HDD Design Report, Revision R0
Enbridge Line 1 Replacement Project
20-inch Schuylkill River Crossing

May 2023

Prepared for:

audubon

AUDUBON ENGINEERING COMPANY, L.P.
10205 Westheimer, Suite 100
Houston, Texas 77042

Prepared by:

J.D.Hair&Associates,Inc.
Consulting Engineers

J. D. HAIR & ASSOCIATES, INC.
6100 S Yale Ave, Suite 1610
Tulsa, Oklahoma 74136-1923

J.D.Hair&Associates,Inc.
Consulting Engineers

6100 S Yale Ave
Suite 1610
Tulsa, Oklahoma 74136
Tel 918-747-9945
Fax 918-742-7408
www.jdhair.com

May 2023

AUDUBON ENGINEERING COMPANY, L.P.
10205 Westheimer, Suite 100
Houston, Texas 77042

Attention: Robert Guerrero, P.E.

SUBJECT: HDD Design Report, Revison R0
Enbridge Line 1 Replacement Project
20-inch Schuylkill River Crossing

Robert,

J. D. Hair & Associates, Inc. (JDH&A) is pleased to submit the following report which presents engineering design criteria and supporting calculations associated with the Schuylkill River crossing to be installed using horizontal directional drilling (HDD).

We appreciate the opportunity to assist Audubon and Enbridge in this endeavor. If you have any questions or need additional clarification related to any of the information contained herein, please do not hesitate to contact us.

Respectfully,

J. D. HAIR & ASSOCIATES, INC.

Jeffrey S. Puckett, P.E.
President

Luke Bever, P.E.
Project Manager

Isabela Spelta, E.I.T.
Project Engineer

Executive Summary

The following report presents a summary of design considerations and engineering calculations associated with the proposed 20-inch Schuylkill River crossing which is to be installed using horizontal directional drilling (HDD). This report also discusses subsurface conditions, feasibility and risk, provides high-level construction estimates, and presents the results of a comprehensive engineering evaluation.

Design geometry associated with the proposed Schuylkill River crossing is consistent with prevailing practice. Depth of cover, radius of curvature, and surface penetration angles are otherwise typical of a 20-inch installation. The design employs 10 and 12-degree surface penetration angles, non-continuous vertical curvature, and radii of curvature equal to 2,000 feet. Moreover, the design achieves 40 feet, or more, of cover beneath the river. The horizontal length of the proposed crossing is 1,101 feet while the true drilled length is 1,111 feet.

Geoengineers, Inc., conducted a subsurface investigation at the proposed crossing location which involved two (2) exploratory geotechnical borings. The investigation generally revealed surficial alluvium, colluvium, and residuum deposits of silty sand to silty clay underlain by mudstone, shale, siltstone, and sandstone bedrock formations. Based on the findings of the geotechnical investigation, JDH&A is of the opinion that the subsurface is amenable to the HDD process and that any challenges which may be present, such as those related to the bedrock material or coarse colluvium deposits, are surmountable by proper equipment and tooling selection. This, in conjunction with the length and diameter of the Schuylkill River crossing, lends to the assessment that the crossing is feasible. This assessment is supported by our knowledge that other installations in the region, confronted with similar geology and comparable lengths, have been completed in the past.

A hydrofracture evaluation was conducted in order to quantify the risk of inadvertent returns. Calculations indicate that under normal drilling operations the prospective crossing is at a low risk for inadvertent returns due to hydrofracture. Although hydrofracture is an unlikely author for inadvertent returns at this location, the overall likeliness for inadvertent returns cannot be ruled out. Existing fractures and fissures within a bedrock mass inherently increase the risk of fluid loss and the potential for inadvertent returns. Considering that portions of the prospective crossing involve passing through poor-quality bedrock, it is conceivable that some form of fluid loss unrelated to hydrofracture may occur.

HDD installation and operational stresses were analyzed under multiple loading scenarios. The results indicate that pipe stresses associated with HDD installation fall within acceptable limits provided that the actual pullback geometry does not vary significantly from that which was used in the installation loading models, that the HDD contractor will not employ any improper construction procedures, and that unanticipated subsurface conditions are not encountered. Lastly, several estimates in relation to HDD construction were conducted as part of JDH&A's evaluation. These include a construction duration estimate and a drilling fluid/spoils estimate. The results of the HDD construction duration estimate were found to be 37 days. This estimate assumes single 10-hour shifts during pilot hole, reaming, and pullback operations and does not include contingency. Details related to the drilling fluid and spoils estimate may be found herein.

TABLE OF CONTENTS

APPENDICES

1 INTRODUCTION

The purpose of this report is to provide a summary of design considerations and engineering calculations associated with the proposed 20-inch replacement crossing of the Schuylkill River near Spring City, Pennsylvania. The crossing is proposed for trenchless installation by method of horizontal directional drilling (HDD). J. D. Hair & Associates, Inc. (JDH&A) has undertaken this report in accordance with the scope of work presented in Audubon's Work Order No: 024896001-WO-JDH001-001.

2 BASE DATA

The HDD design and engineering calculations presented in this report are based on the following base data:

- Topographic survey data provided by Audubon Engineering Company, L.P., Houston, Texas.
- Pipe specification: 20-inch O.D., 0.500-inch W.T., X-65 steel line pipe (information provided by Audubon Engineering Company, L.P., Houston, Texas).
- Pipeline Operating Parameters: 656 PSIG MOP, 1,312 PSIG Pre-test Pressure, 42-degree installation temperature, and 80-degree operating temperature.
- Geotechnical Report prepared by Geoengineers, Inc., Springfield, MO, titled "Geotechnical Engineering Services Data Report, Schuylkill River Pipe Replacement Project, Chester and Montgomery Counties, Pennsylvania", dated February 8, 2023.
- A site reconnaissance of the proposed crossing location conducted by JDH&A in December of 2022.

3 HDD DESIGN CONSIDERATIONS

3.1 Background and General Site Description

The proposed crossing is located in southeastern Pennsylvania splitting the borders of Chester and Montgomery counties, approximately 25 miles northwest of Philadelphia. The project site could be characterized as a mixture of gently rolling hills and valleys, formed by extensive dissection of bedrock strata, with the Schuylkill River and other smaller streams cutting through the landscape. The Schuylkill River, a predominately southeast flowing perennial stream and tributary waterway for the Delaware River, is the prospective crossing's sole obstacle. As JDH&A understands it, the proposed crossing is to replace a section of Enbridge's conventionally laid Line 1 pipeline which will soon be decommissioned as a result of scour and exposure at the river crossing. Due to the nature of the replacement, the proposed HDD will exist directly adjacent to the existing pipeline.

The following photograph provides an overview of the waterway at the proposed crossing location. Photographs were taken in December of 2022. Under normal conditions, the river is likely to possess a water level elevation of 88.0-89.0 (NAVD88) and a depth of approximately 5-6 feet. At the point the river is crossed by the prospective HDD, it possesses a span of approximately 340 feet.

Refer to the following figures for a general overview of the project area and vicinity terrain.

