Addressing geotechnical considerations of horizontal directional drilling using the new design tool BoreAid™

Alireza Bayat
Department of Civil Engineering – University of Waterloo, Waterloo, Ontario, Canada
Karl Lawrence, Mark Knight
Department of Civil Engineering – University of Waterloo, Waterloo, Ontario, Canada

ABSTRACT
In the past few decades, horizontal directional drilling (HDD) has emerged as a method of choice for installing buried pipeline. Each day the boundaries of this new industry are being pushed by the increasing intricacies of projects. The design of HDD however has been clouded by the increasing number of design components and subsequent complexities. A structured framework for HDD design has been implemented in a new software package called BoreAid ™. The software consists of five modular components for: 1) bore planning; 2) calculating loads/deflections; 3) designing the drill sequence; 4) considering consequences of drill; and 5) equipment/tooling selection.
This paper discusses the geotechnical aspects of HDD design and exhibits how each of these is considered within the five modules. A case study is presented to show how the tool collectively considers all aspects (including geotechnical) of the design in a structured manner. Consequently, the paper details how the use of design tools such as BoreAid™ can reduce the risk of failed bores ensure good HDD practices are used, and lower overall project costs.

RÉSUMÉ
Dans quelques décades passées, le forage directionnel horizontal (HDD) a émergé comme une méthode pour le choix pour installer le pipeline enterré. Chaque jour les limites de cette nouvelle industrie sont poussées par les complexités augmentantes de projets. Le design de HDD a pourtant été assombri par le nombre augmentant de composantes de design et de complexités ultérieures. Un cadre structuré pour le design de HDD a été exécuté dans un nouveau paquet de logiciel appelé BoreAid™. Le logiciel se compose de cinq composantes modulaires pour : 1) planification d'ennui; 2) en calculant des charges/déviations; 3) en concevant l'ordre de foreuse; 4) en considérant des conséquences de foreuse; et 5) sélection d'equipment/tooling.
Ce papier discute les aspects geotechnical de design de HDD et expose comment chacun d'entre ceux-ci est considéré dans les cinq modules. Une étude de cas est présentée pour montrer comment l'instrument considère collectivement tous les aspects (en incluant geotechnical) du design dans une manière structurée. Par conséquent, les détails en papier comment l'utilisation d'instruments de design comme BoreAid™ peut réduire le risque d'ennuis ratés, garantissent que de bonnes pratiques HDD sont utilisées et baissent en tout des prix de projet.

1 INTRODUCTION

Since its conception in the early 1970s, horizontal directional drilling (HDD) has evolved into a state-of-the-art industry for the installation of buried pipeline in urban areas. Whenever possible, its non-intrusive nature makes it the preferred method of choice over direct open-cut methods, resulting in economic, social, and environmental advantages. This growth however, has also spawned the need for proper guidelines and practices as seen by an increased number of training manuals, courses and other publications (see Ariaratnam et al. 2000, Bennett et al. 2001, Petroff, 1997, Sener et al. 1995, Svetlic, 1995). These materials focus on improving commonly used practices, implementing proven strategies, and introducing new aspects to be utilized in HDD projects.

Competent design of HDD projects, however, requires an engineer to consider a multitude of factors. Further, clarification of these factors has been inhibited by the inter-complexity and dependent relationships of each of these components. In the past, these individual areas have been hailed as being crucial to the design of a HDD projects by industry professionals in each specific area. Although each professional may pose a valid argument, we assert that it is not the individual components but the collective sum of components that proves crucial in the effective design of HDD projects. This interdependent nature of the problem has also been exhibited in recent HDD literature which provides recommended guidelines and practices (see ASCE, 2005, ASTM-F1962, 2007, and PPI, 2006).

To assist in the development of HDD projects, several commercially available softwares have been created which focus on a particular aspect of the design procedure. For instance,

(a.) DrillPath, created by Infrasoft and discussed in DrillPath, 1996, and Kirby et al., 1997, is an utility which assists the user in the construction of a bore path while considering pipe/soil data, elevation, obstacle information, clearances, and installation loads;

(b.) Plexco (see Plexco, 1998) has developed several tools which consider safe pull strengths, bending radii, buoyant forces, pressures and buckling phenomena;

(c.) Atlas Bore Planner, created by Vermeer (see Shelley, 1998), is a utility to assist the user in designing a bore path which conforms to various design restrictions such as minimum depth of cover, utility clearances, and maximum bending radii.

