increased, the pipe breaks at four places. This is referred to as the 4-hinged condition which is also the point of failure.

Reinforced concrete pipe (RCP) combines the excellent compressive strength of concrete with the tensile strength of steel. The horizontal force (thrust) applied to the pipe during the jacking operation transmits a compressive force along the longitudinal axis of the pipe. This compressive force is usually created by 4 or 6 jacks of 150 to 200-ton capacity. It is not uncommon for projects to require the installation of 84 to 108-inch RCP for distances as great as 1600-LF, and the demand for even longer jacking distances is increasing. The actual thrust load encountered will vary from project to project and is a function of ground conditions and method of installation. Table 3-3 contains typical thrust force per LF required to jack RCP in sandy or hard soil.

ASTM C 76 specification recognizes a 4000-PSI minimum compressive concrete strength for certain pipe sizes which varies with design class and wall type. However, due to the horizontal thrust force applied

Table 3-3. Typical Thrust Force Per Linear Foot Required
To Jack Reinforced Concrete Pipe. [2]

Tonnage Requirements for Pushing Concrete Pipe

Size of Pipe Outside Diameter) -Inches-	Sandy Soil with No Excavation in Front of Pipe	Hard Soil with Excavation in Front of Pipe
18"	1.0 tons	.40 tons
24"	1.4	.52
30"	2.0	.76
36"	2.0	.76
42"	2.3	.88
48"	2.7	1.0
54"	3.0	1.1
60"	3.3	1.2
66"	3.6	1.4
72"	3.9	1.5
78"	4.3	1.6
84"	4.6	1.7
90"	4.9	1.8
96"	5.2	1.9
102"	5.5	2.0
108"	6.2	2.3

Note. This table can be used to approximate the tonnage required. Multiply the values in the table by the total length of pipe in the excavation (in feet).

during the jacking operation and the probability of developing nonuniform (eccentric) loading around the periphery, it is industry's standard practice to specify a 5000-PSI minimum compressive strength. While steam curing is preferred, other curing methods (i.e., misting in combination with warm temperatures) are acceptable which result in the quality and strength required. [2]

Other indirect factors that affect the strength and durability of the RCP include : [42]

1. High quality control standards during the manufacturing process. Reasonable permissible variations shall include :

- a. The RCP (jacking pipe) inside diameter should not vary from the design diameter by more than $3/8$ -inch.
- b. The jacking pipe wall thickness should not vary from the specified wall thickness by more than $3/16$ -inch.
- c. The variation in the laying length of two opposite sides of the pipe shall not be more than $1/8$ -inch per foot for all sizes larger than 24-inch, with an upper limit of $3/8$ -inch for any length of pipe through 84-inch in diameter and a maximum of $1/2$ -inch for 90-inch and larger. This requirement is more restrictive than the

ASTM specification; however, it is justified because the degree of pipe squareness is directly related to the thrust force being uniformly distributed on the periphery of the pipe.

d. Absorption tests should be in conformance with ASTM C-497.

e. All fine and coarse aggregate should be free from contamination as per ASTM C-33.

f. Where feasible, the coarse aggregate should be of the fractured (angular) type.

g. The concrete design mix should contain a minimum of 700 pounds of cement per CY.

2. Properly handling of the pipe from manufacturing through installation.

The most critical component in the pipe jacking system is the pipe joint design and construction, and the behavior of the pipe as the thrust loads are transmitted through the pipe. Normally, the cross-sectional area of the concrete pipe is sufficient to resist the compressive forces created by the jacking operation. For example, a standard 84-inch RCP, Wall B permits only a contact surface of 4-inches to transfer the load across the joint. This translates to a total bearing surface of 1200 square inches being available. The resistance to a uniform direct compressive load

utilizing 5000-PSI concrete strength distributed over the 1200 square inches would result in a 3000-ton total capacity. If the contractor selected six 200-ton jacks, the total thrust capacity would be 1200-ton which is approximately 2.5 times less than the pipe joint can support. [2] Figure 3-2 illustrates how such jacking forces are developed and distributed in a typical concrete pipe jacking operation. The jacking shield will develop forces on the leading edge of the pipe as it is jacked forward independently of the pipe. Next, the intermediate jacking station will develop jacking forces on the pipe in front as it attempts to move forward, and on the pipe at the rear. The primary jacks are located in the jacking pit.

The above example assumes that the compressive load will be distributed uniformly. If alignment problems result in the total compressive load being applied to a small area at the joint then damage is inevitable. Damaged joints in a sanitary or storm sewer system are serious and unacceptable. Therefore, it is extremely important to insure a uniform distribution of load around the periphery of the joint. The use of a joint cushioning material is used to provide uniform load distribution and prevent concrete-to-concrete contact; thus, preventing concrete spalling.

Figure 3-2. Typical Concrete Pipe Jacking Project with Details. [31]

While several acceptable materials can be utilized as a joint cushioning material, experience has proven that plywood is the most effective cushion material. Plywood with a 0.5-inch thickness should be used for all RCP equal to or less than 42-inch diameter, and 0.75-inch thick plywood should be used for RCP equal to and greater than 48-inch diameter. The plywood should be fabricated so that it covers the entire bearing surface. [2] Figure 3-3 illustrates a typical RCP joint with a plywood cushion inserted. It, also, illustrates a precast plug that can be used to pump a bentonite slurry lubricant through during the jacking operation, or it can be used to pump grout through to fill voids between the pipe and surrounding earth.

When non-gasketed pipe joints are specified, the taper on the tongue should be equal to or less than 7-degrees. After plywood has been placed on the bearing surface, a minimum of 2.75-inches of the joint remains. For gasketed joints, the taper on the tongue should not exceed 2-degrees, and the gaskets should comply with ASTM C-443 or ASTM C-361.

Additional reinforcement must be placed in the joint. Acceptable methods are as follows : [42]

1. Stirrups of proper amplitude, applied circumferentially in the tongue and groove joint, welded to each other perpendicularly.

Figure 3-3. Typical RCP Joint Detail with Plywood Cushion and Grout Plug.

See Figure 3-4 for joint reinforcing detail.

2. On all singular reinforcement cages, an 18-inch wrap welded in both tongue and groove portions of the joint.
3. In double cage designs, an 18-inch wrap, consisting of the inner cage area, should be welded to the inside of the outside cage on the groove and an 18-inch wrap, consisting of the inside steel area, welded to the outside of the inside cage on the tongue.

Where feasible, a C-Wall RC pipe should be specified. This provides an extra measure of safety. However, in many cases a B-Wall pipe is adequate. All jacking pipe should have a tongue and groove joint with no rise in exterior pipe surface.

As the load is increased on the three-edge bearing test on a circular RCP, it has a tendency to develop an oval shape. This tendency to change shapes creates tensile and compressive zones in the pipe wall. Tensile stresses result on the inner face of the pipe wall at the crown, invert, and at the outer face of the pipe wall at the spring line. Likewise, compressive stresses result on the inner surface of the pipe wall at the spring line and the outer face of the pipe wall at the crown and invert. [41]

Since concrete possesses excellent compressive

Figure 3-4. Typical Auxiliary Joint Reinforcing for RCP Jacking Pipe.

strength but relatively weak tensile strength, reinforcing steel must be used in the tensile zones similar to any reinforced concrete composite design. Of course, it would be ideal if it were possible to place the steel in the tensile zones with no steel in the compressive zones; however, that is not practical because there would be no way to hold the steel in place. Also, other forces must be taken into consideration such as those encountered during handling. The typical reinforcement techniques are :

1. A single cage.
3. Two full circular cages.
2. Elliptical cages.
4. Quadrant reinforcing.

Experience has proven that as RCP is being jacked it has a tendency to rotate; therefore, only full circular cage reinforcing should be used for trenchless methods of installation. If quadrant mat or elliptical cage reinforcement is used and pipe rotation occurs then the reinforcing may end up being positioned at an undesirable location.

Multiple cages, splices, laps, spacers, and jacking reinforcement should be permanently secured together to produce the designed steel area for the RCP. The single cage of steel reinforcement should have a minimum of 1-inch of cover from the inside pipe wall. RCP with multiple steel reinforcement cages should have a minimum of 1-inch cover over each cage.

3.3 Corrugated Metal Pipe

Corrugated metal pipe (CMP) , also referred to as corrugated steel conduit, is a commonly used construction material for such applications as storm drainage, subdrainage, aerial conduits, underpasses, service tunnels, etc. Corrugating a flat sheet of steel substantially increases its stiffness and strength characteristics. CMP offers the advantages of being thin-wall, lightweight, shop-fabricated, pre-engineered, readily available, and ease of installation.

CMP is classified as a flexible conduit; however, it has been proven to possess excellent structural strength under heavy vertical loads. Vertical loads are subdivided into dead and live loads. The dead loads are developed by the embankment or trench backfill plus stationary superimposed surface loads; and the live loads are moving loads and impact loads, such as, railroads, airports, highways, etc.

Load tests conducted at Iowa State University and the University of North Carolina in cooperation with the United States Bureau of Public Roads, which were initiated approximately in 1912, proved that the soil and steel interaction resulted in excellent structural strength. This soil - steel interaction is a complex composite phenomenon which permit a flexible conduit to act in unison with

the soil to support the total vertical loads imposed on the pipe. For example: large-scale field tests measuring dead loads were run in 1923 on the Illinois Central Railroad at Farina, Illinois by A.R.E.A., with earth pressure cells which indicated that when CMP supported a 35-foot prism of fill, the pipe supported 60-percent of the total load and the remaining soil supported 40-percent. Research is continuing on how to improve this soil-steel interaction so that the soil will accept more of the load. Based on extensive research and field testing detailed height-of-cover tables have been prepared for CMP for highway H 20 and railway E 80 live loads and presented in reference [43] with numerous other design aids and examples.

While CMP is most compatible with trenching methods of installation, it has been utilized with success with certain TEC techniques. CM pipe from 30 to 96-inch in diameter have been installed by the jacking method; however, the most common sizes are 36 to 60-inch. Maximum length of CMP to have been installed by the jacking method exceeds 400-LF. Due to the corrugations, special steps must be taken to minimize the impact of skin friction. For example, this will involve developing a track system for the pipe to slide on. Attempting to push the

CMP through the ground would create excessive jacking pressures. This track system is illustrated in Figure 3-5. Often it is constructed of timbers which is appropriate for ideal tunneling conditions where the soil possesses lengthy stand-up periods. It should not be attempted in dry sand, gravelly soils, soils with large boulders, fills where logs or stumps are anticipated, or where effective dewatering can not be executed. When loose soil materials are encountered, it is possible to attach smooth sheets of light gage steel to the top and bottom pipe sections to reduce skin friction. [43]

Pipe joints are typically bolted together during the jacking operation, and a reinforcing band is used to prevent damage to the pipe at the jacking end.

CMP are compatible with TEC methods that excavate the borehole then permit pipe installation (i.e., slurry horizontal earth boring). With these methods, the pipe could be pushed and/or pulled into place.

CMP can be obtained in a variety of sizes and wall thicknesses. It can be galvanized, fully coated inside and out, fully coated with a paved invert, or fully coated and fully paved. However, when being jacked into position, there is concern regarding how much damage may result to the outside coating and the galvanizing as it is being jack.

Figure 3-5. Elevation Detail for Pipe Jacking with Corrugated Metal Pipe. [43]

3.4 Polyvinyl Chloride Casing Pipe (PVC)

Polyvinyl chloride (P V C) pipe is a thermoplastic construction material which has made substantial achievements. It has gained much popularity because, in addition, to excellent physical characteristics such as light-weight, high strength-to-weight ratio, durability, and resiliency; it offers excellent chemical inertness to most acids, alkalies, fuels, and corrosives.

Polyvinyl chloride was discovered in the nineteenth century; however, it was not until the 1920's, through extensive research endeavors, that European and American scientists were able to transform it to usable materials. In the 1930's, German scientists and engineers developed and produced PVC pipe, and some of the original pipe is still in use today. Since the 1930's, much knowledge and information have been obtained relating to the various applications for PVC pipe. Reference 44 describes in detail the numerous codes and standards that relate to PVC pipe as well as many design aids.

In general, guidelines do not permit the use of plastic materials, either as a casing or carrier pipe, beneath railroads. Although, several railroad companies do permit the use of plastic on a job-by-job basis.

No evidence has been discovered that presents any significant reason for avoiding the use of PVC or polyethylene (PE) as carrier pipes. In many ways, PVC or PE carrier pipe would be a superior material. For example, it is not vulnerable to subsurface galvanic or atmospheric corrosion. [39]

PVC pipe is classified as a flexible pipe construction material. The same dead and live loading principles described in the previous section on CMP directly apply. Flexible pipe design criteria and procedures will be discussed, in detail, in Chapter 4.

PVC does not function well with trenchless methods that utilize jacking to force the pipe through the ground. The flexibility characteristic that is advantageous for supporting vertical loads results in being a disadvantage when used as a casing because of not being able to control the direction. It is commonly used as a casing with methods that allow the borehole to be developed independent of the casing installation (i.e., slurry horizontal boring method). This method is predominantly used for installation of rural water systems when crossing county roads in some states.

PVC is only one type of plastic used as a pipe material. Specific standards that apply to various plastic pipe materials are stated in Chapter 6. For many applications the pipe is installed direct.

3.5 Steel Tunnel Liner Plates (TLP)

Steel TLP can be subdivided into : (1) 2-flange TLP (2) 4-flange TLP. The 2-flange liner plates have flanges only along the circumferential edge and none along the longitudinal edge. The 4-flange liner plates have flanges along each direction. The flanges serve two major functions : (1) provide a means of connection (2) develop a high degree of strength and stiffness. Circumferential flanges and prefabricated corrugations provide a high degree of strength and stiffness to support vertical loads. The longitudinal flanges provide strength and stiffness sufficient to support thrust developed by the tunneling shield.

Soft and/or unstable soil conditions require the use of a shield to obtain adequate production and provide a safe working environment. These shields can be used with manual or mechanical excavation. The use of the 2-flange TLP preclude the use of a shield. As the shield is thrust forward, the reaction of the thrust rams is distributed to the liner plates. The thrust on 2-flange TLP tend to result in buckling and failure in the longitudinal direction. The 4-flange TLP are designed to support the horizontal thrust.[45]

Due to the advantages associated with utilizing tunneling shields, many specifications reviewed during

the course of this research endeavor required their use. Therefore, only the 4-flange liner plates will be discussed in detail in this thesis. The plates are specifically designed and cold formed fabricated so that the completed liner system consists of a series of steel liner plates assembled with staggered longitudinal joints. To insure adequate strength and stiffness, the liner plates utilized must meet specific thickness, area, and moment of inertia specifications.