Photograph 1: Schuylkill River at Proposed Crossing Location

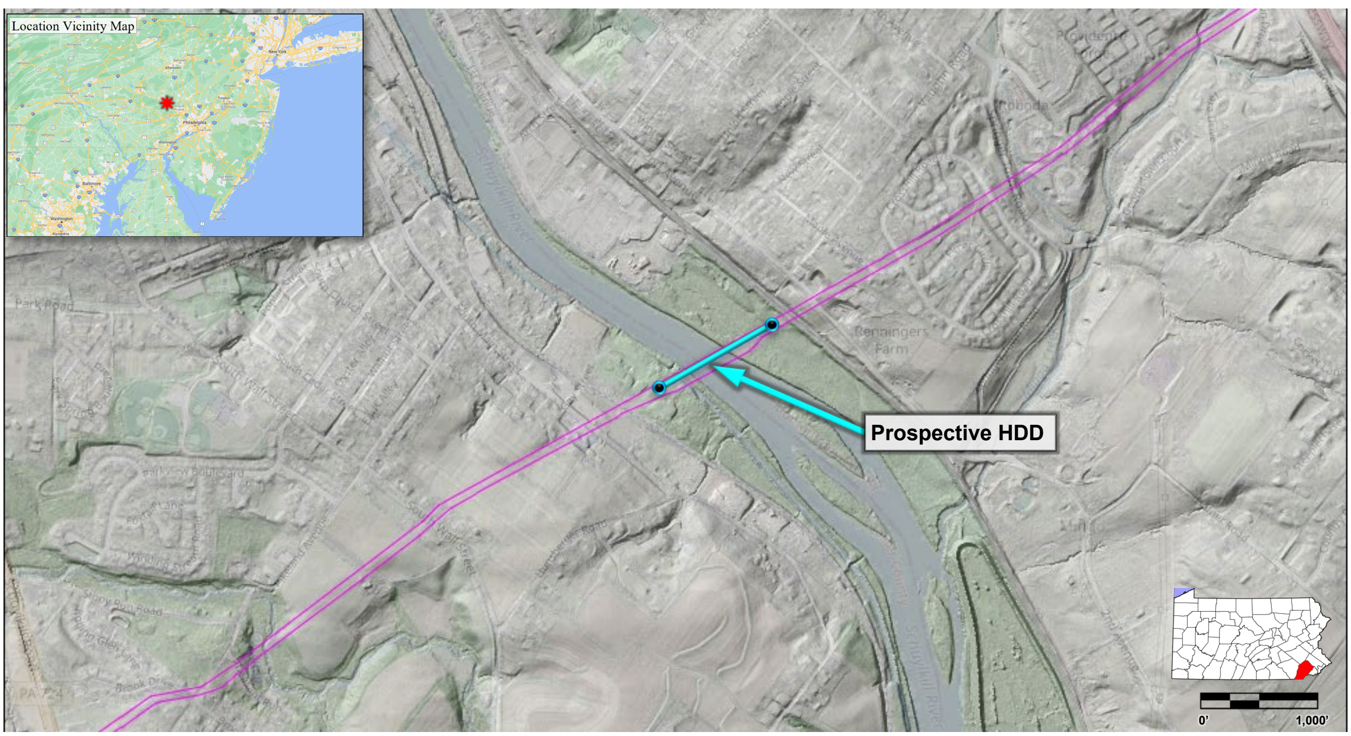


Figure 1: General Crossing Area with Topographic Relief

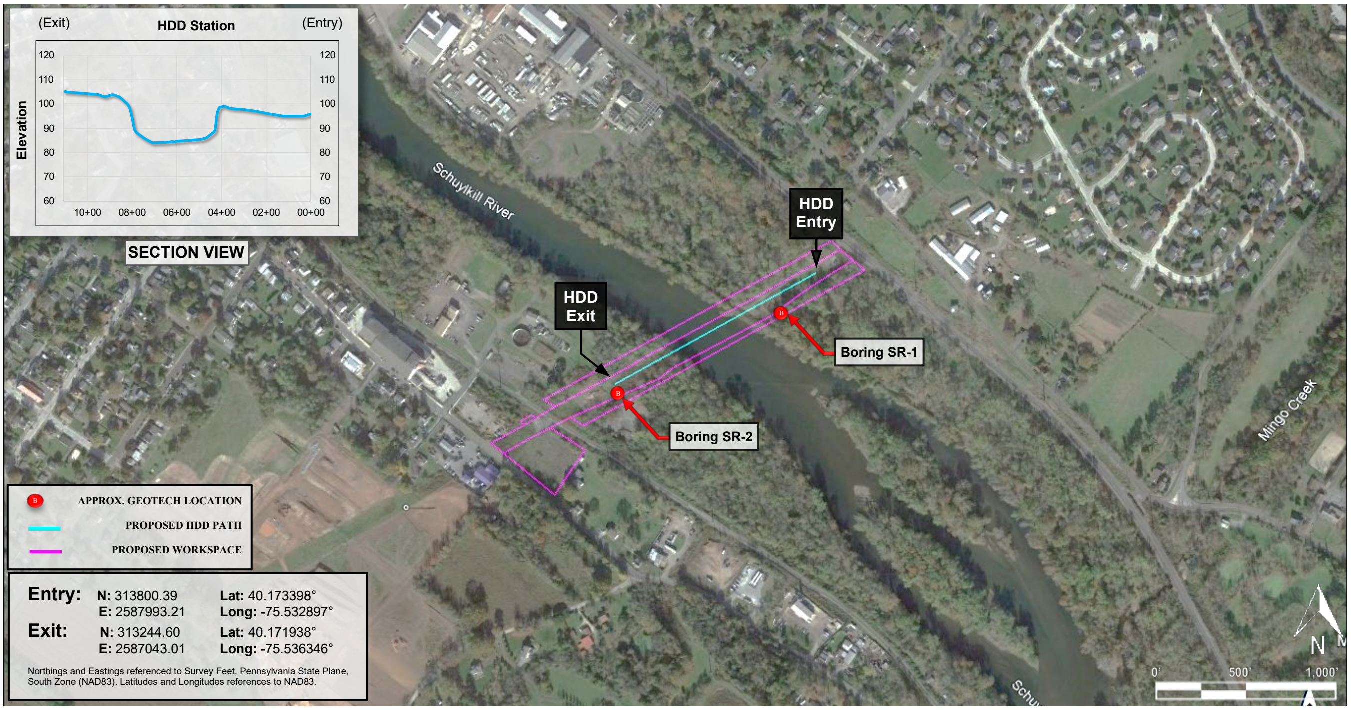


Figure 2: Detailed Crossing Map

3.2 HDD Design Geometry

HDD design geometry was developed for the Schuylkill River crossing in accordance with prevailing industry practices. Depth of cover, radius of curvature, and surface penetration angles may be considered typical. The design employs a 10-degree entry angle, a 12-degree exit angle, non-continuous sag bend geometry, and radii of curvature equal to 2,000 feet. The design achieves approximately 47 feet of cover beneath the center of the river and a minimum of 40 feet at the river banks. Moreover, the design is typical in the sense that it is straight from an alignment perspective, possessing no horizontal curvature. Design geometry ultimately yields a horizontal crossing length of 1,101 feet and a true drilled length of 1,111 feet.

The proposed crossing is situated between the existing Line 1 and Line 2 pipelines. This was done as a result of existing easement and routing considerations. Offset from the existing lines is not equidistant but rather is biased towards the line to be replaced, Line 1. The designed alignment allows for approximately fifteen (15) feet of lateral separation from the existing Line 1 pipeline and a minimum of approximately twelve (12) feet of separation near the crossing's end points when adjusted for allowable tolerances.

Surface penetration angles associated with design geometry, while within typical ranges, are effectively flipped from what is normally employed. Typically, entry angles associated with drilled crossings are greater than their counterpart exit angles. This is largely due to pullback considerations with lower angles requiring less pull section breakover geometry. However, in this case that relationship is reversed with the exit side representing the steeper angle at 12 degrees. This orientation was selected to maximize the available space for pull section staging to the west of the crossing, which is limited due to existing infrastructure. Although employing a steeper exit angle may affect pullback breakover geometry, the benefits afforded by the geometry otherwise are viewed as being more impactful.

The HDD plan and profile design for the proposed Schuylkill River crossing is provided in Appendix 1.

3.3 Design Tolerances

Given the nature of underground construction, the actual drilled path cannot, economically or otherwise, be constructed exactly on the specified designed path. As such, geometrical tolerances or permissible deviations must be assigned in accordance with the designed path and should take account of any number of relevant constraints. Constraints may include known or unknown adverse geotechnical conditions, existing utilities, easement/ROW restrictions, among others.

Positioning tolerances for the Schuylkill River HDD are defined as follows:

1.) **Entry point:** up to 5 feet short or 5 feet long relative to the designed entry point; up to 3 feet right or 3 feet left of the designed alignment

2.) **Exit point:** up to 5 feet short or 15 feet long relative to the designed exit point; up to 3 feet right or 7 feet left of the designed alignment

3.) **Elevation:** up to 5 feet above and 10 feet below the designed profile

4.) **Alignment:** up to 5 feet right or left of the designed alignment unless otherwise defined

Permissible tolerances are generally standard, however, consideration is given specifically to the entry point and exit point tolerances as this is intended to secure adequate offset from the existing adjacent pipeline. Based on the above tolerances, if the pilot hole were to be drilled to a worst-case condition, a minimum of twelve (12) feet of separation would be maintained from the existing Line 1 pipeline.

In addition to positioning tolerances, limitations to curvature were also considered. As noted previously, the Schuylkill River crossing utilizes a design radius of 2,000 feet – which is standard practice for a 20-inch diameter installation. A minimum allowable radius of two-thirds (2/3) of the design radius, or 1,333 feet, has been specified as part of the pilot hole tolerances on the design drawing. Curvature tolerances for the Schuylkill River HDD are defined as follows:

5.) Curve radius: no less than 1,333-feet based on a 3-joint average (assuming range-2 drill pipe)

This radius is typically analyzed during pilot hole drilling over a distance of approximately 90-100 feet, or three (3) joints of range-2 drill pipe. Permitting a reduced radius, similar to that of allowing geometrical deviations, provides the contractor with a degree of flexibility in the event that issues are met due to subsurface conditions or otherwise.

Calculations that verify the acceptability of the specified minimum radius are summarized in Sections 4.1 and 4.2. These calculations also define the absolute minimum allowable bending radius based on combined stress criteria. In the event that a justifiable condition warrants utilizing a radius lower than the minimum radius (1,333-feet), the absolute minimum (602-feet) could serve as a reference in terms of the lowest bounds of acceptability.

3.4 Workspace

3.4.1 Entry Site (Rig Side)

Entry, or rig side, operations are envisioned to take place within the existing easement on the east side of the crossing. This is due to workspace considerations and the fact that the opposite side of the crossing possesses more space for pull section staging. As a result of vicinity topography, a minor elevation differential exists between the crossing's end points of approximately nine (9) feet with the entry site being located at the topographically lower elevation. This is beneficial from a returning drilling fluids perspective and should result in lower annular pressures which may help reduce the risk of inadvertent drilling fluid returns.

Refer to the following photograph for a general overview of the proposed entry site or rig side.

Photograph 2: View of Entry Workspace Area

3.4.2 Exit Site (Pipe Side)

Exit, or pipe side, operations are envisioned to take place within the existing easement on the west side of the Schuylkill River. As noted previously, the west side of the crossing possesses more space in comparison to the east, and therefore, was selected for pipe side operations. While the west side possesses more space, it cannot accommodate the product pipe in a single segment as the maximum unabridged length is approximately 624 feet. Therefore, it is anticipated that the pull section will need to be staged and pulled back in multiple segments. As such, multiple tie-in welds will need to be completed during pullback. Due to existing infrastructure and limited space, pipe staging and pull section handling are anticipated to present some challenges during construction. Contractors should be prepared for tight working conditions and how such notions may affect operational procedures (i.e., managing tail string, trucking of spoil/fluids, pullback, etc.).

Refer to the following photographs for a general overview of the proposed exit site or pipe side.

Photograph 3: View of Exit Workspace Area

Photograph 4: View of Pull Section Staging Area (Extends approximately 640 feet to S Main St.)

3.5 Subsurface Conditions

3.5.1 Anticipated Geology

A cursory review of the area's geology was carried out to establish a general expectation of the subsurface. This expectation is useful during preliminary design proceedings but also plays a role in developing confidence in any future interpretations related to site-specific geotechnical data. Based on mapping sourced from the National Geologic Map Database, the project area is situated within the Brunswick Geologic Formation. Based on this notion, it is anticipated that soil conditions will involve unconsolidated surficial sands, silts, and clays, and at depths, sedimentary bedrock formations consisting of shale, mudstone, and siltstone. Bedrock formations in the area are generally described as being moderately well developed and thinly bedded. The Brunswick Formation is estimated to possess a thickness of approximately 16,000 feet near Pottstown, PA (Low, et al, 2002).

Refer to the following figure for an overview of vicinity geological formations in relation to the proposed crossing site.