These tools, however, do not consider the inter-complexities of this design process – most probably a direct intention of the developing teams so that the individual procedure is not clouded by additional information. As a result, no tool exists which considers: (i) all crucial aspects of HDD design in one complete package; (ii) the global effect of each of these localized areas; and (iii) a structured framework or organization to clarify the inter-complexities involved.

The purpose of this paper is to introduce such a unique structured design framework which was developed in collaboration with the Center for Advancement of Trenchless Technologies (CATT) at the University of Waterloo and was implemented in a new HDD design tool called BoreAidTM (BoreAidTM is a trademark of Terein, Inc.). The chosen name reflects the intention of the tool to aid the contractor, engineer, or project manager in the completion of a competent design for a HDD project. The chosen name reflects the intention of the tool to aid the contractor, engineer, or project manager in the completion of simple and complex HDD projects using ASTM F1962, pipeline design good practice guidelines, and proper design criteria (see ASTM F1962 guidelines, Pipeline Research Council International Inc (PRCI), NASTT and other industry best practice guidelines). In this paper, we introduce the framework upon which BoreAid was developed, discusses the geotechnical aspects of HDD design, exhibit how each of these is considered within the five modules, and present a case study that exhibits the capabilities of this new HDD software tool.

2 STRUCTURED FRAMEWORK

The purpose of this structured framework is to provide a means by which to consider all important aspects of HDD design in a systematic coherent procedure. The structured framework developed herein is implemented into a five step procedure. To be precise in the description, the terminology to be used is that the framework may be decomposed into five modules and these modules consist of individual elements. Information collected in one module may be used in later modules if referenced. The framework is founded on keeping unnecessary information out of the analysis until it becomes pertinent. The five modules of the framework are:

i. Bore Planning
ii. Calculating Loads/Deflections
iii. Designing the Drill Sequence
iv. Considering Consequences of Drill
v. Equipment/Tooling Selection

To complete an efficient design for a HDD project it is necessary to consider each of these modules individually and in order, from module one to module five as listed.

3 BOREAID™ DEVELOPMENT

Boreaid™, developed for the Microsoft Windows platform (2000, XP and Vista), was designed to be extremely user-friendly via input prompted fields, automated warnings/comments/recommendations, and advanced graphical interfaces that allow users to navigate through the virtual site conditions and view all calculated outputs. It allows users to export all relevant data to be printed as part of a contract/design proposal or imported to a spreadsheet programs such as MS Excel.

In each module there are a series of tabs representing elements which are successively accessed by the user in creating the design. Implementation of each module along with tools to aid the designer in the completion of the project is discussed below.

Boreaid™ consists of five distinct modules that allow for the exchange of information from one module to another. The five modules are:

1. Bore Tool (bore planning),
2. Pipe Load Verifier (loads and deflections),
3. Drill Planner (drill sequence, drill time, and drill fluid calculator),
4. Limiting Pressure (hydro-fracture component of drill consequences), and
5. Equipment/Supplies (equipment and tooling selection).

To complete an efficient design for a HDD project, it is necessary to consider each module starting with module one advancing to module five as listed above.

3.1 Bore Tool

The end goal of the Bore Tool module is to determine a path for the pipe while taking all site constraints and other factors into consideration.

First, project specific lengths and pipe type/application need to be specified. Then, the user should select an initial estimate of the pipe DR followed by the drill rod diameter. Topographical aspects such as sudden rises in elevation or valleys/mountains should then be considered. These variations could result in dramatic effects in load calculations to be considered later. Simple or complex topographical site conditions can be developed using BoreAid™, as shown in Figure 1.

Next, geotechnical issues such as soil layering and water table location should be reviewed - areas where voids, cobbles or boulders exist may be areas where a designer may wish to avoid. Site geological layering may then be input using a built-in existing database of sample soils based upon USCS, AASHTO, and typical soil classifications. Default soil mechanical properties are assigned to each layer in this module; however, the user has an option to change all values.

Above and below ground obstacles may then be located so that: (1) surface obstacles inhibiting setup zones are identified (Figure 2); (2) no drill zones for the geotechnical site investigation are identified (Figure 3); (3) underground utilities/buried objects are avoided. Further, each type of obstacle has a corresponding "acceptable clearance zone" based upon existing standards which the path of the bore must not pass through. Appropriate references should be consulted to determine the appropriate clearance zone for each obstacle.