Liner plates are designed to be connected by bolts on both the longitudinal and circumferential joints, and are fabricated to permit the complete erection from inside the tunnel. This erection process is normally executed in the tail section of the tunnel shield. This process results in a varying amount of over excavation. Therefore, grout holes should be pre-fabricated in the plates so that they can be strategically placed to permit grouting as the erection of the tunnel liner plates progresses. The recommended minimum size for the grout holes are 2-inch in diameter; however, 1.5-inch holes have been used with success.

Table 3-4 is a design aid useful in correlating the height of cover limits for noncohesive and cohesive soils with railroad Cooper E 80 and highway H 20 liveloads with impact for various diameters and gages

Table 3-4. Minimum and Maximum Height of Cover for Railroad Cooper E 80 and Highway H 20 Live loads plus Impact for Cohesive and Noncohesive Soils for Various Gages of Tunnel Liner Plates. [46]

HEIGHT OF COVER LIMITS		RAILROAD COOPER E80 LIVELOAD PLUS IMPACT							
GRANULAR SOIL — NONCOHESIVE $\phi \geq 17^\circ$		MINIMUM AND MAXIMUM HEIGHT OF COVER IN FEET							
DIAMETER FEET	12 Gage 0.105	10 0.135	8 0.164	7 0.179	5 0.209	1/4" 0.250	5/16" 0.313	3/8" 0.375	
4	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	
5	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	
6	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	
7	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	
8	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	
9	8-40	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	
10		8-48	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	
11			10-23	9-28	6-40	4-NL	4-NL	4-NL	
12					11-18	6-31	5-45	4-NL	
13							9-25	6-36	
14								10-20	

SATURATED CLAY — COHESIVE $\phi = 8.7^\circ$		MINIMUM AND MAXIMUM HEIGHT OF COVER IN FEET							
DIAMETER FEET	12 Gage 0.105	10 0.135	8 0.164	7 0.179	5 0.209	1/4" 0.250	5/16" 0.313	3/8" 0.375	
4	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	
5	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	
6	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	
7	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	
8	6-38	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	
9	8-27	5-44	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	
10		6-34	4-47	4-NL	4-NL	4-NL	4-NL	4-NL	
11			10-17	9-22	7-31	4-40	4-NL	4-NL	
12					12-13	8-23	5-35	4-45	
13							9-22	6-29	
14								10-17	

NL — No Limit, ϕ — Soil Friction Angle

HEIGHT OF COVER LIMITS		HIGHWAY H20 LIVELOAD PLUS IMPACT							
GRANULAR SOIL — NONCOHESIVE $\phi \geq 17^\circ$		MINIMUM AND MAXIMUM HEIGHT OF COVER IN FEET							
DIAMETER FEET	12 Gage 0.105	10 0.135	8 0.164	7 0.179	5 0.209	1/4" 0.250	5/16" 0.313	3/8" 0.375	
4	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	
5	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	
6	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	
7	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	
8	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	
9	4-40	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	
10		4-48	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	
11			4-26	4-30	4-40	4-NL	4-NL	4-NL	
12					4-24	4-31	4-45	4-NL	
13						4-20	4-28	4-36	
14							4-19	4-24	

SATURATED CLAY — COHESIVE $\phi = 8.7^\circ$		MINIMUM AND MAXIMUM HEIGHT OF COVER IN FEET							
DIAMETER FEET	12 Gage 0.105	10 0.135	8 0.164	7 0.179	5 0.209	1/4" 0.250	5/16" 0.313	3/8" 0.375	
4	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	
5	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	
6	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	
7	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	
8	4-36	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	
9	4-29	4-44	4-NL	4-NL	4-NL	4-NL	4-NL	4-NL	
10		4-34	4-47	4-NL	4-NL	4-NL	4-NL	4-NL	
11			4-23	4-25	4-31	4-40	4-NL	4-NL	
12					4-21	4-26	4-35	4-45	
13						4-18	4-24	4-30	
14							4-16	4-22	

NL — No Limit, ϕ — Soil Friction Angle

of TLP. Figure 3-6 illustrates physical dimensions associated with typical tunnel liner plates. [46] This figure, also, illustrates the typical options available concerning tapped holes and couplings.

TLP are classified as flexible conduits and are designed as a soil-steel interactive system. This results in the ground, which produces the deadload conditions, to supply resistance and support for the load. As a flexible conduit, the TLP assembly distributes and transmits the load to the surrounding earth. For example, as the tunnel liner plates are loaded vertically, they deflect inward at the top and outward at the sides. The earth around the sides resist this deflection through the compaction characteristics of the soil developing passive force equal in magnitude and opposite in direction to the force exerted by the lining. [47]

Bolts and nuts used with the 4-flange tunnel liner plates should not be less than 0.5-inch diameter for plates equal to or less than 7-gage, and not less than 5/8-inch diameter for plates heavier than 7-gage. They should have the quick-acting coarse threads, and should conform to ASTM specification A 307, Grade A. When galvanizing is desired, the bolts and nuts should be hot dipped galvanized in accordance with ASTM specification A 153.

Two-inch tapped hole

Two-inch tapped hole with plug

Two-inch half coupling

The 37-11/16" size develops diameters in whole feet, one plate being required for each foot of diameter. Half Plates permit diameters in multiples of 6-in. Plain 2-in. punched grout holes or grout holes tapped for 2-in. pipe and supplied with or without 2-in. pipe plug screwed in place, provided where required.

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TUNNEL LINER PLATE SIZES AND WEIGHTS

Gage	Thickness Inches	16" Wide	
		Full Plate L=37-11/16"	Half Plate L=18-27/32"
12	0.1046	24.5 lbs.	13.3 lbs.
10	0.1345	31.3 lbs.	17.0 lbs.
8	0.1644	38.0 lbs.	20.6 lbs.
7	0.1793	41.3 lbs.	22.4 lbs.
5	0.2092	48.0 lbs.	25.9 lbs.
1/4"	0.2500	55.5 lbs.	29.9 lbs.
3/16"	0.3125	68.5 lbs.	36.8 lbs.
3/8"	0.3750	81.3 lbs.	43.5 lbs.

Figure 3-6. Typical Tunnel Liner Plate Detail and Physical Dimensions. [46]

The mechanical properties of tunnel liner plates should conform to ASTM specification A 569, and possess the following minimum properties :

42,000-PSI * * * Tensile strength

28,000-PSI * * * Yield strength

30-% * * * Elongation in 2-inches

In most installations, the tunnel liner plates are constructed for temporary facilities to support the opening until the carrier pipe can be properly inserted; after which, the void between the carrier pipe and tunnel liner is filled. Therefore, in this situation, extending the life of the tunnel liner plates with coatings or galvanizing is not justified. However, for situations in which the plates are to be utilized as a finished structure then the plates should be zinc or bituminous coated. All galvanizing should be in conformance with AREA 1-4-25 or AASHTO M167. All bituminous coatings should comply with AREA 1-4-13 or AASHTO M 190 specifications.

Detailed design procedures for tunnel liner plate TEC projects are presented in Chapter 4. These procedures are based on the flexible pipe principle which allows the surrounding soil to behave as part of the structural support system. As the pipe deflects at the top it develops increased side pressure which compacts the soil and offers increased counter-support.

3.6 Hobas Fiberglass Pipe

Hobas fiberglass reinforced plastic (FRP) pipe is a relatively recent addition to the construction materials available which are considered compatible with trenchless excavation methods. The centrifugal casting of the FRP process was developed in Europe over 20 years ago. It has been widely accepted, and currently Hobas pipe is manufactured in the U.S.A., Switzerland, Austria, Sweden, Italy, England, Jordan, Japan, and Australia. The patented Hobas manufacturing system utilizes an external rotating mold to build up the pipe wall from the exterior surface to the interior surface.

The pipe is manufactured from chopped glass fiber roving, polyester resin, and sand. The sophisticated wall structure can be varied to produce the desired characteristics for any pipe application such as high hoop strength and stiffness for pressure pipe or high stiffness for non-pressure pipe. [48]

While the mold is revolving at a relatively slow speed, the resin, glass, and sand are fed in at controlled rates. The resin is specially formulated not to polymerize during the filling process. When all of the material has been positioned in the mold its rotational speed is increased to produce centrifugal forces up to 75 g. These forces are sufficient to

compress the wall composition against the mold causing total de-aeration and full compaction. Hot air is then passed through the mold to facilitate curing. The process is completely computer controlled for each type of pipe size and class. It has been proven to produce consistent quality pipe with very smooth internal and external surfaces. It is manufactured in standard 20 - foot lengths with a diameter range of 18 to 96 - inches. [48]

The stiffness of a pipe indicates the ability of the pipe to resist vertical (dead and live) loads as well as internal pressure. The stiffness is a function of the pipe wall design and wall thickness. Thus, the thicker the wall the higher the stiffness and the higher the load bearing capacity.

All FRP used for jacking purposes should comply with ASTM specification D 3262-87. The reinforcing glass fibers should be commercial grade E-glass filament, and the sand should be 99 % silica with a maximum moisture content of 0.20 % . [48]

CHAPTER 4 - DESIGN METHODOLOGY

This chapter presents the design principles and practices associated with trenchless excavation construction (TEC) techniques. The construction procedures and applied forces are unique as compared to traditional trenching methods. Methods utilized for projects $\leq$ 42-inches must be accomplished remotely. The operator has no visual contact with the material being excavated. Therefore, other indicators must be relied on for decision making purposes. For projects greater than 42-inch in diameter, methods are available which allow the operator to see the cutting face. Changed conditions and/or obstacles encountered can require major equipment and methods modification.

The construction materials being installed must support vertical pressure created by the dead, live, impact, and construction loads as well as the horizontal pressure created by the jacking and/or pulling forces necessary to insert the pipe in the ground. These forces are significantly different than the materials would be exposed to with trenching methods. With several of the methods described in chapter 2, the jacking force must be sufficient to propel the pipe and the tunneling shield or tunnel boring machine.

The project developmental process phases are: (1) Project definition / concept; (2) Preliminary planning; (3) Detail design; (4) Construction; (5) Start-up. Developing a knowledge of the subsurface conditions should not be delayed until the construction phase. This input should be factored into the development process at the beginning. As much information as possible should be obtained from : (1) Existing geological surveys, (2) Interviewing residents in the area while making site visits, (3) Interviewing contractors that have worked in the area previously. Such information, may be significant in considering the merits of the alternatives involving TEC projects.

The preliminary planning phase will identify the need, location, and extent of TEC work to be conducted. Routinely, TEC methods are utilized to pass under various structures and obstacles; however, due to the inherent benefits of being able to install utilities without destroying the surface and disrupting traffic, businesses, and residential areas, these methods have been used to install complete utility systems. This trend is expected to increase as more designers and owners are exposed to the capability of the trenchless methods. During this phase, geological investigations need to be conducted on the selected site to confirm the suitability of trenchless methods.

The project design phase must insure that the detailed plans and specifications are compatible with conditions above and below ground. The designer should be familiar with the various methods available in the industry to accomplish the objective to insure that competition is not restricted unnecessarily as well as that only suitable methods are utilized. Each method has limitations; without knowledge of the subsurface conditions, it is not possible to match material, equipment, and methods with conditions.

On some projects the trenchless portion may only comprise a small percentage of the total. It is not uncommon for this small percentage to be the most significant and hazardous. Anytime excavation is being conducted under structures (i.e., railroads, roadways, etc.), it deserves special attention during design and construction. Naturally, the degree of attention will depend on the project characteristics. For example, a 200-LF, 42-inch diameter steel casing being installed under a heavily traveled interstate highway will deserve a great deal more consideration than a 40-LF, 2-inch diameter water service line under a rural road.

The consensus of opinion, among the construction industry, was that when the contractor has been expected to carry the total risk one of two consequences will result, and both are not in the best interest of the

project, owner, or contractor. One consequence is that the owner will pay too much because a competent contractor must charge for the inherent risk. This risk can be minimized by informing the contractor of the subsurface conditions. The other consequence, which probably has the most adverse impact, is when the owner gets a bargain price. This usually happens when the contractor has not accurately evaluated the conditions, and has not charged for the risk. This optimism usually results in problems, disputes, claims, delays, and abandonment often result leading to more cost than providing sufficient subsurface data.

TEC projects are, typically, constructed by specialty subcontractors. These firms cover wide geographical areas. Project durations are short. It is impossible for a TEC contractor to conduct geological investigations on every project. They must rely on others for this information. If it is not available, then unreasonable risks are placed on the TEC contractor because project performance is directly related to being able to evaluate the anticipated conditions. The objective should be to provide sufficient information to all interested bidders to permit adequate evaluation of the risks. Both designers and contractors agreed that lower prices were obtained when sufficient information was provided.

4.1 Geotechnical Considerations

Materials, equipment, and the TEC method selected must be compatible with anticipated conditions. It is important that subsurface exploration be conducted from ground level to a minimum of 3-feet below the bore pit floor. The designer needs this data to properly develop details and specifications, the contractor needs it to insure that his strategy is appropriate, and the regulatory agencies need it to insure that the proposed work is in accordance with their guidelines. Without this data, success is left to chance. Lengthy delays and additional costs develop when anticipated conditions are misjudged.

The geological investigation should define significant soil properties with particular attention directed to ground water table level and fluctuation. Distinction needs to be made between cohesionless and cohesive soils as this will dictate significant difference in the dead loads imposed on the casing.

It is beyond the scope of this research endeavor to describe the various soil test procedures and classification systems. These are covered adequately in numerous basic soil mechanics textbooks. The primary intent of this discussion is to emphasize how ground behavior impacts the design and construction methods.

In most situations, neither the designer nor the contractor are geotechnical engineers. They are concerned with translating geotechnical data to predict ground-movement behavior. Therefore, it is necessary to describe the soil in terms of its behavior rather than the Unified or AASHTO Classification System. [37]

Often the terms good, bad, or very bad are used to describe the ground condition as it relates to borability. However, these term are relative to the equipment and methods proposed to be used; and are not adequate to properly describe ground behavior and movement. Ground conditions considered bad for one method may, in fact, be good for another method. To overcome this communication problem, the tunneling industry has standardized on the following categories :

1. Firm Ground : Ground in which there is no perceptible movement between the face excavation and the time it takes to install the tunnel roof section. This could be in terms of days. This can include a great variety of soils between the coarse-grained varieties, such as sand or sandy gravel with a clay binder, and extremely fined-grained soil such as silt, intact clay.
2. Raveling Ground : Ground in which the tunnel roof gradually breaks up into chunks, flakes, or angular fragments. At some point in time, pieces begin

to fall out of the roof, leaving cavities. The time that elapses from the start of the excavation until the first bit of ground drops out of the roof is referred to as stand-up time. This stand-up time is a function of soil properties and width of the tunnel. Raveling is the most common form of ground behavior. Highly cohesive soils result in firm ground; whereas, highly cohesionless soils run or flow.