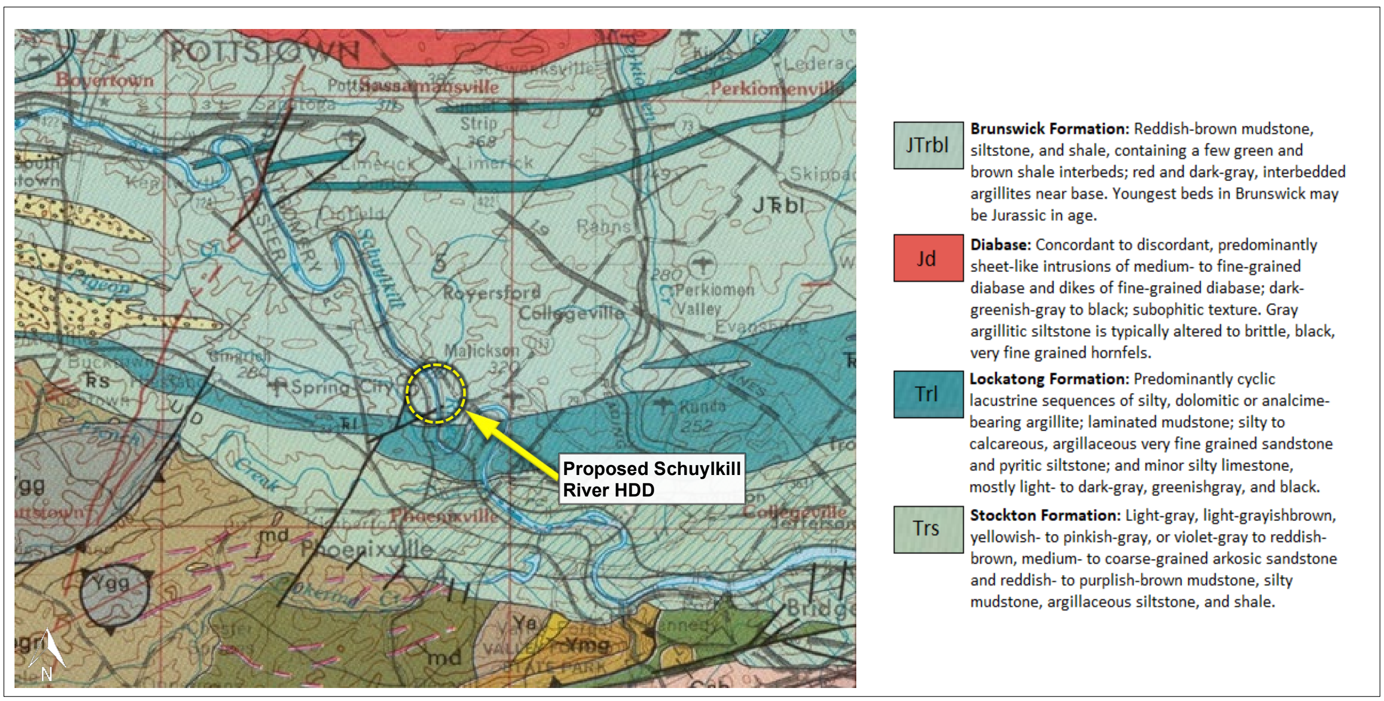


Figure 3: Selection from Lyttle, P.T. and Epstein, J.B., 1987, Geologic map of the Newark Quadrangle, New Jersey, Pennsylvania, and New York: U.S. Geological Survey

3.5.2 Site Specific Investigation

Geoengineers, Inc., performed a site-specific geotechnical investigation at the proposed crossing location which involved two (2) exploratory borings. The borings were performed along the alignment of the proposed crossing with one (1) boring located near each end point. Borings SR-1 and SR-2 were performed on the east and west side of the Schuylkill River, respectively. The borings were drilled to termination depths ranging from approximately 103 feet to 114 feet below ground surface. Subsurface features were revealed to be fairly consistent between the two (2) borings. Relative strength and material qualities varied slightly from weaker to stronger, and lower to higher, from borings SR-1 to SR-2, respectively. Refer to the following tables for a generalized overview of subsurface conditions.

Table 1: Summary of Subsurface Conditions (Boring SR-1)

Boring	Depth (feet)	General Stratum Description
SR-1	0 – 3.5	**Topsoil**: Topsoil with organic matter; medium dense
	3.5 – 8	**Silty Clay**: Clay with varying amounts of silt; stiff
	8 – 13.5	**Clayey Silt** with Sand: Silt with varying amounts of clay; with sand; stiff
	13.5 – 20	**Gravel** with Silt and Sand: Poorly graded gravel; with silt and sand; medium dense to very dense
	20 – 40	**Claystone**: Sedimentary rock; very thinly to medium bedded, moderately weathered; soft to medium hard; **UCS 4,517 psi**
	40 – 90	**Shale:** Sedimentary rock; thinly to medium bedded, slightly to moderately weathered; medium hard to hard; **UCS 6,772 - 12,833 psi**
	90 – 100	**Sandy Siltstone:** Sedimentary rock; thinly bedded, fresh; medium hard; **UCS 6,505 psi**
	100 – 103	**Shale:** Sedimentary rock; thinly bedded, moderately weathered; soft

Table 2: Summary of Subsurface Conditions (Boring SR-2)

Boring	Depth (feet)	General Stratum Description
SR-2	0 - 6	**Silt:** Clusters of silt; with organic matter; medium stiff to stiff
	6 – 8.5	**Clayey Silt**: Silt with varying amounts of clay; stiff
	8.5 – 13.5	**Silty Sand**: Sand with varying amounts of silt; medium dense
	13.5 – 18.5	**Sand** with Silt and Gravel: Well-graded sand, with silt and gravel; dense
	18.5 – 19	**Sandy Clay**: lean clay with varying amounts of sand; hard
	19 – 54	**Shale:** Sedimentary rock; very thinly bedded, moderately weathered; soft to hard; **UCS 6,576 - 8,940 psi**
	54 – 59	**Sandy Siltstone:** Sedimentary rock; thinly bedded, slightly to moderately weathered; hard
	59 – 62	**Shale:** Sedimentary rock; thinly bedded, moderately weathered; soft
	62 – 69	**Sandstone**: Sedimentary rock; thinly bedded, fresh; hard
	69 – 76	**Sandy Siltstone:** Sedimentary rock; thinly bedded, slightly weathered; very hard; **UCS 23,220 psi**
	76 – 114	**Shale:** Sedimentary rock; very thinly to thinly bedded, slightly weathered; medium hard; **UCS 4,238 - 6,600 psi**

As noted previously, Boring SR-1 was performed on the east side of the Schuylkill River. The boring was situated approximately 260 feet southwest of the proposed HDD entry point and approximately 90 feet offset laterally from the proposed HDD alignment. Subsurface conditions revealed within Boring SR-1 included varying layers of silt, clay, sand, and gravel underlain by sedimentary bedrock formations. Surficial overburden deposits extended from the surface to a depth of approximately 20 feet. Beyond that, the subsurface was characterized as claystone, shale, or sandy siltstone until the boring was terminated at 103 feet. A single particle size distribution test was performed on Boring SR-1. At approximately 15 feet, gravel content was measured to be 52.3 percent.

Boring SR-2 was performed on the west side of the river, approximately 60 feet south of the HDD exit point. Subsurface conditions revealed as part of Boring SR-2 were not substantially different from those seen in the east boring. Varying layers of silt, clay, sand, and gravel were encountered until a depth of approximately 19 feet from which shale, with varying layers of sandy siltstone and sandstone, were encountered until the boring's termination at 114 feet. A single particle size distribution test was performed on Boring SR-2 which revealed a gravel content of 24.1 percent at a depth of approximately 15 feet.

Rock core samples from both borings were tested for unconfined compressive strengths (UCS). Compressive strengths varied from as low as 4,238 psi to as high as 23,220 psi, with the average from thirteen (13) total tests being 8,242 psi. Moreover, analysis on the rock cores was performed to characterize the rock quality designation (RQD). The average RQD values for Boring SR-1 and SR-2 were found to be 52 and 57, respectively – indicating "fair" quality bedrock when averaged across the borings. With some exceptions, RQD values generally increased as function of depth with more competent material existing near the boring termination depths. In addition, four (4) rock core samples were tested for Cerchar Abrasiveness Index (CAI) and tensile splitting strength (TSS). The CAI test results revealed slightly to extremely abrasive classifications. Samples SR-1 (90-91.50 feet), SR-1 (94-94.5 feet), SR-2 (65-65.75 feet), and SR-2 (71.5-72 feet) had a CAI value of 3.53, 2.14, 4.08, and 4.66, respectively. Tensile splitting strength tests utilizing the same rock core samples resulted in 3745 psi, 1067 psi, 752 psi, and 2733 psi, respectively.

Notable hazards encountered during the exploration include consolidated ground conditions (i.e., sedimentary bedrock) and the fact that those formations may possess high strengths, fractures, and/or be highly abrasive. Operational impacts due to the strong and potentially fractured/abrasive nature of the bedrock may be expected, however, impacts are not perceived as being insurmountable. That said, prospective drilling contractors should be well aware of the potential challenges and likeliness for contingency measures to overcome said conditions.

Refer to the project geotechnical report dated February 8, 2023, for more detailed subsurface information.

3.6 Feasibility Considerations and Notable Risks

Three (3) concepts may be used to assess the feasibility of HDD for any given crossing. These concepts include technical feasibility, contractual feasibility, and economic feasibility. An HDD crossing is technically feasible if it can be installed within the anticipated subsurface using existing tools and techniques, regardless of uncertainties surrounding the cost of installation. An HDD crossing is generally contractually feasible if the cost and resources required of an installation can be accurately estimated in advance allowing contractors to submit lump sum bids. Lastly, an HDD crossing is economically feasible if the installation cost is less than that of alternative construction methods. Prior to the assessment of either economic or contractual feasibility, it must first be established whether a given HDD is technically feasible.

Technical feasibility and any challenges to such notion as it relates to the Schuylkill River HDD are addressed in the report sections to follow. Contractual and economic feasibility, while important, are beyond the scope of this report.

3.6.1 Inadvertent Returns

As is the case with all pipeline crossings to be installed by HDD, there is a chance that inadvertent drilling fluid returns, also known as "frac-outs" will occur. Although inadvertent returns can generally be contained and controlled with sandbags, silt fences, or hay bales, and do not typically prevent a successful installation, they can be problematic if they surface in a sensitive waterbody or wetland. From an HDD operational standpoint, maintaining drilling fluid circulation to the extent possible is key to reducing the risk of inadvertent drilling fluid returns. Approaches that may be taken to promote drilling fluid circulation include, but are not limited to, sizing of the borehole frequently to keep the annular space clean and unobstructed, controlling penetration rates to prevent a plunger effect, monitoring and adjusting drilling fluid rheology as necessitated by in-situ conditions, monitoring downhole pressures using an annular pressure tool to detect sudden changes in pressure, and setting surface casing as needed to stabilize loose overburden soils. Moreover, it is generally recommended that a surface monitoring protocol be implemented so that inadvertent returns, should they occur, can quickly be detected in order to reduce the extent of impact.

The risk of inadvertent returns, as noted previously, cannot be completely ruled out for any pipeline crossing. Refer to Section 5 of this report for an assessment of the risk with regard to hydrofracture.

3.6.2 Bedrock Misalignment

In any instance where a drilled crossing intersects bedrock there is a risk that the product pipe, or other tooling, experiences some form of misalignment and becomes stuck or damaged. Misalignment at the transition zone between soil and rock can occur for a number of reasons including improper ballasting, differential wear, or borehole migration. In an ideal situation, bedrock is intersected only once over the course of a designed path. Furthermore, it is preferable that that transition occur where overburden slowly transitions to bedrock in terms of relative density/strength. The lesser the contrast between soil and rock, the lower the potential for differential wear and misalignment becomes.

Contingency measures that reduce the risk of misalignment at the bedrock transition begin at the design level by extending the entry and exit tangents to beyond that which is believed to be the top of bedrock before initiating curvature. Steeper penetration angles may also alleviate some risks associated with misalignment. Risk is further reduced at the construction level by exercising extreme caution transitioning to and from bedrock, and if applicable, implementing a proper buoyancy control program.