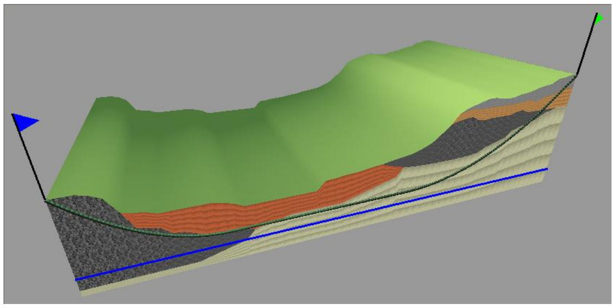

Figure 1. Different Topographical Condition

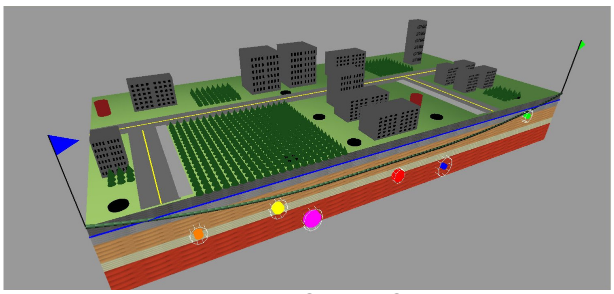

Figure 2. Above and Below Ground Obstacles

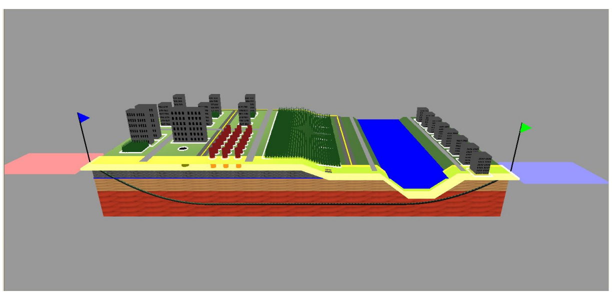

Figure 3. Set up and No Drill Zones

Depending on the approach, calculating the bore path requires three key parameters: the entrance angle, the exit angle, and the depth of cover. Restrictions on these parameters may be imposed by the client, topography, obstacles, and/or the drill equipment.

Further design constraints may be classified into two main categories: geometrical and obstacle constraints. Key constraints adhered to in common practices are:

Geometrical constraints:

(i) bore entry/exit angles: ASTM F1962 recommends a bore and bore exit angle less than 10 degrees measured from the ground surface;
(ii) minimum depth of cover: for instance, ASTM F1962 suggests a minimum depth of cover of 15ft (5m) below a river;
(iii) radius of curvature: the radius of curvature should be more than the specified minimum radius of curvature for the pipe and drill rod.

Obstacle constraints:

(iv) surface/subsurface obstacles such as roads, sidewalks, buildings, environmental areas,
(v) utilities: the path of the pipe must not pass through existing acceptable clearance zones for obstacles;
(vi) unfavorable soil: following from good practice guidelines, the path of the pipe should avoid areas of unfavorable soils;

Acceptable paths must satisfy all defined conditions. During the site investigation the designer should also be aware of other characteristics which could prohibit the use of HDD as an effective means of construction or that may result in high risk of problems during construction. Such characteristics are the presence of cobbles/boulders, gravel, other debris (ex., wood, buried foundations from old infrastructure, etc.) or high artesian pressures.

Using an iterative process alterations may be made to until the path which best satisfies all site restrictions is found. Exceptions to some of these restrictions may be made depending on previous experience of the designer but ideally the path should satisfy all constraints.

3.2 Load Verifier

Once an adequate path is found it is necessary to calculate the resultant pipe installation and long-term loads and deflections. Module 2 requires the designer to collect key properties of the pipe (type, length, DR, OD, internal pressure, allowable tensile and compressive stresses), soil (unit weight, friction angle, cohesion), bore (borehole diameter, silo width, length), slurry (unit weight, hydrokinetic pressure) and installation parameters (friction coefficients). Operational loads (earth pressure, water pressure, net pressure) and deflections (earth load deflection, buoyant deflection, Reissner effect) are then calculated based upon the bore path determined in module 1 and using various assumptions about bore (Terzaghi soil arching, bore is deformed (Stein method) or the bore is collapsed). Calculation of installation loads/stresses (bending, pullback) and deflections applied to the pipe are included in the next element of this module. Various methods exist for calculating these values, a few of which are discussed in ASCE (2005), ASTM-F1962 (2007), Bennett et al. 2001, PPI (2006). Pipe deflection, unconstrained collapse pressure, and tensile stress/strain are checked. The use of rollers and/or ballasts may be introduced to improve conditions if necessary. This module depends on the specific properties of the pipe proposed for installation. In the implementation of this framework, the designer should be able to select different types of pipe and repeat modules 1-2 with as little difficulty as possible. Presently, BoreAid^{TM} allows the selection of pipes constructed out of steel and polyethylene.