3. Running Ground : Ground with a stand-up time of zero. As soon as the lateral support is removed from a surface that rises at an angle ≥ 34 -degrees running movement of soil particles begin and continues until the soil surface reaches approximately 34-degrees. This behavior is limited to clean, coarse sand-gravel located above the water table.
4. Flowing Ground : Ground in which both water and ground move into the excavated area from all sides including the bottom. This behavior is limited to inorganic silt, fine silty sand, clean sand or gravel, or sand-and-gravel with some binder. Running behavior is a function of the degree of cohesion present, permeability, and the hydrostatic head due to the water table.
5. Squeezing Ground : Ground which slowly advances into the tunnel without signs of fracturing.

Subsidence of the ground surface should be closely monitored for this type of condition. This type behavior is limited to soft and medium clay and very fine-grained, organic silt.

6. Swelling Ground : Ground volume increases with an increase in water content. In all other situations, the ground behaves like a stiff, firm clay. [37]

The Horizontal Earth Boring And Pipe Jacking Manual No. 2 [2], uses the following soil categories :

1. Dry Stable Sand.	6. Dry Unstable Sand.
2. Wet Stable Sand.	7. Wet Unstable Sand.
3. Sugarsand.	8. Wet Stable Clay.
4. Wet Unstable Clay.	9. Dry Stable Clay.
5. Large Boulders.	10. Fill Material.

While the soil categories used by the trenchless excavation contractors differ significantly from those used by the large diameter tunneling industry, it should be recognized that in each case the emphasis is on its behavior. Therefore, they are directly correlated to each other. It must be remembered that the two industries are uniquely different, and the soil categories must be compatible. Good tunneling ground is not necessarily good boring ground. For example, ground with 12-inch boulders is not a problem for a 48-inch tunneling project, but it will completely stop an auger horizontal earth boring project.

Since the trenchless excavation industry has standardized on the soil categories described previously, they will be used to reference the ground behavior characteristics.

The significance between dry stable sand and dry unstable sand is the degree of binder present. For a sand to be dry and stable (self-supporting), it must contain some cohesive properties, or it would flow. By knowing that it is stable indicates to the contractor what type of equipment should be utilized and the nature of the operating procedures. Wet sand can be stable because the moisture content will develop cohesiveness, but as the moisture content increasing the same material can become very unstable.

Boulders and obstacles are major problems to any type of trenchless excavation technique. Provisions must be established to detect their presents and how to handle their removable. The TEC method selected and approved for a particular project must be a function of the subsurface conditions. If line and grade are not critical and the diameter is small, then systems are available that offer directional control. If a boulder is encountered, the drill stem can be pulled back and directed around. Ground containing boulders and obstructions are the most difficult conditions to contend with.

4.2 Casing Pipe

The term casing pipe will be used to describe the load carrying pipe. As previously discussed, much research is being conducted on establishing the need for a pipe to encase a carrier pipe. This research, both for highways and railroads, is particularly concerned with pipes which transport petroleum products which require elaborate corrosion protection systems.

The approach taken in this research endeavor was to consider the traditional TEC project in which a casing pipe is used to encase a carrier underneath a structure. Thus, the major objective of TEC is to install the casing in such a manner so as to prevent present and future ground surface settlement. The most common cause of surface settlement is the removal of a larger volume of ground than is occupied by the casing pipe. Ground loss can be a result of the following :

1. Ground loss at the face which occurs with unstable, running, flowing, or squeezing type soils.
2. Ground loss due to overcutting. This is due to wing cutters on the cutting head, and when boulders or other obstructions are encountered that must be removed prior to continuing the boring operation.
3. Ground loss due to the O.D. of the shield, micro-tunneling machine, or tunnel boring machine being

larger than the casing pipe that is being installed. There may be no overcut with respect to the shield, but significant overcut with respect to the pipe O.D.

4. Ground loss may occur through the joints of the casing material. [50]

Only through proper design procedures and compatible construction equipment, materials, and methods can ground subsidence be minimized. Proper design procedures should address the following :

1. Type of Ground.	7. Superimposed Loads
2. Location.	8. History
3. Depth of Cover.	9. Casing Joint Strength
4. Size of Casing Pipe.	10. Critical Buckling
5. Length of Casing Pipe.	11. Handling Practice
6. Level of Groundwater.	12. Casing Deflection.

The type of ground is important because of its influence on the loading conditions imposed on the casing pipe. "A detailed knowledge of the subsurface conditions is a prerequisite to the avoidance of highly localized or catastrophic subsidence." [51] The subsurface investigation for trenchless excavation projects is as important as for the design of a foundation. Even small commercial building projects require soil investigation, yet it is surprising the volume of projects that are bid which contain large casings to be installed under interstate highways

without any subsurface investigations. The designer and the contractor must be able to determine the behavioral characteristics of the subsurface, the groundwater conditions, and the ground's ability to be drained or grouted. The safety of the operation and the consequences at the ground surface depend on proper investigation and interpretation of the subsurface conditions. [51] "Detailed exploration and careful description of the characteristics of the materials are essential to permit the bidders to gain a correct concept of the nature of materials with which they must contend. Otherwise, large claims for encountering unexpected conditions are certain." [51]

Figure 4-1 illustrates the classifications of construction conditions for determination of loads on buried conduits are : (1) trench construction, (2) embankment construction, and (3) tunnel construction. The tunnel construction classification is appropriate for all TEC methods. The forces which pertain to gravity loads on casings installed by TEC methods are similar to those installed by trenching methods with the exception that soil cohesion is taken into consideration. Even though cohesion may exist in the trench or embankment classification, it is neglected due to uncertainty in determining the coefficient. When the soil remains in an undisturbed state, the coefficient

can be assumed with reasonable accuracy. It has been established that, due to cohesion, the ring stress in a circular casing is considerably less than if the overburden pressure were applied as a uniform pressure. Figure 4-2 is a cross-sectional drawing illustrating a conduit installed with a TEC method and the undisturbed zone above the conduit which provides cohesion.

In addition to the direct circumferential compressive forces (ring stresses), the casing pipe must be designed to carry bending forces that occur in planes at right angles to the axis of the casing. A flexible casing is not affected to any significant degree by bending stress because the change that develops in the horizontal diameter is equal to the change in the vertical diameter. Also, the casing pipe must be designed to carry any local irregularities of deformation, loading, or stress which includes failure by buckling or any other mode. [51]

At the present time, theoretical studies as well as full-scale field observations have resulted in the conclusion that loads imposed on a flexible casing pipe installed by the trenchless methods will not correspond to the classical states of active and passive earth pressures, or even earth pressure at rest. The appropriate design procedure must consider the overriding influence of the deformation of the soil

Figure 4-1. Classification of Construction Conditions for the Determination of Loads on Conduits. [53]

Figure 4-2. Cross-Sectional Detail of a Conduit Installed with Trenchless Excavation Construction (TEC) Methods. [53]

mass which provides considerable strength. These procedures must provide for :

1. The ring load to be expected.
2. The anticipated distortions due to bending.
3. The possibility of buckling.
4. Any significant job specific external condition.[51]

Since Professor Anson Marston, Iowa State University, published the Marston's Theory of Loads on Underground Conduits in 1913, it has been considered the 'state-of-the-art' in the determination of loadings on buried pipe throughout the world. However, Professor Marston's student, M. G. Spangler, observed that the theory was not adequate for flexible pipe design. Spangler noted that flexible pipes may provide little inherent strength in comparison to rigid pipes, yet when buried, a significant ability to support vertical loads is derived from the passive pressures induced as the sides of the pipe move outward against the earth. This fact coupled with the idea that the pipe deflection may also be a basis for design prompted M. G. Spangler to publish his Iowa Formula in 1941." [44]

"In 1955, Reynold K. Watkins, a graduate student of Spangler's, was investigating the modulus of passive resistance through model studies and examined the Iowa Formula dimensionally. The analysis determined that 'e' could not possibly be a true property of the soil

in that its dimensions are not those of a true modulus. As a result of Watkin's effort, another soil parameter was defined. This was the modulus of soil reaction, $E=er$. Consequently, a new formula called the Modified Iowa Formula was written." [44]

The first step in the design process is to select a casing material type. This will be a function of the project characteristics. The material selected will be classified as either a rigid or flexible casing. RCP is classified as a rigid pipe while CMP, tunnel liner plates (TLP), PVC pipe, steel pipe, and HOBAS pipe are classified as flexible casing materials.

The significant difference between rigid and flexible pipe is in their stress behavior. When a rigid pipe is subjected to vertical loads (live and dead), it resists those loads primarily through the structural properties of the pipe. RCP is the predominant type of rigid pipe. The concrete portion of the composite design is excellent in compression, and the reinforcing steel accepts the tensile forces which are developed as loads are applied and deflection occurs. However, since deflections are insignificant, only a negligible contribution to the load carrying capacity of the pipe is received from the active lateral pressure of the surrounding soil.

With a flexible pipe, deflection due to vertical

loads are resisted by support provided from the earth along the sides. This passive resistance to the outward movement of the sidewalls increases the side pressure until they are approximately equal to the vertical pressure. When this condition is reached, the pressure acting on the ring may be considered to be uniform and to be acting radially without deviation seriously from the actual pressure pattern. The pipe will then act as a compression ring. [52]

Regardless of whether the casing is rigid or flexible, the vertical loads must be determined. These loads are classified as live, dead, impact, concentrated, or distributed, and they result in the following two major forces developing on the pipe :

1. Weight of the overhead prism of soil within the width of the trenchless excavation.
2. Shearing forces generated between the interior prisms and the adjacent material due to friction and cohesion of the soil.

For calculations of gravity earth loads on casings installed by a TEC method, Marston's formula can be modified to represent this component of dead load. This modification is indicated in equation 4-1.

$$W_t = C_t B_t (w B_t - 2 c) \quad \text{EQN. 4-1}$$

- W_t = Load on the casing, lb./LF
 w = Unit weight of soil above casing, lb./CF
 B_t = Max. width of trenchless excavation, Ft.
 c = Cohesion coefficient, lb./SF
 C_t = Load coefficient which is a function of the ratio of the distance from the ground surface to the top of the casing to the width of the casing excavation and the coefficient of internal friction of the soil. Figure 4-3 presents the load coefficient, C_t , for pipe in undisturbed soil for:

$$ku' = 0.165, 0.15, 0.13, \text{ and } 0.11$$

Also, equation 4-2 illustrates the mathematical relationship involved.

$$C_t = \frac{1 - e^{-2ku'H/B_t}}{2ku'} \quad \text{EQN. 4-2}$$

- e = Base of natural logarithms
 k = Rankine's ratio of lateral to vertical pressure.

$$= \frac{\sqrt{u+1} - u}{\sqrt{u+1} + u} = \frac{1 - \sin \phi}{1 + \sin \phi} \quad \text{EQN. 4-3}$$

 $u = \tan \phi$ = Coefficient of Backfill internal friction.
 $u' = \tan \phi'$ = Coefficient of friction between backfill material and the sides of the trench.
 H = Height of fill above the pipe, Ft.

This is the same formula used to determine loads on pipe installed by the trenching method with the

Figure 4-3. Diagram for Load Coefficient, C_t , for Casing Installed with Trenchless Excavation Construction (TEC) Methods. [53]

exception of being modified to take into consideration cohesion. The selection of the proper coefficient of cohesion, "c", is extremely important. It varies widely even for similar types of soils. It is strongly recommended that, whenever possible, the "c" value be determined by appropriate laboratory tests. When laboratory tests are not possible, the representative values located in Table 4-1 can be utilized. Regardless of the method used for selecting a "c" value, care should be exercised to insure it is conservative because of all the unknown factors, such as moisture content.

Research and extensive field investigations have substantiated that the dead loads calculated for TEC conditions will be less than those computed for any of the methods indicated in Figure 4-1. However, if construction methods are utilized that result in excessive excavation or the void between the casing and earth is not grouted properly, then the cohesion of the undisturbed material above the casing is destroyed and loads in excess of those calculated will be encountered. Thus, if this condition is anticipated or encountered then the loads should be computed by the Marston formula without the cohesion effect.

Both AASHTO and AREA live load classifications recognize the distribution of live loads through earth fills and their intensities reaching pipes at varying

Table 4-1. Coefficient of Cohesion "c" for Various Soil Materials. Values of ku and ku' are as noted in Figure 4-3. [53]

Material	Values of c (psf)
Clay, very soft.....	40
Clay, medium	250
Clay, hard	1,000
Sand, loose dry	0
Sand, silty	100
Sand, dense	300
Top soil, saturated.....	100

Table 4-2. Highway H 20 and Railway E 80 Live Loads plus Impact Loads for Various Heights of Cover. [46]

Highway H 20 Loading* + Impact		Railway E 80 Loading* + Impact	
Height of Cover In ft.	Pressure, psf	Height of Cover In ft.	Pressure, psf
1	1800	2	3800
2	800	5	2400
3	600	8	1600
4	400	10	1100
5	250	12	800
6	200	15	600
7	175	20	300
8	100	30	100

*Neglect live load when less than 100 psf; use dead load only.

heights of cover. The intensity of live loads are distributed at the surface of any horizontal plane in the subsoil such that the greatest intensity is at the vertical axis directly beneath the point of application and decreases in all directions outward from the center of the point of application. Thus, as the distance between the horizontal plane and the surface increases, the intensity of the load decreases.

The highway pavement design is important when evaluating the live load on a buried casing. For example, if a flexible or rigid pavement has been designed for heavy duty traffic, then the intensity of a truck wheel load on the casing has been reduced to the point that it is negligible. However, if a flexible pavement has been designed for light duty traffic but then is subjected to heavy truck traffic, then the flexible pavement should be treated as just fill material over the pipe. [30]

For highway loadings, the conventional truck loading as specified by AASHTO is universally accepted for the design of casings. The total truck load is considered as distributed to the wheels as illustrated in Figure 4-4 which also indicates the clearance of passing trucks. For railroad loadings, the Cooper's conventional engine wheel concentrations as specified by the AREA are universally accepted for the design of

casings. These loadings represent the wheel loads of two consolidation type locomotives and are designated according to the thousands of pounds at each driver. The most common class of railroad loading now in use is the Cooper's E-80 which is illustrated in Figure 4-5. The loads indicated are the axle loads and are for one track. Table 4-2 summarizes highway and railroad live loads, including impact, to facilitate design calculations. [46]

In general, the external loads on circular casings are computed by Equation 4-7. This procedure is applicable for both rigid and flexible casing designs.

$$P_T = P_l + P_d \quad \text{EQN. 4-4}$$

P_T = External pressure on the casing pipe.

P_l = Vertical live load pressure at top of the casing.