3.6.3 Incompetent Bedrock

Excessive fracturing and fissuring of bedrock material increases the risk of operational difficulties. Risk related to incompetent bedrock are similar to those of coarse-grained content (i.e., cobbles and boulders) in that there is an inherent inability to fluidize the material with pressurized drilling fluid nor is there adequate stability to mechanically cut the material, as is the case with competent bedrock. Operational difficulties resulting from incompetent rock may include circulation loss, borehole instability, excessive tooling wear, or outright failure of downhole equipment.

Contingency measures associated with incompetent rock are limited due to the nature of the issue. Grouting or the use of lost circulation materials may be employed to combat circulation or borehole instability issues. In cases where the features are reasonably accessible from the surface, it may be possible to install casing to stabilize and isolate the drilled portions where specific concerns exists. Implementing a more robust coating specification may also be pursued to protect the pull section from abrasions and gouging which can occur in heavily fractured rock formations.

3.6.4 Specialized Pilot Hole Guidance

Conventional magnetic HDD guidance systems utilize both directional downhole (inclination and azimuth) surveys and surface monitoring (induced magnetic field) surveys to estimate the positioning of the pilot hole. Due to the width of the river at the crossing location, in addition to the prominence of the waterway, it is unlikely a conventional surface monitoring system could be employed across the length of the crossing. Although it is possible to conduct pilot hole operations for some distance without a surface monitoring system, there is a greater risk of deviating from the designed path associated with doing so. Substantial re-drilling efforts or acquisition of additional right of way may then be necessary to mitigate such deviations.

In order to assure that the pilot hole is constructed as designed and within the ROW, it is likely that the selected contractor will have to employ a gyroscopic steering tool (often referred to as simply a “gyro”). A gyro provides reasonably accurate directional guidance without relying on the use of a conventional secondary surface system. One disadvantage to the gyro is the exclusivity of equipment itself. That is to say that the tool is costly and may be relatively hard to secure for construction, particularly for lower to mid-tier contractors, as only a handful of units and trained technicians exist. While gyros are not as uncommon today as they once were, construction schedules and project managers should at a minimum consider the availability of the tool.

3.6.5 Soil Abrasivity

Soil abrasiveness can influence tooling effectiveness and wear. Highly abrasive materials can lead to increased construction durations, increased tooling costs, and potentially tooling failures if wear rates are either under-considered or not considered at all. The abrasiveness of rock/soils may also affect processing equipment at the surface (i.e., reclaiming units and pumps) through returning fluids. If abrasive formations are unavoidable, contingency measures may be limited to appropriate planning. Such planning may include sourcing applicable tooling, having redundancies in place for any susceptible equipment, and accounting for any schedule impacts related thereto.

Prospective contractors should be made well aware of abrasive geology prior to construction. In an effort to bring attention to this condition, an additional note was placed on the design drawing.

3.6.6 Tie-In Welds

Whenever HDD pullback is halted for a prolonged amount of time, there is a risk that the product pipe could become stuck downhole. In certain scenarios, prolonged downtime during pullback is unavoidable, as is the case where the pull section cannot be fabricated and pulled back in one continuous segment. Delays associated with joining multiple pipe strings during pullback greatly increase the risk of the pipe becoming stuck. Crossings existing within unconsolidated soils, such as sand and clay, are generally at a greater risk of becoming stuck since the stability of the reamed hole degrades over time. Crossings installed through bedrock inherently involve a lower degree of risk because the reamed hole is relatively stable. However, nearly all rock crossings involve some portions of overburden and therefore stopping during pullback, regardless of soil conditions, is generally regarded as undesirable.

The most effective contingency to reduce the risk of a tie-in weld is to simply remove the need for the weld (whether that be by acquiring additional workspace, shortening the proposed crossing, etc.). However, in scenarios where that is not possible, such as with this crossing, steps can be taken to reduce the risk. Such steps may include having a comprehensive weld strategy in place prior to pullback, having all manpower and all equipment on site ready to complete the welding, joint coating, etc., in the shortest amount of time possible, and having specialty tools such as a pneumatic hammer onsite or pipe thruster ready to assist in regaining momentum should the drill rig alone prove insufficient to move the pipe. The order in which the pipe segments are pulled back may also alleviate some risk. Typically, pipe segments are pulled back in manner so as to produce the most favorable relationship between stoppages and length of pipe installed underground.

3.7 Assessment of Feasibility

Given a length of 1,111 feet and a diameter of 20-inches, the proposed Schuylkill River installation falls well within current HDD industry capabilities. Although challenges in the form of pull section staging and poor quality, abrasive bedrock may be encountered, it is our opinion that conditions are ultimately surmountable. This assessment is supported by our knowledge that comparable crossings involving similar challenges have been completed in the past without major incident. Provided that an HDD contractor is selected with relevant experience, and sound judgement is used with respect to downhole tooling and drilling techniques, a prospective crossing in this area has a high probability of success. Consequently, JDH&A is of the opinion that the proposed crossing, or one thereabouts closely resembling it, is feasible.

4 PIPE STRESS ANALYSIS

4.1 Installation Stress

Loads and stresses associated with installation by HDD were analyzed using methods developed by JDH&A for the Pipeline Research Council International, Inc., (PCRI). Details with respect to the "PRCI Method" can be found in Section 5 of *Installation of Pipelines by Horizontal Directional Drilling, An Engineering Design Guide.*[1]

Two (2) installation scenarios for the proposed 20-inch O.D., 0.500-inch W.T., X-65 steel pipe were evaluated. The first scenario assumes that the pull section will be installed along a reamed hole that follows the exact design centerline shown on the plan and profile drawing included in Appendix 1. The second scenario assumes a worse-case model in which the pull section is installed along a reamed hole that is drilled 20 feet deeper than the designed profile, 50 feet longer than the designed length, and with a radius of curvature reduced to two-thirds (2/3) of the respective design radius. A summary of the assumptions used in each loading scenario is provided in Table 3. In practice, the actual loading scenario experienced during pullback will likely fall somewhere between the two (2) cases.

Table 3: Loading Scenarios

Loading Scenario	Path Geometry	Drilling Fluid Weight	Buoyancy Condition	Above Ground Load
Number 1 As-Designed	Length: As-designed Depth: As-designed Radius: 2,000'	9 ppg 12 ppg	Empty	Assumed Negligible
Number 2 Worse-Case	Length: 50' Longer Depth: 20' Deeper Radius: 1,333'	9 ppg 12 ppg	Empty	Assumed Negligible

In summary, for each of the loading scenarios investigated, tensile, bending, external hoop, and combined stresses are within acceptable limits as defined by the PRCI Method. Therefore, it is our opinion that the proposed pipe is suitable for installation by HDD.

---

[1] *Installation of Pipelines by Horizontal Directional Drilling, An Engineering Design Guide*, prepared under the sponsorship of the Pipeline Research Committee at the American Gas Association, April 15, 1995, Revised under the sponsorship of the Pipeline Research Council International, Inc., 2015.

This conclusion is based on three (3) assumptions:

1.) the geometry of the pull section segment will not exceed that of the loading scenarios described above

2.) the HDD contractor will not employ any improper construction procedures

3.) unanticipated problematic subsurface conditions will not be encountered

A summary of the estimated pulling loads for each installation scenario is provided in following table. Please refer to Appendix 2 for detailed installation stress calculations. It is important to keep in mind that the PRCI method considers pulling tension, pipe bending, and external pressure. It does not consider anomalies such as point loads that may result from certain subsurface conditions (e.g., a rock ledge or boulder), which under certain circumstances, could cause damage to the pipeline.

Table 4: Summary of Results –Installation Stress Analysis

Loading Scenario	Path Geometry	Drilling Fluid Weight (ppg)	Pulling Load (lbs.)	PRCI Stress Checks
Number 1	As-Designed	9 ppg 12 ppg	43,552 64,203	Pass
Number 2	Worse-Case	9 ppg 12 ppg	48,473 69,381	Pass

4.2 Operating Stress Analysis

A pipeline installed by HDD involves elastic bends that result as the product pipeline is pulled through the reamed hole. Flexural stresses associated with elastic bends were analyzed in combination with longitudinal and hoop stresses, that develop during hydrostatic testing and subsequent operation of the pipeline, to verify applicable limits specified in ASME B31.8 (2010). Four (4) scenarios for pipeline operation and testing were investigated. Details relative to the variables used in each scenario are provided in Table 5.

Table 5: Operational & Testing Parameters

Scenario	Radius (ft.)	Max. Pressure (psig)	Installation Temperature (ºF)[1]	Max Operating Temperature (ºF)
Number 1 (Operation)	Design (2,000’)	656	42	80
Number 2 (Operation)	Minimum (⅔ Design) (1,333’)	656	42	80
Number 3 (Operation)	Absolute Minimum (602’)	656	42	80
Number 4 (Hydrostatic Testing)	Absolute Minimum (602’)	1,312	42	42

[1] Taken as 10% lower than the region’s mean average earth temperature (Collins, 1925)

In summary, pipe stresses resulting from loading scenarios 1, 2, and 3, which involve the same pipeline operating parameters but different radii of curvature, are within acceptable limits as governed by ASME B31.8 (2010). Scenario 4 reduces the radius of curvature until combined stresses reach 90 percent of SMYS. Under this condition, the radius falls to 602 feet, which defines the “absolute minimum” radius. Should the Owner define an alternative stress limit, the absolute minimum could vary. Scenario 4 is based on a hydrostatic testing condition (2 x MAOP) and thus is not relatable to ASME code. Refer to Appendix 3 for detailed results of operational stresses.

5 HYDROFRACTURE

5.1 General Information Related to Hydrofracture

Hydrofracture is a phenomenon in which drilling fluid pressure in the annular space of a drilled hole exceeds the strength of the surrounding soil mass, resulting in deformation, cracking, and fracturing. The fractures may then serve as flow conduits for drilling fluid, allowing the fluid to escape into the formation and potentially up to the ground surface. Drilling fluid that makes its way to the ground surface is known as an inadvertent drilling fluid return or, more commonly today, a “frac-out.”

Although hydrofracture may be one mechanism by which frac-outs occur, it is not the only one. In fact, it is thought that frac-outs due to true hydrofracture only occur in a small percentage of cases.[2] Drilling fluid flows in the path of least resistance. Ideally, the path of least resistance is through the annulus of the drilled hole and back to the fluid containment pits at either the entry or exit points. However, the path of least resistance may also be through naturally occurring subsurface features such as fissures in the soil, shrinkage cracks, or porous deposits of gravel. Drilling fluid may also flow to the surface alongside buried piers, piles, utility poles, or other similar structures.