3.3 Drill Planner

The purpose of this module is to design a pilot bore/reaming sequence which is achievable based on existing equipment. Parameters of the project such as the overcut ratio, drill rod length, soil to fluid ratio, pump characteristics (rate, efficiency), and tank volume are input at this stage. The pilot bore and reaming sequence is determined based upon the available drill bits/reamers, pump rate, and storage tank volume (Figure 4). Drill times per unit drill rod or some other unit length are used to determine the volume of soil to be cut and volume of drill fluid required to complete the project. Finally the total drill time (time the drill rig will require to complete the bore, neglecting rod replacement times, setup times, etc.) are calculated.

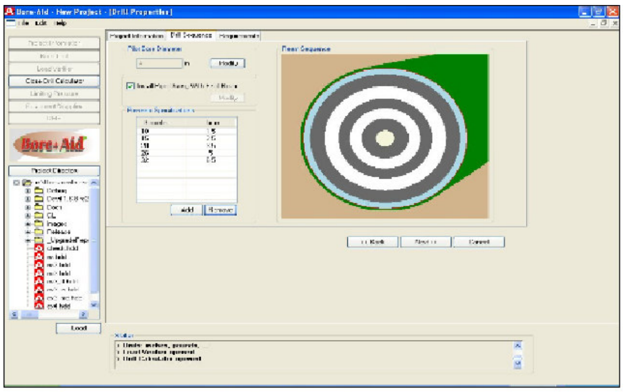

Figure 4. Screenshot of Utility to Enter Pilot Bore and Reaming Sequence

3.4 Limiting Pressure

There are three main consequences of the project that the designer should be aware of and/or have estimates of before or during the project. These are hydro-fracture, or frac-out, heave and subsidence. Hydro-fracture occurs when the pressure exerted inside the bore exceeds some limiting pressure, related to the weight of the overburden among other factors, causing the drill fluid to move outward from the bore and often reaching the surface. Soil voids can also be particularly troublesome in dealing with this problem. Heave and subsidence is the resultant effect at the surface due to HDD project which may occur during the project or over time. The “bumping” or “dipping” of the surface may be acceptable in some rural areas, but in urban areas this may create problems

3.5 Equipment/ Supplies

The final stage of this design framework is to use the analysis of the first four sections to make a decision on the equipment and tooling. Pullback and pump capacity are two major criteria to consider when selecting the drill rig. Alternatively, this information may be used to determine if the drill rig currently owned by the contractor is viable or not. In implementation, the designer should have the ability to modify previous aspects of the design to increase/decrease expected values of these parameters if desired. For instance, if the pullback capacity of the drill rig yields an inadequate factor of safety, then the bore path and specific pipe should be accessible for modification. If the pump rate factor of safety is inadequate, then the user should be able to modify reaming sequences and/or bore path. The other extreme should also be considered where factors of safety are too conservative.

4 APPLICATION TO SIMPLE DRILL DESIGN

In this section BoreAid™ is used to construct site conditions and perform load calculations/equipment recommendations for a typical simple HDD project. The client wishes to install an 8in nominal diameter HDPE DR 9 pipe that has a surface length of 670.5 m.

4.1 Geotechnical Considerations

Site conditions consist of a layer of well graded sand (with an internal friction angle of 30 degrees) from the ground surface to a depth of 16 meters. The water table is assumed to be at the ground surface.

4.2 Bore Path Design

The bore is constructed automatically in BoreAid using the entrance/exit angles and the minimum depth of cover. In this project entrance and exit angles were chosen as 10 and 12 degrees, respectively, and the depth of cover was taken to be 10.7 m. In determining this path, BoreAid calculates the required radius of curvature and checks to see if this value falls within acceptable limits. BoreAid also allows the user to access the calculated bore path information. For instance, the user can print the bore path via drill rod locations along the path.

Table 1. Calculated pressures and pipe deflections

	Deformed (Terzahgi method)	Deformed (Stein method)	Collapsed
Earth Pressure (kPa)	19.5	13.0	113.3
Water Pressure (kPa)	104.6	104.6	104.6
Surcharge (kPa)	0.0	0.0	0.0
Internal Pressure (psi)	0.0	0.0	0.0
Net Pressure (kPa)	124.1	117.6	218
Earth Deflection (%)	0.77	0.51	4.48
Buoyant Deflection (%)	0.071	0.071	0.071
Reissner Effect (%)	5.8E-6	5.8E-6	5.8E-6
Net Deflection (%)	0.84	0.58	4.55

4.3 Load Calculations

In this project, the operational loads calculated by BoreAid are given in Table 1. The values in this table represent pipe deflections at the location of maximum net pressure. BoreAid contains an interface to plot and export all of the above parameters along the bore. Installation loads are also calculated and are summarized in Table 2. Finally, there is an interface within BoreAid to check that all loads/deflections fall within acceptable limits for design. Should one of the values result in a factor of safety less than one, a warning is issued.