P_d = Vertical dead load pressure at top of the casing.

There are two separate design procedures. One for rigid pipe and one flexible pipe. These procedures will be illustrated by an example for each. Reinforced concrete pipe will be used for rigid pipe, and tunnel liner plate will be used for flexible pipe.

RCP is classified as a rigid composite construction material, and the design procedures must evaluate the bending stresses created by the vertical loads. As

Figure 4-4. Highway H 20 Live Load Distribution of Loaded Truck Weight as Specified by AREA. [46]

Figure 4-5. Railway E 80 Live Load Distribution for Cooper's Conventional Engine Loading as Specified by AREA. [46]

discussed previously, the design of RCP is based on D-loads used in the three-edge bearing test to select the proper wall type and class. Equation 4-5 is used to calculate the anticipated D-load.

$$D\text{-load} = (P / L_f * D) \text{ F.S.} \quad \text{EQN. 4-5}$$

D-load = D-load to produce either a 0.01-inch crack ($D_{0.01}$) or ultimate load ($D_{ult.}$) in the three-edge bearing test in terms of lbs./LF per foot of inside diameter of the pipe.

P = Total external load on the pipe, lbs./LF

L_f = Load factor

D = Inside horizontal Span, Ft.

F.S. = Factor of Safety

The load factor, L_f , is the ratio of the supporting strength of an installed pipeline to the strength in the three-edge bearing test. It is assumed that the jacking method of trenchless excavation provides intimate contact around the lower exterior surface of the pipe and the surrounding earth which is an ideal bedding condition. This intimate contact is provided by either close control of the borehole excavation to insure its conformity with the dimensions and shape of the pipe; or, if the borehole is over-excavated, then the space between the pipe and borehole

must be filled with sand, grout, concrete, etc. For this type of installation, the recommended load factor should be 3 ; however, if the borehole is slightly over-excavated and the space between the borehole and the pipe is not filled, then a minimum load factor of 1.9 is recommended. [34]

RCP DESIGN EXAMPLE

Select the proper class of 60-inch I.D. RCP with a wall type C to be jacked under a state highway. The length of line is 68-LF, and the height of cover above the pipe is 6-feet. The type of ground above the pipe is a brownish-yellow clay which has a unit weight of 120-lbs./CF. The O.D. of this pipe is 73.5-inches. The design procedures as described in reference [30] will be utilized.

Step 1 - Determine dead load.

Enter Table 43 on page 156 and select a coefficient of cohesion ($c = 200$) which is considered very conservative.

Enter Figure 138 on page 332 with $H = 6$ -feet and $B = 6.4$ -feet and select $W = 4,000$ -lbs.

Enter Figure 139 on page 333 with $H = 6$ -feet and $B = 6.4$ -feet and select a soil cohesion term of 10. Therefore, the effect of cohesion on the total vertical load will result in a reduction of : $10 * 200 = 2,000$ -lbs.

W_E = Trench Term - Cohesion Term

W_E = 4,000-lbs. - 2,000-lbs = 2,000-lbs.

Step 2 - Determine Live Load.

Enter Table 44 on page 157 for $H = 6$ -feet and $D = 60$ -inch and select a design highway live load ($W_L = 208$ lbs./ LF of pipe).

Step 3 - Determine load factor, L_f

Assume that ideal conditions exist as described above; thus, Load factor $L_f = 3.0$

Step 4 - Determine Factor of safety, F.S.

Assume that a factor of safety of 1.0 based on the 0.01-inch crack for the three-edge bearing test will be applied.

Step 5 - Selection of pipe strength

$$D\text{-load} = \frac{2,208\text{-lbs.}}{3.0 * 6.1} * 1.0 = 120\text{-lbs./LF}$$

The design objective is to select a RCP which would withstand a minimum three-edge bearing test for the 0.01-inch crack of 120-lbs./LF of the pipe I.D.

Class I RCP with Wall C can support a D-load of 800-lbs./LF per foot of pipe diameter which will be 6.7 times greater than the strength required.

Class II RCP with Wall C can support a D-load of 1000lbs. / LF per foot of pipe diameter. (8.3 times greater than the strength required.)

Class III RCP with Wall C can support a D-load of 1350-lbs./LF per foot of pipe diameter which will be 11.25 times greater than the strength required.

While each of these classes provide adequate strength to support all vertical loads, it is recommended that a minimum of a Class III pipe be selected.

Tunnel Liner Plates (TLP) are designed as flexible pipe under earth fills which derive their ability to support loads from their inherent strength plus the passive resistance pressure of the soil as they deflect and the sides of the pipe move outward against the soil side fills. Flexible pipe fails by excessive deflection and collapse or buckling rather than by rupture of the pipe walls as in the case of pipes made of brittle materials. Therefore, design of flexible pipes is directed toward determination of the deflection under load. A field supporting strength resulting in a deflection of 5% of the nominal diameter of the pipe is considered by many engineers to be a suitable criterion for design. Design criteria for buckling and longitudinal seam strength are suggested by Townsend. [53]

Equation 4-6 is Spangler's Iowa Formula, the most common formula for calculating flexible pipe deflection.

$$\Delta X = D_e \frac{K W_c r^3}{E I + 0.061 E' r^3} \quad \text{EQN. 4-6}$$

Where :

ΔX = Horizontal and vertical pipe deflections in inches.

D_e = Deflection lag factor.

K = A bedding constant.

W_c = Vertical load on the pipe in lbs./inch.

r = Mean radius of the pipe in inches.

E = Modulus of elasticity of the pipe material in PSI.

I = Moment of inertia per unit length of cross section of the pipe wall in (inches)⁴/inch.

E' = $e r$, the modulus of soil reaction in psi.

e = Modulus of passive resistance of the enveloping soil in psi/inch.

The deflection lag factor, empirically determined, compensates for the tendency of flexible pipes to continue to deform for some period of time after the full magnitude of load has developed on the pipe. Recommended values range from 1.25 to 1.50.

The bedding constants, K , illustrate the influence of the width of pipe bedding. It is dependent on the angle subtended by the pipe bedding, and varies from 0.110 for point support to 0.083 for bedding the full width of the pipe. $K = 0.10$ is the most common design value.

The TLP must depend on the surrounding ground to carry the imposed loading. A slight deflection of the lining, held to an amount consistent with the final dimensions required in the completed structure, mobilizes the passive resistance of the surrounding ground (except in a liquid media). This passive resistance causes the lining to carry the loading in compression, a function of area, the moment of inertia, and resistance to buckling.

The design procedures for TLP are :

Step 1 Determination of vertical (live / dead) loads

anticipated. This will be in accordance with the procedures previously described.

Step 2 TLP manufacturers typically provide safe load tables to assist designers. See Table 4-3.

These tables are based on the following :

If $D < r/k = 92.4$ then $f_b = 28,000 \text{ psi}$ EQN. 4-7

If $92.4 \leq D \leq 128.7$ then $f_b = 42,000 - 1.27[kD/r]^2$ EQN. 4-8

If $D > r/k = 128$. then $f_b = 12E / [kD/r]^2$ EQN. 4-9

The stress determined by these equations, when multiplied by the TLP cross section and divided by the safety factor, represents the maximum the liner plate ring should be permitted to carry in compression or thrust :

$$C \leq f_b A / \text{S.F.} \quad \text{EQN. 4-10}$$

Table 4-3. Permissible Safe Loads On Circular Tunnel Liner Plates for Various Diameters and Gages. [47]

[illegible]

Equation 4-11 is utilized to calculate the permissible safe load in lbs./SF :

$$P_v = C/R \quad \text{or} \quad f_b A / (S.F.)(R) \quad \text{EQN. 4-11}$$

Where :

f_b = Allowable stress, psi

E = Modulus of elasticity = 29×10^6 psi

k = Varies from 0.22 for soils with $\phi > 15$ degrees
to $k = 0.44$ for soils with $\phi < 15$ degrees.

D = Diameter of TLP in inches.

r = 75% of radius of gyration. See Table 4-4.

A = Effective cross sectional area of the TLP in (inches)² / LF. Since the TLP is considered to be a thin web connected by angles, and a ring is comprised of a number of plates, the full cross section is not effective. From tests and theory, the effective area is taken as 50% of the theoretical area.

R = Radius of TLP = $D/2$ in feet.

S.F. = Safety Factor = 2

Step 3 Check for stiffness with Equation 4-12.

$$\text{Minimum Stiffness} = E I / D^2 \quad \text{EQN. 4-12}$$

The minimum stiffness shall be ≥ 111 .

There is not much information available on jacking forces required for type, size, length, and ground conditions. Reference [2] does contain a table provided

Table 4-4. Sectional Properties of 4 - Flanged Tunnel Liner Plates for Various Gages. [47]

Thickness		Properties For 16" Section		
Inches	Gage	Area (Effective) In. ²	r(Effective) Inches	I In. ⁴ /inch
0.1046	12	1.0736	0.4388	0.0459
0.1345	10	1.3735	0.4360	0.0580
0.1644	8	1.6704	0.4334	0.0697
0.1793	7	1.8174	0.4322	0.0754
0.2092	5	2.1102	0.4297	0.0866
0.2500	1/4"	2.5053	0.4264	0.1012
0.3125	5/16"	3.1013	0.4218	0.1226
0.3750	3/8"	3.6862	0.4176	0.1428

I — Moment of Inertia

r — Radius of Gyration

Effective Area = 50% Actual Area

Effective r = 75% Actual r

Table 4-5. Ultimate Design Longitudinal Joint Seam Strength (Section 1.13.4 of AASHTO Specification). [47]

Plate Thickness		Ultimate Strength
Gage	Decimal	KIPS/FT
12	.1046	26.0
11	.1196	----
10	.1345	43.0
8	.1644	50.0
7	.1793	54.0
5	.2092	67.0
3	.2391	81.0
1/4"	.250	----
5/16"	.3125	115.0
3/8"	.375	119.0

by the Rodgers Hydraulic Catalogue No. R107-1078 that correlates jacking force for sandy soil and hard soil for various RCP sizes. Most contractors base their anticipated jacking force estimation on experience from previous projects. However, the most detailed analysis is presented in reference [35]. The equations will be presented for the purpose of illustrating their relationship to the jacking force required.

$$P = P_1 + P_2 + P_3 \quad \text{EQN. 4-13}$$

Where :

P = Required jacking force in lbs.

P_1 = Penetration resistance force in lbs.

P_2 = Pipe / soil friction resistance force in lbs.

P_3 = Pipe weight friction resistance force in lbs.

$$P_1 = \pi * D * \gamma * T * (H + D/2) \tan^2 (45 + \phi/2)$$

Where :

D = O.D. of lead pipe in Ft.

T = $(\text{O.D.} - \text{I.D.}) / 2$

γ = Soil Density in lbs./ CF

H = Earth Cover in Ft.

ϕ = Soil internal friction angle in degrees.

$$P_2 = 0.5 * \pi * D * \mu * L * [W + 0.5(W_1 + W_2)]$$

μ = Friction coefficient between pipe and soil.

L = Jacking distance in Ft.

W = Vertical earth pressure in lbs./SF = $k * h_o$

h_o = Soil Slacking height by arching efficiency.

$$= [B_1 / (K * \tan \phi)] (1 - e^{-K * \tan \phi * H / B_1})$$

K = Terzaghi's coefficient, $K = 1$

$$B_1 = B_o + h_1 * \tan(45^\circ - \phi/2)$$

$$h_1 = \gamma_o * [(1 + \sin(45^\circ - \phi/2))]$$

$$B_o = \gamma_o * \cos(45^\circ - \phi/2)$$

W_1, W_2 = Horizontal earth pressure at the
top and bottom of the pipe in lbs./SF

$$W_1 = C_e * \gamma * h_o$$

C_e = Coefficient of active earth pressure

$$= \tan^2 (45^\circ - \phi/2)$$

$$W_2 = C_e * \gamma * (h_o + D)$$

$$P_3 = 0.25 * \pi * W_p * \mu * L$$

W_p = Dead weight of pipe in lbs./LF

μ = Friction coefficient between pipe and soil.

L = Jacking length in Ft.

The intent of this chapter was to provide the basic concepts which relate to the design of load carrying buried conduit. These principles and practices apply to conduits installed by TEC methods. It has established that dead loads imposed on conduits installed by these techniques are considerably less than when installed by the trenching technique. Both rigid and flexible design procedures were presented as well as the factors that impact the determination of jacking forces that are required to jack the pipe through the earth.

4.3 Carrier Pipe

The design of the carrier pipe will be a function of its intended purpose and encasement design. When the encasement has been designed as a permanent structure then the loads imposed on the the carrier will be minimum; whereas, if the encasement is designed only to be a temporary facility then the carrier must be designed to carry all loads as previously described for the casing pipe. The designer should be cognizant of the critical nature of utility and transportation system intersection. Extra care should be exercised by all parties (designer, contractor, inspectors, owners, etc.) to insure that stringent quality control measures are adhered to at such crossings. When failures occur beneath transportation facilities, the end result is catastrophic.

The carrier pipe should be supported within the casing to prevent unnecessary movement. For example, a water line installed in a casing without proper support is free to move and vibrate due to dynamic forces created by the movement of the water (i.e., water hammer). This condition can result in joint separation, pipe damage, etc. This support can be provided with a variety of commercially available spacers or insulators as well as using treated lumber with metal bands. The

spacing of such supports should be in accordance with the pipe manufacturer's recommendations. It is also common practice to fill the casing void with sand, grout, or other filler material. This aids in stabilizing the pipe; however, care must be exercised to insure that the filler material is not causing the carrier to float or create undesirable stresses.

Bulkheads are constructed at the end of the casing to insure that the carrier and casing are compatible. Many failures occur at this point due to ground movement (settlement). The bulkheads do not need to provide complete watertightness except with petroleum products where steel carriers are inserted in steel casings. The bulkheads prevent the intrusion of soil into the casing which in turn results in ground subsidence near the pit areas. Therefore, masonry bulkheads have proven to be adequate for water and wastewater carriers. There exists several commercially available casing end plugs that will insure watertightness for situations where this characteristic is desirable.

4.4 Protection Practices

In most situations, the casing pipe is designed as a permanent facility. This is particularly important

for water and wastewater carriers because this permits the conveyance of the fluid from beneath the transportation facility in the case of a carrier pipe rupture. Otherwise, erosion and soil deterioration can occur creating hazardous conditions. For carrier pipes transporting petroleum (flamable) products, it is uncertain whether encasement serves the intended purpose or creates a hazardous environment. This uncertainty is described in detail in the recent research endeavors described previously in this thesis [40], [39], and [52]. These independent research projects indicate that, based on investigations of actual failures, other protective techniques may be advisable. These protective techniques include providing extra carrier wall thickness and extra depth. It has been substantiated that the quality of materials and methods of installation have improved tremendously since the standards and specifications were developed which most railroad and highway agencies require.