5.2 Hydrofracture Evaluation Strategy

The risk of hydrofracture can be determined by comparing the estimated confining capacity of the subsurface to the estimated annular pressure necessary to conduct HDD operations. If the anticipated drilling fluid pressure in the annulus exceeds the confining capacity of the subsurface, there is risk that inadvertent drilling fluid returns due to hydrofracture will occur. The point at which the estimated annular pressure exceeds the confining capacity, represents the theoretical point at which plastic yielding reaches the ground surface resulting in an inadvertent drilling fluid return.

5.3 Soil Confining Capacity

The confining capacity for the proposed crossing was calculated in accordance with the Delft Cavity Expansion Method (Delft Geotechnics[3]; Luger and Hergarden[4]). The Delft Method and resulting

[2] Step by Step Evaluation of Hydrofracture Risks for HDD Projects, North American Society for Trenchless Technology, NoDig Conference, Grapevine, TX., Bennett, R.D., Wallin, K., (2008)

[3] “A Report by Department of Foundations and Underground Engineering Prepared for O’Donnell Associates of Sugarland, TX.”, Delft Geotechnics, 1997

[4] “Directional Drilling in Soft Soil; Influence of Mud Pressures”, Luger, H.J., Hergarden, A.M., Proceedings of the International No-Dig Conference, Washington D.C., 1988

equations are based on cavity expansion theory[5] and are applicable to homogenous unconsolidated subsurface formations. When assessing heterogeneous soil conditions, the Delft Method requires engineering judgement with respect to the selection of geotechnical parameters that are used in the associated equations. The parameters chosen in this analysis were selected to provide conservative results and are based on site-specific geotechnical characterizations, Standard Penetration Test (SPT) results, and unconfined compressive strength testing. Since the subsurface involves multiple soil types, each involving distinct engineering properties, a dynamic weighted average approach was used to model the subsurface.

5.4 Consolidated Formations (Bedrock) Pressure Considerations

The Delft Method, which is a widely accepted method for estimating the potential for hydrofracture on HDD installations, was established for crossings beneath levees in unconsolidated soil formations. Therefore, the method is not applicable to crossings installed through bedrock. As it relates to HDD installations, an established or widely recognized method for calculating confining pressures associated with bedrock has yet to be developed. The principal reasoning for this is that annular pressures associated with HDD installations are generally very low in comparison to the pressures necessary to initiate fracturing in bedrock.

In light of increasing sensitivities surrounding inadvertent drilling fluid returns, JDH&A has estimated bedrock confining pressures in an effort to further evaluate risk. Confining pressures for rock were estimated using two (2) methods. The first method utilizes the Delft Method and assumes bedrock conditions can be modeled as a dense uncemented sand. Because of the nature of the calculations, dense sand achieves a high confining capacity and thus a low risk of hydrofracture. Although simple, analyzing bedrock as a dense sand model using the Delft equations is useful in the sense that if the risk of hydrofracture is low under unconsolidated sand conditions, they will be equally as low or lower under consolidated bedrock conditions.

The second method used to calculate confining capacities in bedrock borrows principles from conventional downhole drilling and is based on procedures detailed in Chapter 16 of *Petroleum Production Systems* (Economides and others, 1994).[6] This method utilizes principal stresses, combined with typical geotechnical solutions and rock strength values, to estimate bedrock fracturing pressures. Conservative engineering judgment was again employed with respect to selection of geotechnical parameters.

5.5 Estimated Annular Pressure

The estimated annular pressure is calculated by summing frictional losses and hydrostatic pressures of the drilling fluid. Frictional losses for HDD pilot hole operations are calculated using the conservative Bingham Plastic Model, which is described in Chapter 4 of the Society of Petroleum Engineers' *Applied Drilling Engineering*.[7] Most drilling fluids conform to Bingham plastic behavior as they do not retain a

---

[5] *Expansion of Cavities in Infinite Soil Mass*, ASCE Journal of the Soil Mechanics and Foundations Division, Vol. 98: 265-290, Vesić, A.S., 1972

[6] *Petroleum Production Systems,* Michael J. Economides [et al], Englewood Cliffs, NJ, PTR Prentice Hall, 1994

[7] *Applied Drilling Engineering,* Society of Petroleum Engineers, Richardson, Texas, A. T. Bourgoyne, Jr. [et al], 1991

constant viscosity and require a minimum pressure or threshold shear stress to induce flow. In addition to frictional losses, annular pressures include the static head pressure of the vertical column of drilling fluid. This collective value represents the estimated annular pressure as shown on the hydrofracture graphical summary. Variables with respect to drilling fluid rheology and tooling used in these annular pressure calculations are provided in Table 6.

Table 6: Drilling Fluid Parameters

Drilling Fluid Parameter	Value
Effective Pilot Hole Diameter	14 inches
Drill Pipe Diameter	6.625 inches
Drilling Fluid Weight	10.5 pounds per gallon
Pump Flow Rate	400 gallons per minute
Yield Point	29 pounds per 100 ft^2
Plastic Viscosity	15 cP
Frictional Pressure Gradient	0.020 psi per foot

5.6 Hydrofracture Risk Assessment

A graphical summary of the results of hydrofracture calculations discussed in previous sections is attached as Appendix 4. Two (2) graphs are shown. The top graph provides a plot of the subsurface confining capacity vs the estimated annular pressure with the x-axis reflecting the distance from the entry point in feet and the y-axis representing pressure in pounds per square inch (psi). Calculations associated with the “Delft Method” are depicted as a solid blue line while rock fracturing pressures calculated in accordance with Economides’ procedures are depicted as a purple line. The estimated annular pressures are shown as a red line and correspond to the geometry and assumptions detailed previously. Because peak annular pressures are typically observed during pilot hole drilling, the potential for hydrofracture during reaming was not considered.

The lower graph presents an elevation plot of the HDD design, the ground and/or waterbody profile, and the geotechnical boring information and associated tributary areas. Both graphs, upper and lower, correspond in the x-axis which allow for a direct comparison of hydrofracture information at any given point along the design path. A tabular summary of results of the hydrofracture calculations is attached as part of Appendix 4. It should be noted, hydrofracture calculations were analyzed at 10-feet increments along the drill path, however, for presentation purposes the attached tabular data reflects calculations only every 50-feet.

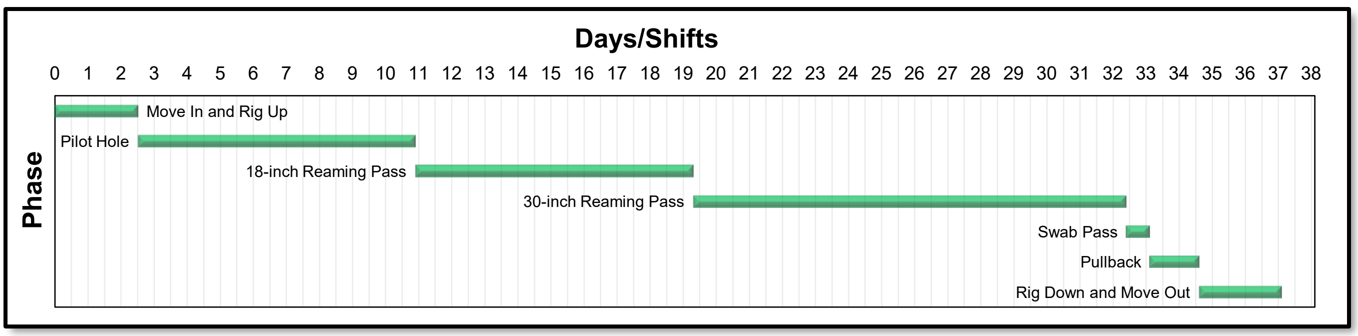
Based on the geotechnical parameters and assumptions discussed previously, under normal drilling operations with full circulation, hydrofracture calculations indicate the estimated annular pressure of the Schuylkill River HDD will remain well below subsurface confining capacities over the vast majority of crossing, indicating an inadvertent drilling fluid return due to hydrofracture is unlikely.

Although the calculated risk of inadvertent returns due to hydrofracture is perceived as being low, JDH&A recommends following best practices laid out in Section 3.6.1. Such practices include maintaining drilling fluid circulation at all times, utilization of an annular pressure monitoring tool during pilot hole operations, continuous electronic monitoring of mud tank volumes, and controlling penetration rates and travel speeds in order to prevent overwhelming the drilling fluid carrying capacity. Lastly, it is important to keep in mind that inadvertent drilling fluid returns may occur due to mechanisms unrelated to hydrofracture. As discussed previously, it remains possible that inadvertent drilling fluid returns can occur by flowing to the ground surface through existing fractures or coarse granular deposits.

6 HDD CONSTRUCTION

6.1 Projected Duration

The estimated duration of construction for the Schuylkill River crossing is 37 days. This estimate assumes single 10-hour shifts during pilot hole, reaming, and pullback operations. Production rates were estimated by JDH&A based on information contained within the Pipeline Research Council International's "*Installation of Pipelines by Horizontal Directional Drilling, An Engineering Design Guide*"[8], as well as past experience in similar subsurface conditions. Refer to Appendix 5 for details relative to the estimate. A chart summarizing the projected duration is shown below for reference.



It is worth noting that the estimated duration is based on operations proceeding in typical fashion and therefore do not account for substantial contingency. The occurrence of unanticipated operational problems could increase the duration of construction by 50 to 100 percent.

6.2 Bore Enlargement

The estimated duration detailed above is based on a hole enlargement diameter of 30-inches. Standard practice dictates that the HDD borehole is to be enlarged to the lesser of 150% or twelve (12) inches greater than the outside diameter of the product pipe.[9] For a 20-inch installation, this value would equate to 30-inches. It is worth noting, in certain situations construction contractors may elect to exceed standard practice (i.e., ream in excess of 30-inches) depending on individual judgment and experience.

6.3 Drilling Fluid and Spoil Estimate

Drilling fluid and spoil volumes have been estimated in accordance with the bore enlargement size detailed previously. Refer to Appendix 5 for details relative to drilling fluid and spoil volumes. Please

---

[8] *Installation of Pipelines by Horizontal Directional Drilling, An Engineering Design Guide*, 2015, pg. 15-16

[9] *Installation of Pipelines by Horizontal Directional Drilling, An Engineering Design Guide*, 2015, pg. 77

note that calculations are based on typical values in conjunction with an assumed circulation loss factor. Calculations are provided as a high-level reference only. Depending on means and methods of individual construction contractors, values may vary significantly.

6.4 Drill Rig Capacity

Loads and stresses associated with installation by HDD were analyzed as part of Section 4.1 of this report. These figures provide a high-level reference for future construction efforts, namely the appraisal of prospective drilling equipment. Depending on as-drilled conditions, such as pilot hole geometry and the density of drilling fluid situated downhole, estimated installation (tensile) loads associated with the Schuylkill River crossing may vary between 43,552 lbs. (9 ppg mud – as-designed geometry) and 69,381 lbs. (12 ppg mud – worse-case geometry). Taking an average of the above figures yields 56,467 lbs. Applying a safety factor of two (2) advances this figure to approximately 112,933 lbs.