Table 2. Summary of Installation Loads

	A	B	C	D
Pullback Stress (kPa)	3585	4550	5653	5998
Pullback Strain	9.1E-3	1.1E-2	1.4E-2	1.5E-2
Pullback Force (kN)	53.3	66.7	84.5	88.9
Bending Strain	0	1.5E-4	2.2E-4	0
Bending Stress (kPa)	0	61.4	88.9	0
Resultant Axial Tensile Stress (kPa)	3585	4619	5791	5998
Resultant Axial Tensile Strain	9.11E-3	1.17E-2	1.46E-2	1.51E-2

4.4 Drill Fluid and Reaming Sequence Design

Table 3 shows the proposed drilling/reaming sequence for the project. For this project a reamer to pipe overcut ratio of 1.5, drill fluid to soil volume ratio of 2.5, total drill fluid tank volume of 2.64 cubic meters, maximum pump rate of 0.26 cubic meters/min, and pump efficiency 80% was selected. The user must also input the expected drilling time per rod.

BoreAid calculates total (and per rod) soil and fluid volumes required for each reamer pass as well as the total drill time. Note that BoreAid issues warnings if the pump capacity is exceeded during any stage of the drilling/reaming.

Table 3. Proposed pilot bore and ream diameters

Pilot Bore	0.076 m
Reamer Pass 1	0.139 m
Reamer Pass 2	0.203 m
Reamer Pass 3	0.254 m
Reamer Pass 4	0.327 m

5 CONCLUSION

In this paper we have introduced a structured framework for HDD design and its implementation in a new software package called BoreAid. We have addressed the geotechnical consideration for horizontal directional drilling and other capabilities of the BoreAid and shown how complicated designs, site conditions, topographies, etc. may be described with ease using BoreAid. BoreAid provides a clear method in which to consider the parameters and makes connections between inter-connected elements of the design. A simple example is described which exhibits only the basic capabilities of the software.

ACKNOWLEDGEMENTS

The authors wish to thank the Center for Advancement of Trenchless Technologies and Department of Civil and Environmental Engineering at the University of Waterloo for their support during the completion of this project.

REFERENCES

Ariaratnam, S. T., Allouche, E. N., 2000. Suggested practices for installations using horizontal directional drilling. Practice Periodical on Structural Design and Construction 5 :(4), 142–149.

ASCE, 2005. Pipeline Design for Installation by Horizontal Directional Drilling. American Society of Civil Engineers, aSCE Manuals and Reports on Engineering Practice No. 108.

ASTM-F1962, 2007. Standard guide for use of maxi-horizontal directional drilling for placement of polyethylene pipe or conduit under obstacles, including river crossings. ASTM International.

Bayer, H. J., 2005. HDD-Practice Handbook. Vulkan-Verlag GmbH (Oldenbourg Publishing Group), essen, Germany.

Bennett, D., Ariaratnum, S., Como, C., 2001. Horizontal Directional Drilling: Good Practices Guidelines. HDD Consortium.

DrillPath, 1996. DrillPath: theory and user manual. Infrasoft, Houston.

Kirby, M. J., Kramer, S. R., Pittard, G. T., Mamoun, M., 1997. Design guidelines and procedures for guided horizontal drilling. part ii. No-Dig Engineering 3:(4), 13–15.

Petroff, L. J., 1997. Design guidelines for directional drilled pe pipe. ASCE Congress on Trenchless TechnologyBoston, MA.

Petroff, L. J., Dreher, P. L., 1997. Design considerations for hdpe for trenchless applications. No-Dig 1997Seattle, WA.

Plexco/Spirolite, 1998. Engineering manual (CD-ROM), 2nd Ed. Chevron Chemical, bensenville, Illinois.

PPI, 2006. Handbook of PE Pipe. Plastic Pipe Institute (PPI).

Sener, E. M., Stein, R., 1995. Mini-horizontal directional drilling manual. North American Society for Trenchless TechnologyChicago, IL.

Shelley, T., 1998. Bore planner maps road to the future. Trenchless Technology 7 (5), 26–27.

Svetlik, H., 1995. Design considerations for hdpe pipe used in directional drilling. No-Dig Engineering 2:(3).