While it has been determined that cathodic protection between casings and carrier presents major challenges for designers and owners, it appears that the source for most problems result from pipeline installation workmanship and is not necessarily a direct result of defective material. For example, the differential settlement between the casing and carrier

often result in contact. Since these metals are at different electrical potentials, corrosion develops which eventually results in a leak that fills the casing pipe. The casing pipe acts as a reservoir containing explosive material ready to ignite at the first sign of a spark, either at the vent pipes or from friction generated from within. The designer and owner must be aware of these weaknesses and take them into consideration when designing a protective system.

The basic philosophy of a casing should not be ignored. That is, one of the main functions of the casing is to convey the fluid from beneath the transportation facility. It may be appropriate to utilize a non-metallic casing for flammable fluids, such as, Hobas, concrete, plastic, etc. This would eliminate the cathodic protection problem while providing a conveyance vehicle. The owners of such facilities could be required to submit periodic sample reports of the air within a casing to determine if a leak exists. Extra care should be taken during the installation process.

4.5 Bore Pits

Requirements for bore pits vary substantially with methods and must be properly protected as per

OSHA requirements as described in earlier sections of this thesis. Figure 4-6 illustrates a typical pit that is timber sheeted for a TEC project. Also, it is common practice to use TLP to construct a vertical shaft in which to work out of. The most common method of pit protection is to slope the embankments back to the proper angle or to use extra wide trench boxes. Trench boxes have proven to be very adequate and flexible. Their width can be varied and they can be stacked for extra depth conditions.

The bore pit should always be designed to allow adequate working room. Many accidents occur as a result from workers being in cramped conditions. A means of exit should be constructed. This may be sloped areas or OSHA approved ladders. Drainage must be provided to handle water that may accumulate in the pit due to ground water and from precipitation.

In the event wood or steel shoring is required, then the system should be designed by qualified individuals who are licensed professional engineers. All jacking pit design must consider the forces created by the jacking operation as well as the earth loadings. Surface drainage should be provided so that surface water does not enter the pit. Adequate protection such as fences, barricades, etc., are needed to prevent pedestrians and vehicles from entering the pit.

TYPICAL BORING PIT DETAILS

NOTE: 1. ALL DIMENSIONS AND MATERIAL SIZES MUST BE SHOWN.

2. 12" EARTH BERM TO BE PLACED AROUND SHEETING.

Figure 4-6. Typical Boring Pit Detail for a Trenchless Excavation Construction (TEC) Project.

4.6 Process Simulation For Trenchless Excavation

The major difficulties with this industry are:

1. Evaluating available information and determining its behavior to select compatible equipment, methods and materials to establish activity durations.
2. Once the behavior and conditions of the site have been predicted, and the actual conditions are substantially different than indicated, the contractor must substantiate his actual cost as compared to his original estimated cost.

The factors affecting item one have been discussed in previous sections. The emphasis of this section will be to discuss how computer simulation can be useful in evaluating the impact of changed conditions. The usefulness will be illustrated through an example of a horizontal earth boring project in which the soil conditions were different thus requiring activity duration modifications.

It is beyond the scope of this research endeavor to describe the detailed mechanics involved with computer simulation. Several books exist that explain this process very effectively [54]. However, it is within the scope of this thesis to illustrate its applicability to this industry. This section concludes that it can be a powerful tool.

By definition, computer simulation is the process of designing a mathematical-logical model of a real system and then experimenting with this model on a computer. This process of developing a simulation model consists of beginning with a simple model which is embellished in an evolutionary fashion to meet problem-solving requirements. Typically, the simulation process involves the following steps : [54]

1. Problem Formulation: Defining the specific problem to be studied and the problem-solving objective.
2. Model Building: The abstraction of the system into mathematical-logical relationships.
3. Data Acquisition: The identification, specification, and collection of the necessary data.
4. Model Translation: Preparation of the model for computer processing.
5. Verification: Computer program execution.
6. Validation: Establishing that a desired accuracy exists between simulation model and the real system.
7. Strategic and Tactical Planning: Establishing the experimental conditions for using the model.
8. Experimentation: Execution of the simulation model to obtain output values.
9. Analysis of Results: Analyzing the simulation outputs to draw inferences and make recommendations.
10. Implementation and Documentation: The process of

implementing decisions resulting from the simulation and documenting the model and its use [54].

The SLAM II simulation computer language was utilized to execute the model. SLAM II was developed by Dr. A.A.B. Pritsker, and is described thoroughly in reference [54]. It allows programming capability to permit models to be embellished in an evolutionary fashion to any level of detail required to reflect the complexities of the system being studied.

Figures 1-1, and 1-2 are the plan, profile, and detail drawings of a typical horizontal earth boring project on which simulation will be applied. The boring equipment and set up is illustrated in Figure 2-2. This represents the auger bore technique. Computer simulation will be restricted to just the boring operation. The horizontal earth boring contractor normally works as a subcontractor on projects of this type. The price is based on being able to move in, execute the bore, then move to the next project. Therefore, delays are devastating. The subcontractor will have a statement in his contract which will allow him to be compensated at some hourly rate should he be delayed for reasons caused by others. This rate is typically approximately \$ 190.00 per hour. Therefore, this rate will be utilized in developing the cost comparison analysis.

The model will be based on the activities described in Table 4-6. The activity durations are represented by triangular distributions. Triangular distributions work well for these types of projects because the duration times must be obtained from experienced field personnel who are very knowledgeable about the capabilities of their equipment and crew. These individuals can be reasonably accurate in providing the minimum, maximum, and most likely duration times. Another benefit is that should this model be used in court or arbitration then these durations can be easily understood by lay persons and easily supported by historical daily reports.

The most common type of changed conditions, which confront the trenchless excavation contractor, relate to subsurface conditions. If the contractor's bid is actually bid on dry stable clay, but encounters wet unstable clay at the jobsite then this will adversely impact the duration of certain activities associated with this project. As indicated previously, the difficulty arises when one attempts to substantiate the actual dollar amount of such an impact.

The common random number generator phenomenon can be used to isolate the impact of changing one variable in a highly random process and keeping all other variables constant.

Table 4-6. Activity Number and Activity Description for a Typical Horizontal Earth Boring Project.

ACTIVITY	DESCRIPTION
1	Set boring machine track in the prepared pit and adjust for line and grade.
2	Place boring machine on the tracks.
3	Install cutting head on leading end of auger.
4	Attach casing and auger to machine.
5	Begin push and continue for the full 4-foot stroke of the hydraulic thrust rams.
6	End push cycle, and retract the hydraulic thrust rams. REPEAT this push and ram retraction process for five 4-foot cycles until the 20-foot casing section has been inserted. (SEE ACTIVITY 5 & 6)
7	Disconnect casing & auger from the HEB machine then by using the hydraulic winch the machine is retracted to the rear of the pit and made ready to receive the next 20-foot casing and auger section.
8	Place casing and auger section on track, attach auger at leading end, weld casing to previously installed casing, attach casing & auger to the HEB machine. Begin push, process 5, 6, & 7 repeat until the 20 - foot casing section has been inserted. REPEAT processes 8 and 9. REPEAT processes 5, 6, 7, & 8 until 100 LP of casing have been installed.
9	Remove auger sections one flight at a time.
10	Remove HEB machine.
11	Remove HEB tracks.

To illustrate the usefulness of this phenomenon, it will be assumed that the contractor is attempting to substantiate how much his firm was damaged due to a change in subsurface conditions. The contractor's agreement references soil borings which indicate a dry stable clay. The agreement also states that should the TEC contractor be delayed for reasons not under his control then he will be compensated at a rate of \$ 190.00 per hour. Table 4-6 illustrates the process subdivided into specific activities. The contractor can then substantiate from his historical data that the activity durations as stated in Table 4-7 are representative for the anticipated conditions; and he can also document that due to encountering wet unstable clay activity number 5, which involves the ram push and cutter excavation, was triangular distributed with a minimum time equal to 60-minutes, mode equal to 70-minutes, and a maximum equal to 85-minutes.

Figure 4-7 illustrates the model that was developed for this process. From this model, the SLAM II computer input statement was developed, and computer simulation was produced for this experiment by utilizing the anticipated durations as well as the impact on the entire project when just one activity duration was changed due to the changed subsurface conditions.

The model was developed with the bore pit, crane,

Table 4-7. Activity Number and the Expected (Optimistic, Most Likely, Pessimistic) Activity Durations Based on Anticipated Conditions for the Typical Horizontal Earth Boring Project.

ACTIVITY NUMBER	DURATION		TIME
	MIN	MODE	MAX
1	30	50	60
2	15	20	30
3	15	17	20
4	20	25	30
5	15	18	20
6	4	6	7
7	15	20	25
8	30	35	40
9	15	20	30
10	15	25	30
11	25	30	35

boring machine, and the crew as resources. These were built into the model because each one could be a source resulting in project delays. However, this specific example is concentrating only on the impact of changed conditions.

By utilizing the anticipated durations, the contractor can document that the total project duration should take approximately 1480 minutes (24.7 hours) or three eight hour shifts. By controlling the seeds for the common random number streams, it can be shown that the duration of the total project was increased to 3425 minutes or 57.1-hours. This impact translates to a difference of 32.4 hours. If this additional time requirement is multiplied by the \$ 190.00 per hour, which was stated in the contract agreement, then extra cost to be paid to the contractor should be \$ 6,156.00.

The computer runs were executed for the project utilizing the anticipated durations with designated seeds for stream numbers 9 and 10. The run included a trace of the complete process for varification purposes. Activity number 5 was modified to reflect the changed conditions. Five computer runs were made utilizing a different seed for streams 9 and 10 for each run.

A summary of the results of the computer runs are indicated as follows :

RUN NO. (j)	ANTICIPATED CONDITION CASE "A" (Minutes)	ACTUAL CONDITION CASE "B" (Minutes)	DIFFERENCE ("A" - "B") (Minutes)
1	1480	3425	1945
2	1440	3360	1920
3	1450	3400	1950
4	1480	3460	1980
5	1450	3380	1930
	=====	=====	=====
	$\bar{X}_A = 1460$	$\bar{X}_B = 3405$	$D = 1945$

Determination of the variance :

$$S_D^2 = 1/n-1 \sum_{j=1}^n (X_{ij} - \bar{X}_1)^2 = 525$$

Determination of the standard deviation :

$$S_D = 22.9$$

$$n = \text{number of runs} = 5$$

$$v = \text{degrees of freedom} = n - 1 = 4$$

Select a 90 % confidence interval

$$\text{Therefore } \alpha = 0.10$$

$$t_{1-\alpha/2} (v = n-1) = t_{.95} (4 \text{ d.f.}) = 2.132$$

$$\begin{aligned} D \pm t_{1-\alpha/2} (v) S_D / n &= \\ 1945 \pm 2.132 (22.9/2.24) &= \\ 1945 \pm 22 & \end{aligned}$$

Therefore, based on the results of these five computer runs, a 90 % confidence interval can be

developed which states that the contractor can be 90 % confident that given the subsurface conditions actually encountered the difference in the total project duration will be increased between 1923 and 1967 minutes.

The purpose of this experiment was to determine how appropriate computer simulation is in substantiating the impact of changed conditions on a horizontal earth boring construction project. This experiment indicates that it is extremely useful in isolating specific variables so that the effects of just that one variable can be evaluated.

CHAPTER 5 - SPECIFICATION RECOMMENDATION

This chapter provides the recommended revised specification to be considered for adoption into the Indiana Department of Highways STANDARD SPECIFICATIONS to replace the current Section 716 - JACKED PIPE. The proposed title for Section 716 is Trenchless Excavation Construction (TEC) Methods. Section 716 should be expanded to include coverage for all methods currently utilized to install utility systems under roadways as identified through this research endeavor.

5.1 SECTION 716 - TRENCHLESS EXCAVATION CONSTRUCTION (TEC) METHODS

716.01 Description. This work shall consist of installing utility systems (i.e., electric power, communications, water, gas, oil, petroleum products, steam, sewage, drainage, irrigation, and similar facilities) utilizing trenchless excavation construction (TEC) methods. These methods include :

I. Horizontal Earth Boring (HEB)	II. Pipe Jacking (PJ)	III. Utility Tunneling (UT)

HEB produces a borehole without the necessity of workers being inside the borehole. These methods include:

(1) Auger HEB - a process that simultaneously forces the casing through the earth while removing the spoil inside the encasement by means of a continuous rotating flight auger. An auger is a flighted drive tube having couplings at each end that transmits torque to the cutting head from the power source located in the bore pit.

(2) Compaction HEB - a process that produces the borehole by compressing the earth immediately surrounding the compacting device.

(3) Slurry HEB - a process that utilizes a drilling fluid (i.e., a bentonite slurry, water, or air) which is transmitted to the drill bit through a hollow drill tubing to facilitate spoil removal and drill bit cleaning.

(4) Water Jetting HEB - a process that utilizes water pressure and flow rate to create a jetting action which places the soil in a quick (liquid) condition to wash/erode the borehole.

(5) Pipe Ramming - a process that utilizes the percussion (impact) tool as a driving hammer to force direct pipe burial.

(6) Directional Drilling HEB - a process that utilizes a specially built drill rig that thrusts the drill stem through the ground while bentonite drill mud operates a down hole motor, functions

as a coolant, and facilitates spoil removal by washing the cuttings to the surface to settle out in a retention pit. The path of the borehole is monitored by a down hole survey system which provides data on inclination, orientation, and azimuth of the leading end. Direction is controlled by a bent housing used to create a steering bias.

(7) SoftBor HEB - a proprietary process characterized as a low flow (1 to 2 GPM) and high pressure (1,000 to 4,000 PSI) soil cutting system. A computerized electronic control system provides steering commands, and remote steering is accomplished through directing the cutting jets at the nose of the tool.

(8) Micro-tunneling HEB - a process characterized as highly sophisticated, laser guided, remote controlled system providing the capability of continuous accurate monitoring and control of the alignment and grade.

PJ is differentiated from HEB by requiring the necessity of workers being inside the pipe during the excavation and/or spoil removal process. Prefabricated concrete, steel, or fiberglass pipe may be utilized as the jacking pipe. The excavation process varies from manual to highly sophisticated tunneling boring machines (TBM).

UT is differentiated from the major tunneling industry by virtue of their size and use (i.e., conduits for utilities rather than as passageways for pedestrian and/or vehicular traffic. Further, while the excavation methods for UT and PJ may be identical, the differentiation is in the lining systems with the most popular being steel tunnel liner plates (TLP), steel ribs with wood lagging (SRw/WL), and wood box tunneling (WBT).