While there is not a standard method for determining equipment sizing, it is generally recommended that a safety factor is employed in relation to the anticipated (tensile) loading conditions. It should be noted that installation (tensile) forces are only one of several forces associated with HDD operations. Depending on site-specific conditions and the final bore diameter, equipment capabilities may need to take account of circumstances beyond that of purely installation (tensile) loading.

6.5 Pull Section Breakover Guidance

An important phase of HDD construction, particularly for steel pipelines, is the lifting and handling of the product pipe, or carrier pipe, during pullback. HDD installation is ultimately accomplished by transitioning surface staged pipe to a reamed hole. This transition is accomplished by curvature, or a breakover bend, formed along the surface which generally must be elevated some distance and supported. The breakover bend changes the orientation of the pipe segment such that it can be transitioned into the reamed hole during pullback. Improper, or absent, consideration of breakover bend geometry may increase the likelihood of the product pipe being overstressed or compromised during the installation process.

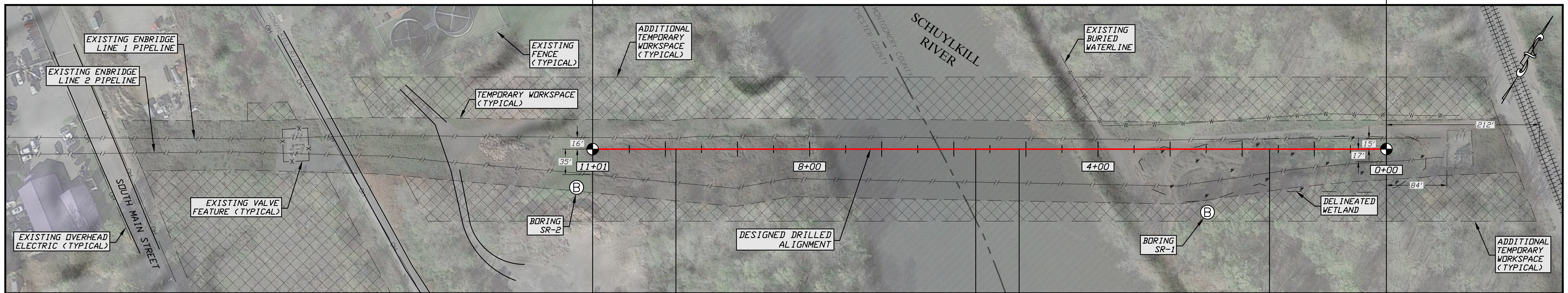
In an effort to address the particular pullback challenges revolving around limitations to workspace, JDH&A has assembled a reference worksheet to provide high level guidance to construction contractors. Conceptual breakover guidance for the proposed Schuylkill River crossing is provided in Appendix 1.

Appendix 1

HDD Plan, Profile, and

Overbend Drawing

HORIZONTAL LENGTH = 1,101'
TRUE DRILLED LENGTH = 1,111'



EXIT POINT @ 12°
11+00.81, 105.25
N 313244.60, E 2587043.01

P.T. 12° SAG BEND
9+85.35, 80.70

P.C. 12° SAG BEND
5+69.53, 37.00
RADIUS = 2,000'

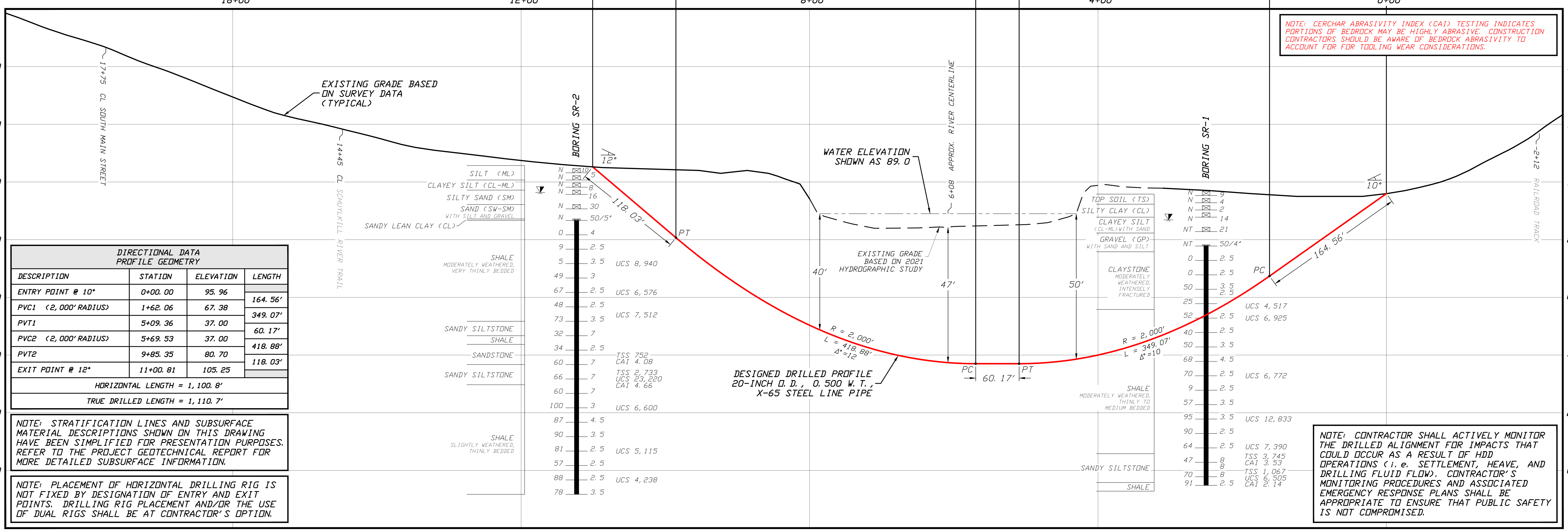
P.T. 10° SAG BEND
5+09.36, 37.00

P.C. 10° SAG BEND
1+62.06, 67.38
RADIUS = 2,000'

ENTRY POINT @ 10°
0+00.00, 95.96
N 313800.39, E 2587993.21

PLAN

SCALE: 1"=80'



NOTE: CERCHAR ABRASIVITY INDEX (CAI) TESTING INDICATES PORTIONS OF BEDROCK MAY BE HIGHLY ABRASIVE. CONSTRUCTION CONTRACTORS SHOULD BE AWARE OF BEDROCK ABRASIVITY TO ACCOUNT FOR FOR TOOLING WEAR CONSIDERATIONS.

DIRECTIONAL DATA
PROFILE GEOMETRY

DESCRIPTION	STATION	ELEVATION	LENGTH
ENTRY POINT @ 10°	0+00.00	95.96	
			164.56'
PVC1 (2,000' RADIUS)	1+62.06	67.38	
			349.07'
PVT1	5+09.36	37.00	
			60.17'
PVC2 (2,000' RADIUS)	5+69.53	37.00	
			418.88'
PVT2	9+85.35	80.70	
			118.03'
EXIT POINT @ 12°	11+00.81	105.25	
HORIZONTAL LENGTH = 1,100.8'			
TRUE DRILLED LENGTH = 1,110.7'			

NOTE: STRATIFICATION LINES AND SUBSURFACE MATERIAL DESCRIPTIONS SHOWN ON THIS DRAWING HAVE BEEN SIMPLIFIED FOR PRESENTATION PURPOSES. REFER TO THE PROJECT GEOTECHNICAL REPORT FOR MORE DETAILED SUBSURFACE INFORMATION.

NOTE: PLACEMENT OF HORIZONTAL DRILLING RIG IS NOT FIXED BY DESIGNATION OF ENTRY AND EXIT POINTS. DRILLING RIG PLACEMENT AND/OR THE USE OF DUAL RIGS SHALL BE AT CONTRACTOR'S OPTION.

NOTE: CONTRACTOR SHALL ACTIVELY MONITOR THE DRILLED ALIGNMENT FOR IMPACTS THAT COULD OCCUR AS A RESULT OF HDD OPERATIONS (i.e. SETTLEMENT, HEAVE, AND DRILLING FLUID FLOW). CONTRACTOR'S MONITORING PROCEDURES AND ASSOCIATED EMERGENCY RESPONSE PLANS SHALL BE APPROPRIATE TO ENSURE THAT PUBLIC SAFETY IS NOT COMPROMISED.

PROFILE

SCALE: 1"=80' HORIZONTAL
1"=20' VERTICAL

GENERAL LEGEND

DRILLED PATH ENTRY/EXIT POINT

GEOTECHNICAL LEGEND

BORING LOCATION — GROUNDWATER LEVEL

UNDISTURBED SAMPLE

53 1.5 ← COMPRESSIVE STRENGTH (TSF)

SPLIT SPOON SAMPLE

53 23 ← PENETRATION RESISTANCE IN BLOWS PER FOOT FOR A 140 POUND HAMMER FALLING 30 INCHES

PERCENTAGE OF GRAVEL BY WEIGHT FOR SAMPLES CONTAINING GRAVEL

CORE BARREL SAMPLE

UCS 6,250 ← UNCONFINED COMPRESSIVE STRENGTH (PSI)
TSS 6,250 ← TENSILE SPLITTING STRENGTH (PSI)
53 6 ← MOHS HARDNESS OR CERCHAR ABRASIVITY INDEX (CAI)
ROCK QUALITY DESIGNATION (PERCENT)

GEOTECHNICAL NOTES

1. GEOTECHNICAL DATA PROVIDED BY GEOENGINEERS, INC., SPRINGFIELD, MO. REFER TO THE PROJECT GEOTECHNICAL REPORT DATED FEBRUARY 8, 2023 FOR MORE DETAILED SUBSURFACE INFORMATION.
2. THE LETTER "N" TO THE LEFT OF A SAMPLE INDICATES THAT NO GRAVEL WAS OBSERVED IN THE SAMPLE. THE LETTERS "NT" INDICATE THAT GRAVEL WAS OBSERVED BUT NO GRADATION TEST WAS PERFORMED.
3. THE GEOTECHNICAL DATA IS ONLY DESCRIPTIVE OF THE LOCATIONS ACTUALLY SAMPLED. EXTENSION OF THIS DATA OUTSIDE OF THE ORIGINAL BORINGS MAY BE DONE TO CHARACTERIZE THE SOIL CONDITIONS, HOWEVER, COMPANY DOES NOT GUARANTEE THESE CHARACTERIZATIONS TO BE ACCURATE. CONTRACTOR MUST USE HIS OWN EXPERIENCE AND JUDGMENT IN INTERPRETING THIS DATA.