Due to the wide range of possibilities concerning job site conditions, economics, and future technological improvements; judgment and flexibility must be employed by all parties to the maximum extent possible. However, strict adherence shall be required unless the installer can substantiate to the satisfaction of the ENGINEER their reason for requesting a variance and that the proposed material, equipment, and methods are superior to those contained herein.

These guidelines and specifications acknowledge that TEC "is more art than an exact science" and that the ultimate success or failure of the installation depends, to a great extent, on the experience and skill of the installer. The intent of these specifications is not to restrict the use of any method, material, equipment, etc., unjustifiably; but, to the maximum extent possible, provide for the safe operation, maintenance, and appearance of the surface

facilities. Therefore, it is necessary that such procedures be reasonably regulated and to provide sufficient detail to insure uniform application and enforcement. Further, these specifications recognize that each TEC drive is uniquely different with its own controlling parameters. It is impractical to establish one set of requirements that apply, in full, to all conditions. A 4-inch bore under a 2-lane rural road should not be required to meet the same regulatory criteria as a 36-inch bore under an interstate highway in an urbanized setting. However, it is just as impractical to attempt to develop specific requirements for every possible project. Therefore, all drives will be categorized into one of three types of conditions. These conditions are : primary, secondary, and tertiary.

Primary Conditions apply to all TEC projects where the nominal diameter of the encasement is greater than 8-inches, and/or the length is greater than 100-LF. It applies to all drives under limited access highway facilities or other sensitive structures. It applies to all crossings with known or anticipated high ground water or other unstable conditions. For example, this condition applies to bores under a multilane facility in an urbanized curb and gutter section where the possibility of failure due to unknown subsurface problems require that maximum effort be extended for the

purpose of classifying the soils, determining soil properties, and predicting soil behavior.

Secondary Conditions apply to all TEC projects where the nominal diameter of the casing is greater than 4-inches but equal to or less than 8-inches, and/or the length is greater than 40-LF but equal to or less than 100-LF.

Tertiary Conditions apply to all TEC projects where the nominal diameter of the casing is equal to or less than 4-inches, and/or the length is equal to or less than 40-LF.

MATERIALS

5.2 716.02 Materials. Materials shall meet the requirements specified in the following subsections of 900.

Steel Pipe	907.10
Reinforced Concrete Pipe	906.02
Plastic Pipe	Not assigned
Steel Tunnel Liner Plates	Not assigned
Steel Ribs with Wood Lagging	Not assigned
Fiberglass FRP Pipe	Not assigned

CONSTRUCTION REQUIREMENTS

5.3 716.03 General Requirements. The following infor-

mation shall be submitted to the ENGINEER for approval. No work shall proceed until such approval is obtained.

- (1) A site location map identifying project location.
- (2) A plan detail of the proposed work area.
- (3) Identification of the exact project location.
- (4) Right-of-way limits and conditions identified.
- (5) Topography including driveways, buildings, etc.
- (6) Existing surface drainage.
- (7) Existing utilities.
- (8) Significant vegetation that will be affected.
- (9) The specific location of the TEC operation.
- (10) Profile of the proposed facility.
- (11) Location and details of access pits.
- (12) Plan location and log of point borings.
- (13) Soil information (subsurface investigation).

In general, the greatest influences on the success or failure of TEC operations are the existing subsurface soil and water conditions. Thus, the most important information on the plans and specifications is the soil boring data. Subsurface information is essential for proper design, construction planning and cost determination. This information will alert the engineer, regulatory agency, and contractor of the need for a dewatering system. It is necessary for selection of a proper cutting head, the proper position of the cutting head within the casing, probability and nature

of obstruction, and changes in soil conditions. Therefore, prior to beginning work on any TEC projects, a subsurface investigation report must be obtained that describes the conditions existing at the boring pits and along the path of the proposed crossing. The purpose of such a report is to insure that subsurface conditions are known and the proposed construction strategy is compatible with these conditions. This will provide the installer with a higher degree of confidence in his construction strategy; thus, reducing risk and providing a sound basis for developing the construction cost. This will reduce the number and costs associated with claims for changed conditions.

TEC for "primary conditions" require the highest level of subsurface information to be required. In order to determine the general subsurface conditions, soil test boring will be required at each access pit and along the path of the proposed TEC project. The number and depth of borings required should be determined by a qualified geotechnical engineer and consistent with site conditions and the design characteristics of the specific project. However, as a guideline, it is recommended that a minimum of 3-soil borings be taken for "primary conditions," 2-soil borings for "secondary conditions," and 1-soil boring for tertiary conditions." Additional soil borings will be required for conditions

which indicate variations in terrain features and subsurface conditions. Typical conditions are when the lines are required to be deep, there is evidence of high ground water table, or rock formations. Corings through paved areas shall be accomplished by qualified persons with appropriate equipment and the test holes are to be refilled and patched at the end of each day's operation. Corings through paved areas should only be accomplished when the information is necessary to develop an accurate profile of the subsurface conditions. It would be unnecessary in areas known to have no significant variation.

All soil borings for the "primary conditions," should permit split-spoon samples to be taken at 2.5 to 5.0-foot intervals by the standard penetration test procedure (ASTM D-1586) which is essential to obtaining reliable soil descriptions of the materials encountered. Representative portions of the samples shall be preserved in vapor proof, clear containers, and returned to the laboratory for inspection and testing. The samples shall be made available for inspection by contractors interested in bidding on the TEC project. For "secondary conditions," test holes can be dug with a backhoe or other construction excavation equipment and the soil classified into broader, general classifications by engineers knowledgeable concerning

soil conditions but not necessarily geotechnical engineers. For "tertiary conditions," soil tests can be made by post hole diggers or hand augers in order to develop a general classification.

All soil borings for "primary conditions" shall be taken to at least 5-feet below the bottom of the pits or the bottom of the proposed line. This information is particularly important for the bore pit design. It indicates to the designer what level of construction effort will be required to stabilize the pit floor to support the TEC equipment. Should unstable conditions or water bearing pockets of pervious soils be encountered, then the soil boring depth should be extended to provide the dewatering system designer with sufficient information to specify depth and spacing of deep wells or well pointing system.

For "primary conditions," when in the opinion of the geotechnical engineer there is sufficient evidence to expect dewatering will be required, then a minimum of three observation wells (piezometers) are to be installed with one at each pit and one in the middle. Thus, water table elevation can be determined at the time of construction as well as the time of the subsurface investigation. In addition, this provides a positive means of insuring that the water table has been adequately lowered prior to beginning the TEC project.

Normally, the piezometers will consist of a perforated plastic or metal pipe extending below the anticipated low ground water level or at least 3-feet below the bottom of the pits or line. The bottom of the piezometer pipe should be capped, and adequate measures taken to prevent the perforations from becoming plugged such as the placement of filter media (sand) around the perforations. The observation wells are to be capped at the top with a removable cap so that ground water readings can be made prior and during construction. This information is an important aspect of the subsurface investigation. Saturated soil conditions along the path of a proposed crossing dictate TEC procedures quite different from that of a crossing through dry materials. Every effort should be made to secure accurate and complete water information.

For "primary conditions," the laboratory testing program should be sufficient to determine the classification, strength, and permeability characteristics of the soils. Normally, this will consist of natural moisture and density determination, sieve and hydrometer analysis, "N" values from the standard penetration test, and the unconfined shear strength tests. In addition, loss on ignition tests should be performed on soils of high organic content, and triaxial shear strength and/or compressibility characteristics

may be required. Based on the results of the field and laboratory investigations, an analysis and recommendations should be made by the soils consultant on such things as potential seepage, dewatering, and stability problems, poor base soils, and the design of bracing and retaining systems.

Every effort should be made to provide not only soil information important for design, but also for TEC. The TEC contractor should be able to interpret the data and relate it to the degree of difficulty. Therefore, the report should contain the data separated into broad categories that have a direct and clear bearing on construction strategy. The following classifications are considered standard in the industry [2] and are used by most equipment manufacturers :

(1) Dry Stable Sand	(6) Dry Unstable Sand
(2) Wet Stable Sand	(7) Wet Unstable Sand
(3) Sugarsand	(8) Wet Stable Clay
(4) Wet Unstable Clay	(9) Dry Stable Clay
(5) Boulders	(10) Fill Materials

For "secondary and tertiary conditions," only the broad soil classifications are necessary. Any wet and/or unstable conditions encountered will require that the TEC project be reclassified as "primary conditions." Any soils not falling clearly into one of the above categories should be described in sufficient detail to

indicate its behavior and possible influence on the construction procedure. Also, if subsurface conditions are known by the designer, as a result of previous work in the immediate area, then the information can be recorded in the subsurface investigation report without additional physical testing.

These requirements are not intended to place undue hardships on any particular party. They are considered to be generally accepted engineering design practice to insure that the design, construction methods, materials, and equipment selected are compatible with the existing conditions.

5.4 716.04 Ground Water Control. If the ground water level is above the invert of the proposed casing or the floor level of the jacking pit, some means of reducing the water level must be designed, installed, and in operation prior to beginning the TEC project. The system shall be compatible with the properties, characteristics, and behavior of the soils as indicated by the soils investigation report. For example, dewatering may not be required in an area where the soil involved has a very high clay content and exhibits stable cohesive characteristics even when saturated. However, particularly for TEC projects, properly operating dewatering systems cannot be over-emphasized.

Ground water may be controlled from sumps constructed inside the excavated areas (pits) when the water entering the pit is from seepage layers/lenses or from pockets of saturated materials which are of a routine and minor nature such that it can be removed effectively without removing any adjacent soil which could weaken or undermine structures or supports for structures. Submittal data submitted by the installer should indicate the proposed method of ground water control. All methods should provide for a sump in the boring/jacking pit. The proposed plan should indicate the sump location, pump type and size, sump design (for example, 2' * 2' * 1' deep, with a gravel filter); and point of discharge, route, and destination.

Should the common and elementary methods of ground water control be inadequate to control large volumes of ground water from entering the pits, then methods shall be utilized to lower the ground water table prior to beginning the TEC project. These methods consist of well points, deep wells, or grouting.

Well point systems shall be properly designed by individuals or firms experienced in this specialty. Submittal data shall include information on the pump, header line, swing joints, risers, well points, filter media, installation method (jetting or driving); and route and point of discharge. The pump shall be of

adequate size and capacity to dewater the TEC project area. The header line connects the pump to the system of swing joints, risers, and well points. It shall be in proper operating condition and sufficient size to pass anticipated flows. Swing joints connect the riser pipes to the header line. Swing joints shall have a workable control valve for regulating air intrusion (tuning) into the system. Riser pipes connect the points to the swing joints. The well points connect to the riser pipe, and the perforations are designed to draw water from the surrounding area without allowing the intrusion of soil.

Deep wells consist of perforated casings that are placed by drilling or augering a vertical hole, and then placing the casing. The perforations are sized to prevent the intrusion of soil materials from adjacent areas. A filter media, such as sand or pea gravel, may be required on the outside of the casing. The diameter of the casing is a function of the ground water flow rate, the larger the diameter then the greater the casing surface which provides the perforations for passage to the pump. The pumping system consists, generally, of electrically operated submersible pumps. These pumps shall be of the size and capacity to pass the anticipated flows. Submittal data shall indicate the pump size and capacity, discharge line size, and discharge point and route.

Grouting can be used to control ground water and stabilize subsurface conditions. The grouting operations shall be accomplished in a proper and predetermined sequence such as to stabilize the area affected by the TEC project. Grouts may be of the cementitious and/or chemical solution types depending on the material to be grouted.

5.5 716.05 Access Pits/shafts. The location of pits should be selected for each particular TEC project based on actual job site conditions. As a general rule, the minimum distance from the edge of pavement to the face of the pit should be 30-feet for "primary conditions," 20-feet for "secondary conditions," and 10-feet for "tertiary conditions." This determination should be made by experienced designers utilizing generally accepted engineering judgment considering the degree of hazards associated with the location. Public safety should be of primary concern. Therefore, in most congested "primary conditions," such as a TEC project for a heavily traveled freeway, it is recommended that the TEC project extend from right-of-way limits to right-of-way limits. When the minimum clearance is not possible to maintain and the ENGINEER determines that hazards exist, then temporary concrete barriers or temporary beam guard rails shall be installed to protect vehicular traffic.

All access pits and open excavation shall be protected with suitable fencing and/or barricades to prohibit access to the work site. Equipment shall not be used in lieu of fencing to protect access pits. A stairway or ladder shall be provided from the ground surface to the bottom of the pit in accordance with OSHA guidelines and regulation. This ladder shall be properly secured at the top and bottom at all times.

All access pits and shafts shall conform with applicable OSHA excavation, trenching, and shoring standards which are contained in the Code of Federal Regulations 29 (C.F.R.) 1926.650 - 1926.653. Banks more than 5-feet high shall be shored, laid back to a stable slope, or some other equivalent means of protection provided where employees may be exposed to moving ground or cave-ins. Sloping of pit walls is an accepted method provided the slope does not exceed the angle of repose. The angle of repose is defined as the greatest angle above the horizontal plane at which a material will lie without sliding.

All excavation support systems shall be planned and designed by a qualified designer when the excavation is in excess of 5-feet in depth, adjacent to structures, subject to vibration, or ground water conditions. This design shall fully consider such factors as depth of cut; possible variation in water content of the material

while the excavation is open; anticipated changes in materials from exposure to air, sun, water, or freezing; loadings imposed by structures, equipment, overlying material, or stored material; vibration from equipment, blasting, traffic or other sources.

All materials used for sheeting, sheetpiling, cribbing, bracing, shoring, and underpinning shall be in good serviceable condition. Timber shall be sound, free from large or loose knots, and of proper dimensions. Braces and diagonal shores in a wood shoring system shall not be subject to compressive stress in excess of values given by :

$$S = 13 - 20(L/D)$$

Where : $L/D = 50$ Maximum

L = Length, unsupported, in inches.

D = Least side of the timber in inches.

S = Allowable stress in PSI of cross-section.

All bracing and shoring shall be installed with the excavation. Portable trench boxes or sliding trench shields may be used for protection of personnel in lieu of a shoring system or sloping; however, they must be designed, constructed, and maintained in a manner which will provide equal protection.

The required size of the pit will be a function of the type of equipment and materials to be used for the TEC project. Proper planning should allow enough room for a safe working environment.

CONSTRUCTION METHODS

5.6 716.06 Horizontal Earth Boring. HEB include methods defined in 716.01. This specification will be limited to describing the conditions under which each technique can be utilized. These conditions will be subdivided into "primary," "secondary," and tertiary" as previously described. These specifications recognize that there are examples where each of these methods have been used successfully for the primary conditions; however, the intent is to provide a more uniform basis for contractors to develop costs on methods that provide the highest reasonable probability of success; and to reduce the tendency for high risk methods being attempted at the expense of public safety.

Track Type Auger Bore Method

This method is approved for each condition with certain limitations. For all "primary conditions," the contractor must submit to the ENGINEER sufficient information establishing his proposed strategy for :

- (1) Providing a positive indication of where the leading edge of the casing is located with respect to line and grade. This indication shall be provided with a water gauge (Dutch level), electronic transmitting and receiving devices, or other approved methods. The contractor shall indicate the intervals for

checking line and grade; and a record shall be maintained at the jobsite.

- (2) Providing all necessary equipment of adequate size and capability to install the TEC project. This shall include equipment manufacturer's information for all power equipment used in the boring operation.
- (3) Providing a means for controlling line and grade.
- (4) Providing a means for controlling overcut to a minimum with the maximum being limited to a 1-inch space around the circumference of the casing pipe.
- (5) Providing a positive means for centering the cutting head inside the borehole. This can be accomplished with a movable steering head or bars welded into the leading end of the casing.
- (6) Providing a positive means for preventing the rear of the cutting head from advancing in front of the leading edge of the casing by more than a maximum of $1/3$ times the casing diameter in stable cohesive conditions with a maximum of 8-inches. In unstable conditions, such as granular, loose, etc. materials the cutting head shall be retracted into the casing a distance that permits a balance between pushing pressure and the ratio of pipe advancement to quality of

soil to assure no voiding is taking place; and the face of the cutting head shall be arranged to provide reasonable obstruction to the free flow of soft or porous material.

- (7) Providing adequate casing lubrication with a bentonite slurry or other approved technique.
- (8) Providing an adequate band around the leading edge of the casing to provide extra strength, and in loose, unstable materials, when the cutting head has been retracted into the casing, it reduces skin friction as well as provides a method for the slurry lubricant to coat the outside skin of the casing.
- (9) Providing at least 20-feet of full diameter auger at the leading end of the casing. The auger size may be reduced, but the reduced auger diameter must be at least 75% of the full auger diameter. For example, if a 42-inch casing is being installed, then at least 20-LF of 42-inch diameter auger should be used at the leading end of the casing. After the first 20-LF, a smaller diameter auger can be used; but it should never be less than $(\text{auger diameter} * 0.75)$.
- (10) Providing water to be injected inside the casing to facilitate spoil removal. The point of injection shall not be within 2-feet of the leading edge of the casing.

All of the above options are required for "primary conditions" unless the ENGINEER has agreed in writing that they are not necessary. While these options may not be required for "secondary or tertiary conditions," their use is highly recommended. The intent is to provide to the maximum extent possible every means for preventing problems that may delay the TEC project and/or endanger public safety. The additional cost associated with these options is justifiable. For "secondary and tertiary conditions," the contractor is responsible for submitting to the ENGINEER sufficient information indicating his proposed strategy for providing compatible materials and equipment.

Cradle Type Auger Bore Method

This method is only approved for use on "secondary and tertiary conditions" unless specifically approved in writing by the ENGINEER or it can be substantiated that the proposed method can comply with all of the requirements and capability as established for primary conditions for the Track Type Auger Bore Method. The contractor is responsible for submitting to the ENGINEER sufficient information indicating that his proposed materials, equipment, and method are compatible with the anticipated conditions.

Compaction methods

Compaction methods include the push rod, rotary,

and percussion (impact) techniques. Unless specifically approved otherwise in writing by the ENGINEER, these methods are only approved for use for the "teritary conditions." It is the responsibility of the contractor to submit to the ENGINEER sufficient information indicating that his proposed materials, equipment, and method are compatible with the anticipated conditions.

When effective sensing and guiding systems are utilized with any of the compaction methods, then they may be used for "secondary conditions;" however, the maximum size shall be limited to 4-inch.

Slurry Method

The slurry method shall be limited to tertiary conditions unless specifically approved by the ENGINEER in writing. It is the responsibility of the contractor to submit to the ENGINEER sufficient information indicating that his materials, equipment, and method are compatible with the anticipated subsurface conditions. The slurry shall be of a bentonite mixture unless the anticipated conditions are a stiff clay of uniform consistency. The slurry pressure and flowrate shall be monitored and controlled to prevent an erosion of the face. All cutting must be mechanical with an appropriate cutting bit, and not with any jetting action of the slurry. The borehole may be reamed or expanded to a maximum of 6 - inches in diameter.

The annular space between the borehole and casing shall be filled with grout installed under pressure.

Water Jetting

This method is not approved for any conditions under any circumstances.

Pipe Ramming

This method is approved for "secondary and tertiary conditions" only. The closed end method can be utilized for sizes up to 4-inches in diameter in compressible soils; however, the open-end method shall be used for all sizes greater than 4-inches. The leading edge of the casing shall have a minimum 6-inch wide band welded to the outer skin of the casing to provide additional strength and aid in reducing skin friction. Water may be injected into the casing to facilitate in spoil removal; however, the water may not be injected within 2-feet of the leading edge of the casing. When pipe ramming is used for secondary conditions, a bentonite slurry shall be used to lubricate the outside skin of the casing for casings greater than 6-inches in diameter. It is the responsibility of the contractor to provide the ENGINEER with sufficient information indicating that his materials, equipment, and method are compatible with the anticipated conditions.

Directional Drilling

Directional drilling is approved for use for all "primary conditions." The contractor shall furnish the ENGINEER complete geological data, in addition to the soil investigation report, which substantiates that the cutting bit will be at a depth and in such soil formations that the washing action from the bentonite slurry (driller's mud) circulation system and mud migration will not be a hazard. The contractor must demonstrate that the void space between the casing O.D. and the borehole will be sufficiently stabilized. It is the contractor's responsibility to submit to the ENGINEER sufficient information indicating that his materials, equipment, and methods are compatible with anticipated conditions.

Flow Jet

Approved for use on "secondary and tertiary conditions" only. The Flowmole system may be used for primary conditions when specifically approved in writing by the ENGINEER for each location.

Micro-Tunneling

Approved for "primary conditions." It is the responsibility of the contractor to submit to sufficient information indicating that material, equipment, and methods are compatible with the anticipated conditions.

5.7 716.07 Pipe Jacking. Each pipe section shall be jacked as the excavation progresses in such a way which leaves no length of excavated tunnel exposed at any time. Excavation may be manual or mechanical; however, it shall be controlled so that over-excavation does not result in a void between pipe O.D. and the ground of more than 1-inch. Any excavation which may exceed this limit or may result from removal of boulders or other obstructions shall be pressure grouted. The pipe shall be jacked in place without damaging the pipe joint or the barrel.

A bentonite slurry (driller's mud) may be applied to the external surface of the pipe to reduce skin friction.

A jacking frame shall be provided for developing a uniform distribution of the jacking forces around the periphery of the joint to protect the joint bell. Special care must be taken by all parties to insure that the thrust reaction backstop is constructed in such a manner that it is normal (square) with the pipe to be jacked; and special care should be taken when setting the pipe guide rails in the pit to insure the correctness of the alignment, grade, and stability.

All excavation shall be accomplished within an approved steel tunneling shield or other approved methods to protect the pipe and provide independent

steering capability. All proposed systems shall be laser guided utilizing a self-leveling laser with special care shall be taken to prevent "over-steering." Therefore, alignment and grade shall be checked at intervals not to exceed 3-feet.

5.8 716.08 Utility Tunneling. The lining and bracing of the tunnel bore shall be carried on concurrently with the excavation operations. The lining system shall be considered temporary construction; and the lining system shall be steel tunnel liner plates, steel ribs with wood lagging, steel ribs with steel lagging, or wood box tunnel. After the installation of the lining system, the contractor shall completely fill with grout all void spaces between the outside of the tunnel lining system and the surrounding soil. The grouting operation shall follow the excavation and lining operation as soon as practicable. The grouting pressure shall be such that it will not result in a distortion of the lining system. Grouting shall be kept as close to the heading as possible. All excavation shall be conducted from within a tunnel shield or other protective support that provides independent steering capability and vertical face support to prevent sloughing. The erection of the tunnel lining system shall be accomplished in the tail section of the shield or a tunnel boring machine.

When rib and lagging are utilized, it shall immediately be expanded outward and upward to produce continuous contact with the surrounding earth when emerging from the tail section. After rib expansion, the rib joints shall be so designed and constructed so that full surface bearing is provided across the joint. The lagging shall be installed so as to develop a tight enclosure inside the excavated area.

5.9 716.09 Ventilation. Adequate ventilation shall be provided for all bore/tunnel pits and shafts and all horizontal bores and tunnels in which men must enter. Design of the ventilating system shall include such factors as the volume required to furnish fresh air for the workers, the volume to remove obnoxious and dangerous gases and fumes, and the volume to remove dust that may be caused by the cutting of the face and other operations. The minimum amount of fresh air that should be supplied shall be 200-CFM. Air testing shall be as required for the specific conditions to insure that the gas concentrations are:

Carbon Monoxide	$\leq 0.005\%$
Methane	$\leq 0.25\%$ (5% of explosive limit)
Hydrogen sulphide	$\leq 0.001\%$
Oxygen	$\geq 20.0\%$

Ventilating pipes shall be of appropriate size,

well-supported, strong, and tight. Air quality, air quantity air monitoring, and ventilation in tunnel and shaft construction shall comply with Subpart S of the Construction Industry Occupational Safety and Health Administration (OSHA) Standards (29 CFR 1926/1910) as published in the U.S. Department of Labor publications OSHA 2207, 1985.

5.10 716.10 Lighting. Adequate lighting shall be provided for the nature of the activity being conducted by workers inside the tunnel or pipe jacking project. Power and lighting circuits shall be separated and thoroughly insulated. The lighting voltage shall not exceed 115. All lights shall be placed in porcelain light fixtures in vapor tight enclosures and metal guards.

5.11 716.11 Grouting. Grouting shall consist of a cement, fine sand, and water mixture. The proportion of sand to cement ratio shall not exceed 5:1. The volume of water shall be as required to produce a flowable, pumpable consistency. It is the responsibility of the contractor to submit to the ENGINEER sufficient information indicating that the grouting will be accomplished with suitable heavy duty grouting equipment and pump capable of forcing the mix through the grout holes of the casing/liner system into all voids that are to be

filled. Grout may contain super plasticizers, fly ash, lightweight cellular concrete, etc.

5.12 716.12 Casing/Carrier Void Filler. After the installation of the carrier pipe, the remaining space between the casing and the carrier shall be filled with a grout as described in Section 716.11, or an approved granular material. It is the responsibility of the contractor to submit to the ENGINEER sufficient information indicating all proposed equipment, materials, and method for filling this void.

5.13 716.13 Bulkheads. The upstream annular opening between the casing and carrier shall be sealed with brick and mortar, and the downstream annular opening shall be sealed with brick without mortar.

5.14 716.14 Obstructions / Changed Conditions. If an obstruction that stops the forward progress of the project is encountered, the cause of the stoppage shall be determined. When the cause has been identified, the installation method shall be so modified to best suit the actual conditions encountered. If the obstruction is classified as an unforeseen or changed condition, then extra cost involved due to the modified installation method shall be paid on a time and material basis; and

the ENGINEER shall notify the contractor of any design modifications. Should the stoppage be a result of the contractors equipment, materials, and/or method then all extra cost will be at the contractor's expense. However, in either case, before proceeding, the contractor shall notify the ENGINEER, in writing, of any proposed modification.

5.15 716.15 Abandonment. In the event a line cannot be completed and it must be abandoned in-place, then the casing must remain in-place and be filled with grout.

5.16 716.16 Measurement. All TEC projects shall be measured for payment based on the actual installed measurement from end of casing to end of casing along the centerline.

5.17 716.17 Payment. All TEC projects shall be paid for based on the unit price bid. This unit price bid amount shall be payment in-full for any and all work associated with the complete installation of the project including all necessary excavation, backfilling, jacking, grouting, filling, installation of the carrier pipe, bulk heads, vents, etc.

5.18 Materials

907.10 Steel casing pipe

For "primary and secondary" conditions, only new, smooth wall carbon steel pipe will be accepted. This pipe shall conform with ASTM A139, Grade B (No Hydro). No hydrostatic testing will be required for casing pipe. Used pipe may be accepted for tertiary conditions provided the supplier certifies the pipe complies with all physical requirements of ASTM A139, Grade B; and it has a smooth outside wall surface. Steel casing pipe shall have a minimum yield strength of 35,000-psi.

The size of the steel casing should be at least 6-inches larger than the largest outside diameter of the carrier pipe. However, soil conditions should also be considered. The soil investigation phase should indicate the possibility of boulders and other obstructions. The casing size should be at least three times greater than the largest boulder anticipated. The following indicates maximum bore length for various casing diameters.

<u>Pipe Size</u> (inch)	<u>Maximum Length</u> (feet)
6	40
8 - 10	80
12 - 14	100
16 - 18	120

While straight seam pipe or seamless pipe are highly recommended, spiral weld pipe may be used

provided the welds for the spiral are 100% welded, and the welds height over the outside wall surface is to be equal to or less than 3/16-inch. All steel pipe is to be bare inside and out, with the following minimum nominal wall thicknesses (MNWT):

Pipe Size Nom. Dia. (inch)	RR-XINGS MNWT	HWY-XINGS MNWT	RR or HWY XING MNWT
	<200 LF (inch)	<200 LF (inch)	>200 LF (inch)
6 - 12	0.250	0.250	0.375
14 - 16	0.281	0.250	0.375
18	0.312	0.250	0.375
20	0.344	0.312	0.375
24	0.406	0.312	0.406
30	0.469	0.375	0.469
36	0.532	0.500	0.532
42	0.563	0.500	0.563
48	0.625	0.625	0.625
54	0.688	0.625	0.688
60	0.750	0.625	0.750
66	0.813	0.625	0.813
72	0.875	0.750	0.875

All steel casing pipe shall be square cut and have dead even lengths which are compatible with the auger lengths when used with the auger boring method, and shall comply with the Article 4.2, 4.3, and 4.4 of Section 4 of the American Petroleum Institute (API) specification for steel pipe.

API 4.2 Roundness. The difference between the major and minor outside diameters shall not exceed 1% of the specified nominal outside diameter or 0.25 inch whichever is less.

API 4.3 Circumference. The outside circumference shall be within $\pm 1\%$ of the nominal circumference or within ± 0.50 inch, whichever is less.