TOPOGRAPHIC SURVEY NOTES

1. TOPOGRAPHIC SURVEY DATA PROVIDED BY AUDUBON ENGINEERING COMPANY, L.P., HOUSTON, TEXAS. ADDITIONAL DATA OBTAINED FROM THE PENNSYLVANIA SPATIAL DATA ACCESS (PASDA), PENNSYLVANIA DEPARTMENT OF CONSERVATION AND NATURAL RESOURCES, PAMAP PROGRAM.
2. NORTHINGS AND EASTINGS ARE IN U.S. SURVEY FEET REFERENCED TO PENNSYLVANIA STATE PLANE COORDINATES, SOUTH ZONE, NAD83.
3. ELEVATIONS ARE IN FEET REFERENCED TO NAVD88, UNLESS OTHERWISE NOTED.

DRILLED PATH NOTES

1. DRILLED PATH STATIONING IS IN FEET BY HORIZONTAL MEASUREMENT AND IS REFERENCED TO CONTROL ESTABLISHED FOR THE DRILLED SEGMENT.
2. DRILLED PATH COORDINATES REFER TO CENTERLINE OF PILOT HOLE AS OPPOSED TO TOP OF INSTALLED PIPE.

PILOT HOLE TOLERANCES

THE PILOT HOLE SHALL BE DRILLED TO THE TOLERANCES LISTED BELOW. HOWEVER, IN ALL CASES, RIGHT-OF-WAY RESTRICTIONS AND CONCERN FOR ADJACENT FACILITIES SHALL TAKE PRECEDENCE OVER THESE TOLERANCES.

1. ENTRY POINT: UP TO 5 FEET FORWARD OR BACK FROM THE DESIGNED ENTRY POINT; UP TO 3 FEET RIGHT OR LEFT OF THE DESIGNED ALIGNMENT
2. EXIT POINT: UP TO 5 FEET SHORT OR 15 FEET LONG RELATIVE TO THE DESIGNED EXIT POINT; UP TO 3 FEET RIGHT OR 7 FEET LEFT OF THE DESIGNED ALIGNMENT
3. ELEVATION: UP TO 5 FEET ABOVE AND 10 FEET BELOW THE DESIGNED PROFILE
4. ALIGNMENT: UP TO 5 FEET RIGHT OR LEFT OF THE DESIGNED ALIGNMENT UNLESS OTHERWISE DEFINED
5. CURVE RADIUS: NO LESS THAN 1,333 FEET BASED ON A 3-JOINT AVERAGE (ASSUMING RANGE 2 DRILL PIPE)

PROTECTION OF EXISTING FACILITIES

CONTRACTOR SHALL UNDERTAKE THE FOLLOWING STEPS PRIOR TO COMMENCING DRILLING OPERATIONS.

1. CONTACT THE UTILITY LOCATION/NOTIFICATION SERVICE FOR THE CONSTRUCTION AREA.
2. POSITIVELY LOCATE AND STAKE ALL EXISTING UNDERGROUND FACILITIES. ANY FACILITIES LOCATED WITHIN 10 FEET OF THE DESIGNED DRILLED PATH SHALL BE EXPOSED.
3. MODIFY DRILLING PRACTICES AND DOWNHOLE ASSEMBLIES AS NECESSARY TO PREVENT DAMAGE TO EXISTING FACILITIES.

COMMONWEALTH OF PENNSYLVANIA
REGISTERED PROFESSIONAL ENGINEER
JEFFREY S. PUCKETT
No. PE086530
4/6/2023

ISSUED FOR BID - 04/06/23

LINE 1 REPLACEMENT PROJECT

PLAN AND PROFILE
20-INCH PIPELINE CROSSING OF THE SCHUYLKILL RIVER BY HORIZONTAL DIRECTIONAL DRILLING

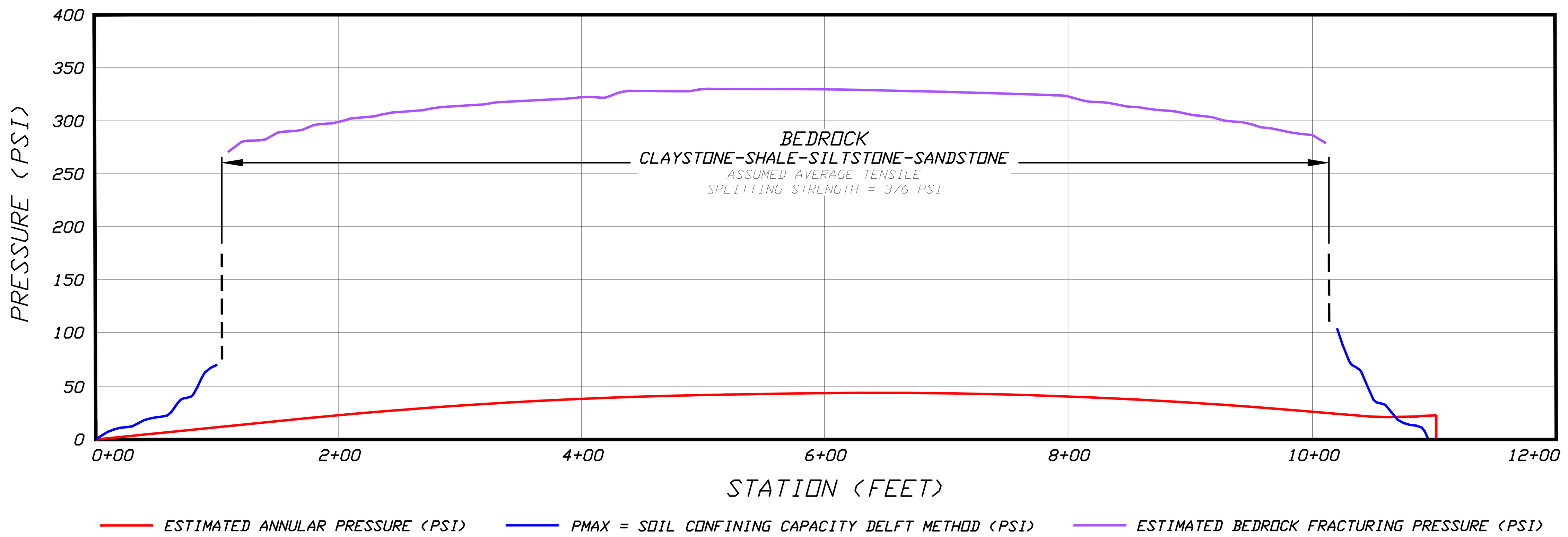
LOCATION: CHESTER & MONTGOMERY COUNTY, PENNSYLVANIA

DRAWN	DATE	CHECKED	APPROVED	SCALE	DRAWING NUMBER	REVISION
ACM	10/24/22	LKB	JMS	SHOWN FOR D-SIZED PLOT	SR1-HDD-040623-01	1

NO.	DATE	REVISION DESCRIPTION	BY	CHK'D	APP.
1	04/06/23	ISSUED FOR BID	IDS	LKB	JSP
0	03/30/23	ISSUED FOR REVIEW	LKB	IDS	JSP

J.D.Hair&Associates,Inc.
Consulting Engineers
6100 S. Yale Ave
Suite 1610
Tulsa, Oklahoma 74136

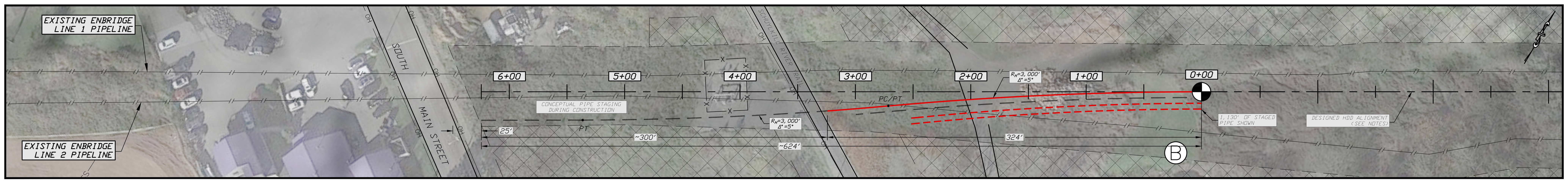
PROJECT NO. Audubon\2233
SHEET NO. 1



HYDROFRACTURE PRESSURE CURVES

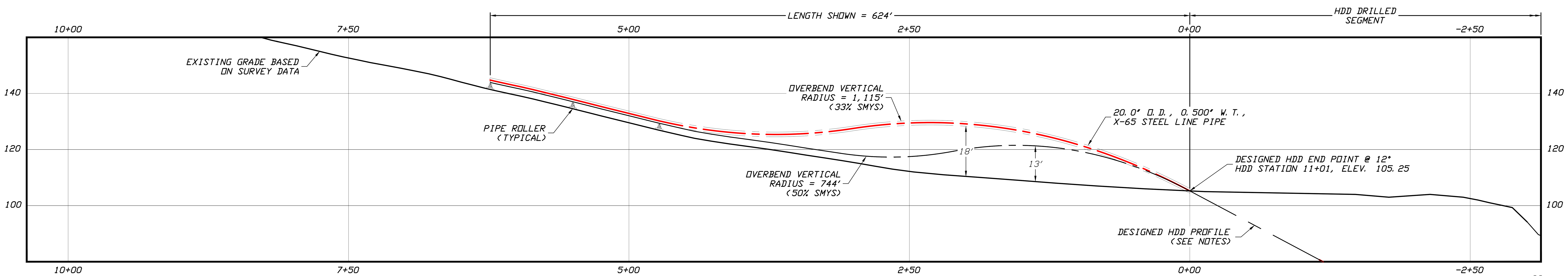
LINE PIPE SPECIFICATION	20.00" O.D., 0.500" W.T., X-65
PIPE COATING	TBD
MAXIMUM OPERATING PRESSURE	656 PSIG
ASSUMED INSTALLATION TEMPERATURE	42°F
ASSUMED MAXIMUM OPERATING TEMPERATURE	80°F
HYDROSTATIC TEST PRESSURE	1,312 PSIG
DESIGNED HDD HORIZONTAL LENGTH	1,101 FEET
DESIGNED HDD TRUE DRILLED LENGTH	1,111 FEET
EMPTY PIPE UPLIFT FORCE (9 / 12 PPG MUD)	+ 42.7 LB/FT / + 91.7 LB\FT
BALLASTED PIPE WEIGHT (9 / 12 PPG MUD)	-80.1 LB/FT / -31.2 LB\FT
CALCULATED PULLING LOAD (PRCI)	138,762 POUNDS (BASED ON WORST-CASE MODEL WITH NO BUOYANCY CONTROL AND FoS = 2)

CRITICAL INFORMATION



OVERBEND PLAN

PLAN
SCALE: 1"=50'