API 4.4 Straightness. The maximum allowable straightness deviation in any 10 foot length shall be 1/8 inch. For lengths over 10 feet, the maximum deviation of the entire length may be computed by the following formula, but not to exceed 3/8 inch in any 40 foot length.

$$1/8 \times \text{total length, feet} / 10 = \text{Maximum Deviation}$$

906.02 Reinforced Concrete Pipe (RCP)

These specifications are for RCP when being installed by the pipe jacking method. The pipe shall conform with ASTM specification C-76 and ASTM C-361. In addition, the pipe shall meet the following minimum requirements:

- (1) 5,000-psi concrete compressive strength.
- (2) Class III, IV, or V as required by load calculations and shall have a C - wall.
- (3) Full circular inner and/or outer reinforcing cage.
- (4) Multiple layers of steel reinforcing cages, wire splices, laps, spacers shall be permanently secured together by welding in place.
- (5) Straight outside pipe wall, no bell modification.
- (6) No elliptical reinforcing steel allowed.
- (7) Single cage reinforcement shall have a 1-inch minimum cover from the inside wall.
- (8) Double cage reinforcement shall have a 1-inch minimum cover from each wall.

- (9) Joints may be of the non - gasketed, or gasketed type. A non-gasketed joint shall have no more than a 7-degree taper. Gasketed joints shall have approximately a 2-degree taper, and the gasket shall conform to ASTM C-443 or C-361. A joint utilizing a steel ring cast into the outside surface of the joint together with a gasket has been successful.
- (10) Additional joint reinforcement shall be installed and shall extend as deep as possible into the bell and spigot without destroying the continuity of the joint concrete. This additional reinforcement shall be furnished as stirrups of proper amplitude, applied circumferentially in the bell and spigot, welded to each other perpendicularly; or for singular cages, an 18-inch wrap can be welded in both bell and spigot; or in double cage design, an 18-inch wrap, consisting of the inner cage area, should be welded to the inside of the outside cage on the bell and an 18-inch wrap, consisting of the inside steel area, welded to the outside of the inside cage on the spigot.
- (11) All fine and coarse aggregate used in the manufacturing process shall be free from contamination as per ASTM C-33. When available, the coarse aggregate should be of the fractured type. The mix design should contain 700-lbs. of cement per CY;

and nonchloride type additives and accelerators for strength and chemical resistance shall be permitted.

- (12) Jacking pipe shall be yard cured for a minimum of 10-days. Steam curing is preferred, but other types of curing, such as water misting in combination with very warm temperatures, shall be allowed.
- (13) The tolerances for jacking pipe shall include : The inside diameter shall not vary from the design diameter by more than $3/8$ -inch; the wall thickness shall not vary from that specified by more than $3/16$ -inch; variation in laying length of two opposite sides of the pipe shall not be more than $1/8$ -inch per LF for all sizes larger than 24-inch with a maximum of $3/8$ -inch for pipe through 84-inch and a maximum of $1/2$ -inch for pipe 90-inch in diameter and larger.
- (14) 1.5-inch diameter tapped grout holes are to be provided at the 2, 4, 8, and 10 o'clock positions. The frequency of pipe sections with grout holes vary from every other pipe to every tenth pipe depending on soil conditions, height of cover, and length of jacking run. The tapped grout fittings should extend from the inside surface to the outside surface.

Plastic Pipe

Plastic pipe may be installed as a casing material or as an uncased carrier by certain TEC methods. However, closed end jacking or open end jacking without an auger for continuous cleanout of the bore as the jacking progresses, will not be allowed. Plastic pipe must meet or exceed the following strength and composition standards :

PVC (Polyvinyl-Chloride)	ASTM D 1785
PE (Polyethylene)	ASTM D 2447
PE (Polyethylene) gas pipes > 3.5"	ASTM D 2513
PB (Polybutylene)	ASTM D 2662
CAB (Cellulose Acetate Butyrate)	ASTM D 1503
ABS (Acrylonitrile-Butadiene-Styrene)	ASTM D 1527
RTRP (Reinforced Thermosetting Resin)	ASTM D 2996

An air pressure test for leaks shall be conducted immediately upon completion of each crossing at a minimum test pressure of 20-psi. The following two test methods are acceptable.

- (1) Standard 24-hr. pressure test with recording chart.
- (2) Test utilizing a dragnet type leak detecting device, or other equivalent testing equipment capable of detecting pressure drops of 0.5-psi. The test length should be as specified by the testing equipment manufacturer for the conditions of the project.

Leaking plastic pipes that cannot be repaired satisfactorily to meet the pressure test requirements are to filled with concrete by pressure grouting, or other approved methods; and abandoned in place.

Plastic pipe couplings and joints shall meet or exceed all applicable ASTM strength and composition

standards for the particular type pipe being used. The coupling thickness shall be such that the overall casing diameter is increased by no more than 3/4-inch total. All couplings and joints shall be leakproof. Joints shall be made sufficiently strong to withstand the stresses of jacking, with joints completely set and cured prior to placement of the pipe.

Steel Tunnel Liner Plates (TLP)

TLP shall be of the 2-flange or 4-flange type using either the flanged or lapped seam type. TLP shall be cold formed steel plates fabricated from hot rolled, carbon steel sheets or plates conforming to ASTM specification A-569. The minimum mechanical properties of the flat plate and sheets before cold forming shall be :

Tensile Strength	42,000-psi
Yield Strength	28,000-psi
Elongation in 2-inches	30-%
Plate Thickness	10-Gauge

All liner plates shall be punched for bolting on both the longitudinal and circumferential seams, and the joints shall be fabricated so as to permit complete erection from inside the tunnel. Nuts and bolts shall be quick acting coarse thread and shall conform to ASTM specification A-307, Grade A. The size, number, and location of the bolts shall be sufficient to provide the required joint strength.

TLP shall be designed for each particular application to provide strength commensurate with the tunnel diameter and depth of cover. The deflection of the tunnel lining shall not exceed 3-percent, and the following minimum safety factors shall be utilized:

Seam Strength	3.0
Buckling	2.0
Stiffness	2.0

TLP with 2-inch diameter grouting connections and plugs shall be furnished in sufficient quantity to provide connections as follows:

<u>TUNNEL DIAMETER</u>	<u>MINIMUM GROUT CONNECTIONS</u>
< 5-feet	2 every third ring
5.5-ft. - 9.0-ft.	3 every third ring
9.5-ft. - 12.0-ft.	4 every third ring
> 12-feet	5 every third ring

The location of the holes shall be spaced around the periphery of the tunnel liner plates to suite field conditions which will permit the proper grouting sequence so as to insure complete filling of voids outside the tunnel liner plates.

Reinforcing H - beam ribs shall be furnished with webs punched for bolting, including the flange plates at the joints; and installed between the rings of plates where the strength of the plates alone is not adequate to meet the required section modulus in order to safely carry all loads applied to the tunnel liners.

Steel Ribs With Wood Lagging

The fabrication and erection of ribs and other tunnel supports shall conform to applicable parts of the "Specifications for the Design, Fabrication and Erection of Structural Steel for Buildings", and the "Code of Standard Practice for Steel Buildings and Bridges", both of which are published by the American Institute of Steel Construction. The ribs sections shall be designed and manufactured to fit closely for bolted butt plate connections at the rib joints. The bolted connections shall be capable of developing the full strength of the ribs. Rib spacing shall be a function of the loads and soil conditions, but shall not exceed 4-feet. Steel ribs, beams, channels, plates, shapes, and bars shall conform to the requirements of ASTM A36; and the bolts shall conform to the requirements of ASTM A325. Prior to bending, the steel ribs shall conform to the tolerances allowed by ASTM A6. The steel ribs shall be H-beams with a minimum size of 4-inches and a minimum weight of 10-lbs. per LF.

Wood lagging shall be classified as a hardwood with a minimum allowable bending stress (F_b) equal to 1,800-psi; and a minimum dimension of 3-inches.

Fiberglass FRP Pipes

All pipe shall be centrifugally cast fiberglass reinforced polyester resin manufactured in accordance

with the requirements of ASTM D 3262-87 which is "Standard Specification for 'Fiberglass' (Glass-Fiber-Reinforced Thermosetting - Resin) Sewer Pipe". The reinforcing glass fibers shall be E-glass filaments with binder and sizing compatible with resins. Sand shall be minimum 98% silica with a maximum moisture content of 0.2%.

5.19 Accuracy

A function of the specific project requirements. Unless specified otherwise, the accuracy shall be 1.0%.

CHAPTER 6 - CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary of Investigations

This research endeavor was based on the premise that adequate construction specifications are the key elements for a successful project for the owner, designer, and contractor team. Inadequate specifications have been defined as those that are incomplete, inaccurate, faulty, ambiguous, vague, misleading, and impossible. No productivity study, method improvement scheme, process modeling program, design / construction phase integration effort, participative management concept, etc. can offset the damage and destruction which result from inadequate specifications. Adversary relationships between the team members are an inevitable product of poor specifications.

Inadequate specifications are directly correlated to the amount of rework, increased job costs, poor productivity, delays, disputes, legal claims, etc. that typically develop on construction projects. This was confirmed, as part of this research, through thorough evaluation of numerous projects that were reported

to have developed problems. This evaluation process included reviewing actual job related records and specifications; reviewing arbitration proceedings and decisions; conducting jobsite investigations; and interviewing contractors, regulatory agencies, owners, and designers.

Considerable time and energy were devoted to researching a wide array of problems relating to trenchless excavation construction (TEC) projects with the presumption that to develop effective guidelines and specification that communicate the necessary information which deter problems, one needs a strong background in the nature of previous problems commonly encountered.

Specifications should communicate clearly and accurately to the contractor the desired end product. To the maximum extent possible, the contractor should be allowed flexibility in selecting the methods, equipment, and materials in providing the end product. No method, equipment, and / or materials should be prohibited without proper justification. Normally, it is in the best interest of the owner and consistent with the established free enterprise system to encourage competition to the maximum extent possible. This philosophy should not be applied without judgment. Enough TEC projects have been performed throughout the

United States to establish accepted principles and practices so that effective specification can be developed which permit only those methods, equipment, and materials that result in the desired end product.

Every attempt should be made to provide the contractor with as much information, such as subsurface conditions, concerning the proposed project as reasonably possible. TEC contractors do not have the flexibility as open-excavation contractors. Major commitments for equipment and materials must be made long before the work begins; therefore, changed conditions often require major delays and extra costs while the contractor develops an alternate strategy.

Disclaimer phrases and "hold-harmless" clauses should be avoided in the specifications when used to protect the designer when inadequate specifications are used and insufficient information has been provided. This places unfair risk on the contractor. It is unfair because there is no way to evaluate its value. This often results in competent contractors, who have thoroughly evaluated the projects requirements, not getting the project because an overly optimistic contractor, who has not evaluated the conditions properly, submitted a much lower bid. This, normally, is just the beginning of a long drawn out sequence of delays, problems, public danger, increased costs.

Accomplishing the objectives of this research endeavor required obtaining a thorough understanding and knowledge base of the TEC industry. This industry is poorly structured and complicated by the rapidly expanding technological advances. Therefore, to develop the knowledge base required developing a communication network with the experts and getting on jobsites to observe and investigate typical problems and procedures.

Over 35 jobsites were visited in 10 states to observe the various methods, materials, and equipment utilized throughout the United States. Many of the projects visited were ones that problems had developed. It was essential to investigate such problems in order to obtain the facts and try to determine what could have been done to prevent such problems from occurring. Special attention was directed at areas of conflicts and contradictions. For example, why did some states ban the use of spiral weld pipe while others accepted it? Why did some specifications ban the slurry bore process and others permitted it. The answer to these and many other questions had to be addressed if adequate specifications were to be developed.

Special effort was made to obtain maximum input from the construction industry. Much of this was accomplished through soliciting active participation and involvement from the NUCA Horizontal Earth Boring, Pipe

Jacking, and Utility Tunneling Special Task Force. This group consisted of the major TEC contractors, equipment, and material manufacturers across the United States. The Task Force was divided into the following 3 subcommittees : (1) Horizontal Earth Boring, (2) Pipe Jacking, and (3) Utility Tunneling. Each subcommittee was charged with pooling resources and experiences to develop what they perceived to be the ideal specification for each area. The Task Force conducted 4 workshops at various locations then made their recommendations to the author.

The author received a "Certificate Of Achievement" for successfully completing an intensive 5-day seminar on Horizontal Earth Boring conducted by American Augers, Inc. in Tempe, Arizona. Three 1-day seminars were conducted for the Indiana Department of Highways (IDOH).

Over 100 specifications were reviewed along with all known literature associated with TEC.

6.2 Conclusions

Specific conclusions that developed as a result of these research efforts were :

1. Significant variation exists in the specifications being used in the industry.

2. A severe lack of understanding of the TEC construction techniques exists in the industry.
3. The available literature and information available concerning TEC methods, materials, and equipment was very limited and fragmented.
4. TEC technology is advancing very rapidly, but the specifications and owners awareness of the state-of-the-art is not keeping pace.
5. With certain methods, the United States is lagging behind other parts of the world in technological advances; however, in other areas the U.S. industry is leading. For example, the United States is obviously lagging behind in the development of the highly sophisticated micro-tunneling equipment; but, they are the leaders in the directional drilling techniques which were developed from technology transferred from the petroleum industry.
6. There exists a real need for the development, adoption, evaluation, and upgrading of standard specifications in the TEC industry.
7. There is a need for the development of an information dissemination and education program to train personnel at all levels concerning TEC materials, methods, and equipment.
8. An expert system could be of tremendous benefit to designers and regulatory agency representatives.

6.3 Recommendations

This research endeavor has substantiated a direct relationship between project performance and specifications. It has developed a model specification for a special area of the construction industry. However, it must be tested and updated as necessary.

A positive by-product of this research endeavor was the data base and information network that was created involving contractors, material suppliers, equipment manufacturers, designers, owners, and academia. This network possesses tremendous potential for future development. These are the experts in the TEC industry that can provide the data necessary for an expert system.

It is recommended that :

1. Circulate the guidelines and specifications to the various segments of the TEC industry, and solicit comments and recommendations.
1. The specifications should be considered for adoption by state and local highway departments and that training programs be conducted for the construction and permit personnel of the highway department to make them aware of the guidelines.
2. A system should be developed to notify the highway department when problems develop and/or procedural

changes must be made. An investigation should be conducted to continue to collect historical data on which to make intelligent specification modifications.

6.4 Future Research

One common problem that is associated with each TEC method is the detection of existing underground utilities. Utility owners are becoming more conscientious about knowing where their lines are especially since more states are enacting and enforcing laws concerning delineating specific responsibility to the owners. However, even with the best mapping systems available, there is still a need for a detection system that can be used with the TEC method that will alert the operator to an obstruction before damage is done.

There is a severe lack of data on the behavior of various soil types with each the TEC methods. More research is needed in the geotechnical area to be able to understand and verify that the proposed specifications are reasonable.

A research effort should be made into the feasibility of developing a nationwide training and certification program that would be required for all highway agency, consultants, and contractors personnel that design, execute, and accept TEC projects.

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