OVERBEND ELEVATION

PROFILE
SCALE: 1"=50' HORIZONTAL
1"=20' VERTICAL

STEEL LINE PIPE PROPERTIES

- OUTSIDE DIAMETER = 20.00 INCHES
- NOMINAL WALL THICKNESS = 0.500 INCHES
- UNIT WEIGHT = 104.13 POUNDS/FOOT
- SPECIFIED MINIMUM YIELD STRENGTH (SMYS) = 65,000 PSI

OVERBEND STRESS CRITERIA

- MAXIMUM ALLOWABLE BENDING STRESS = 32,500 PSI (50% OF SMYS)
- MINIMUM ALLOWABLE OVERBEND RADIUS = 744 FEET (50% OF SMYS)
- OVERBEND RADIUS AS-SHOWN = 1,115 FEET (33% OF SMYS)
- MAXIMUM OVERBEND SUPPORT SPACING (SIMPLE SPAN) = 116 FEET
- MAXIMUM OVERBEND SUPPORT SPACING (CANTILEVERED SPAN) = 58 FEET
- MAXIMUM DRAG SEGMENT ROLLER SPACING (BASED ON L/360 DEFLECTION LIMIT) = 87 FEET

OVERBEND NOTES

1. THE OVERBEND GEOMETRY INDICATED ON THIS DRAWING DEMONSTRATES ONE OF MANY POSSIBLE CONFIGURATIONS THAT WOULD BE CONSIDERED ACCEPTABLE WITH REGARD TO ALLOWABLE STRESSES. CALCULATED BENDING STRESSES IN THIS CONFIGURATION FALL BELOW 50% OF THE SPECIFIED MINIMUM YIELD STRENGTH OF THE 20-INCH STEEL PIPE BASED ON MOMENT-CURVATURE AND PURE BENDING. DYNAMIC LOADS INVOLVED WITH POSITIONING, LIFTING, AND/OR HANDLING OF THE STEEL PIPE DURING PULLBACK HAVE NOT BEEN CONSIDERED IN THIS ANALYSIS. CONTRACTOR RETAINS ALL RESPONSIBILITY FOR HANDLING THE PULL SECTION SO THAT THE PIPE AND THE CORROSION COATING ARE NOT DAMAGED.
2. CONTRACTOR IS RESPONSIBLE FOR DETERMINING ACTUAL LIFT POINT LOCATIONS, LIFT HEIGHTS, AND LIFTING EQUIPMENT NECESSARY TO ENSURE THAT OPERATIONS ARE CONDUCTED SAFELY AND THE PIPE IS NOT DAMAGED OR OVERSTRESSED.
3. THE OVERBEND GEOMETRY SHOWN IS BASED ON THE PULL SECTION ENTERING THE REAMED HOLE AT THE EXIT POINT LOCATION AND EXIT ANGLE INDICATED ON THE HDD DESIGN DRAWING. NOTE THAT MODIFICATIONS MAY BE REQUIRED BASED ON THE ACTUAL LOCATION AND ANGLES AT THE COMPLETION OF REAMING OPERATIONS.
4. THE OVERBEND GEOMETRY TABLES INCLUDED ON THIS DRAWING ARE INTENDED TO PROVIDE HIGH-LVEL GUIDANCE WITH REGARD TO POTENTIAL LIFTING HEIGHTS ALONG THE LENGTH OF THE OVERBEND. TWO OVERBEND SCENARIOS HAVE BEEN INCLUDED, ALTHOUGH IT SHOULD BE NOTED THAT THE CONTRACTOR IS NOT LIMITED TO THESE SCENARIOS. THE HEIGHTS THAT HAVE BEEN PROVIDED REPRESENT VERTICAL DISTANCES FROM THE EXISTING GRADE TO THE BOTTOM OF THE PIPE. NOTE THAT LIFT HEIGHTS MAY NEED TO BE MODIFIED BASED ON ACTUAL GRADE ELEVATIONS AT THE TIME OF CONSTRUCTION.

OVERBEND GEOMETRY TABLE (1,115' RADIUS AS SHOWN)

OFFSET (X)	HEIGHT* (Y)	OFFSET (X)	HEIGHT* (Y)	OFFSET (X)	HEIGHT* (Y)
0+10	1.04	2+10	17.84	4+10	3.31
0+20	2.84	2+20	17.70	4+20	3.11
0+30	4.54	2+30	17.38	4+30	2.98
0+40	6.15	2+40	16.98	4+40	2.89
0+50	7.61	2+50	16.42	4+50	2.71
0+60	8.98	2+60	15.68	4+60	2.57
0+70	10.26	2+70	14.78	4+70	2.50
0+80	11.45	2+80	13.72	4+80	2.50
0+90	12.51	2+90	12.54	4+90	2.50
1+00	13.48	3+00	11.30	–	–
1+10	14.35	3+10	10.07	–	–
1+20	15.13	3+20	8.96	–	–
1+30	15.78	3+30	7.95	–	–
1+40	16.35	3+40	7.04	–	–
1+50	16.82	3+50	6.19	–	–
1+60	17.21	3+60	5.43	–	–
1+70	17.51	3+70	4.79	–	–
1+80	17.73	3+80	4.26	–	–
1+90	17.85	3+90	3.85	–	–
2+00	17.89	4+00	3.53	–	–

* HEIGHTS NOTED ARE FROM GRADE TO BOTTOM OF PIPE

OVERBEND GEOMETRY TABLE (744' MINIMUM RADIUS)

OFFSET (X)	HEIGHT* (Y)	OFFSET (X)	HEIGHT* (Y)	OFFSET (X)	HEIGHT* (Y)
0+10	1.87	2+10	8.72	–	–
0+20	3.59	2+20	7.74	–	–
0+30	5.17	2+30	6.80	–	–
0+40	6.62	2+40	6.00	–	–
0+50	7.87	2+50	5.28	–	–
0+60	8.99	2+60	4.59	–	–
0+70	9.97	2+70	3.97	–	–
0+80	10.81	2+80	3.41	–	–
0+90	11.49	2+90	2.96	–	–
1+00	12.02	3+00	2.67	–	–
1+10	12.41	3+10	2.53	–	–
1+20	12.67	3+20	2.51	–	–
1+30	12.76	3+30	2.50	–	–
1+40	12.72	3+40	2.50	–	–
1+50	12.54	3+50	2.51	–	–
1+60	12.24	3+60	2.50	–	–
1+70	11.80	–	–	–	–
1+80	11.23	–	–	–	–
1+90	10.53	–	–	–	–
2+00	9.69	–	–	–	–

* HEIGHTS NOTED ARE FROM GRADE TO BOTTOM OF PIPE

ISSUED FOR BID – 04/06/23

LINE 1 REPLACEMENT PROJECT

REFERENCE DRAWING
20-INCH PIPELINE CROSSING OF THE SCHUYLKILL RIVER BY HORIZONTAL DIRECTIONAL DRILLING

LOCATION: CHESTER & MONTGOMERY COUNTY, PENNSYLVANIA

DRAWN	DATE	CHECKED	APPROVED	SCALE	DRAWING NUMBER	REVISION
LKB	2/14/23	IDS	JSP	SHOWN FOR D-SIZED PLOT	SR2-HDD-040623-01	1

NO.	DATE	REVISION DESCRIPTION	BY	CHK'D	APP.
1	04/06/23	ISSUED FOR BID	IDS	LKB	JSP
0	03/30/23	ISSUED FOR REVIEW	IDS	LKB	JSP

J.D.Hair&Associates,Inc.
Consulting Engineers
6100 S. Yale Ave
Suite 1610
Tulsa, Oklahoma 74136

PROJECT NO.
Audubon\2233

SHEET NO.
2

Appendix 2

Installation Loading and Stress Calculations

Loading Scenario	Path Geometry	Drilling Fluid Weight (ppg)	Pulling Load (lbs.)	PRCI Stress Checks
Number 1	As-Designed	9 ppg 12 ppg	43,552 64,203	Pass
Number 2	Worse-Case	9 ppg 12 ppg	48,473 69,381	Pass

Installation Stress Scenario

20-inch O.D., 0.500-inch W.T., Grade X-65,
As-Designed Geometry, 9 ppg mud, Un-ballasted Model

J.D.Hair&Associates,Inc.
Consulting Engineers

HDD Installation and Pipe Stress Analysis

Project Information			
Project :	Enbridge Line 1 Replacement Project	User :	LKB
Crossing :	20-inch Schuylkill River Crossing	Date :	3/29/2023
Comments :	Installation stress model based on as-designed drilled path - 9 ppg drilling fluid and no buoyancy control measures		

Line Pipe Properties			
Pipe Outside Diameter =	20.000	in	
Wall Thickness =	0.500	in	
Specified Minimum Yield Strength =	65,000	psi	
Young's Modulus =	2.9E+07	psi	
Moment of Inertia =	1455.91	in^4	
Pipe Face Surface Area =	30.63	in^2	
Diameter to Wall Thickness Ratio, D/t =	40		
Poisson's Ratio =	0.3		
Coefficient of Thermal Expansion =	6.5E-06	in/in/°F	
Pipe Weight in Air =	104.13	lb/ft	
Pipe Interior Volume =	1.97	ft^3/ft	
Pipe Exterior Volume =	2.18	ft^3/ft	

HDD Installation Properties			
Drilling Mud Density =	9.0	ppg	
=	67.3	lb/ft^3	
Ballast Density =	62.4	lb/ft^3	
Coefficient of Soil Friction =	0.30		
Fluid Drag Coefficient =	0.025	psi	
Ballast Weight =	122.86	lb/ft	
Displaced Mud Weight =	146.87	lb/ft	

Installation Stress Limits[1]			
Tensile Stress Limit, 90% of SMYS, F_t =	58,500	psi	
For D/t <= 1,500,000/SMYS, F_b =	48,750	psi	No
For D/t > 1,500,000/SMYS and <= 3,000,000/SMYS, F_b =	44,460	psi	Yes
For D/t > 3,000,000/SMYS and <= 300, F_b =	43,420	psi	No
Allowable Bending Stress, F_b =	44,460	psi	
Elastic Hoop Buckling Stress, F_{he} =	15,950	psi	
For F_{he} <= 0.55*SMYS, Critical Hoop Buckling Stress, F_{hc} =	15,950	psi	Yes
For F_{he} > 0.55*SMYS and <= 1.6*SMYS, F_{hc} =	32,121	psi	No
For F_{he} > 1.6*SMYS and <= 6.2*SMYS, F_{hc} =	16,296	psi	No
For F_{he} > 6.2*SMYS, F_{hc} =	65,000	psi	No
Critical Hoop Buckling Stress, F_{hc} =	15,950	psi	
Allowable Hoop Buckling Stress, $F_{hc}/1.5$ =	10,633	psi	

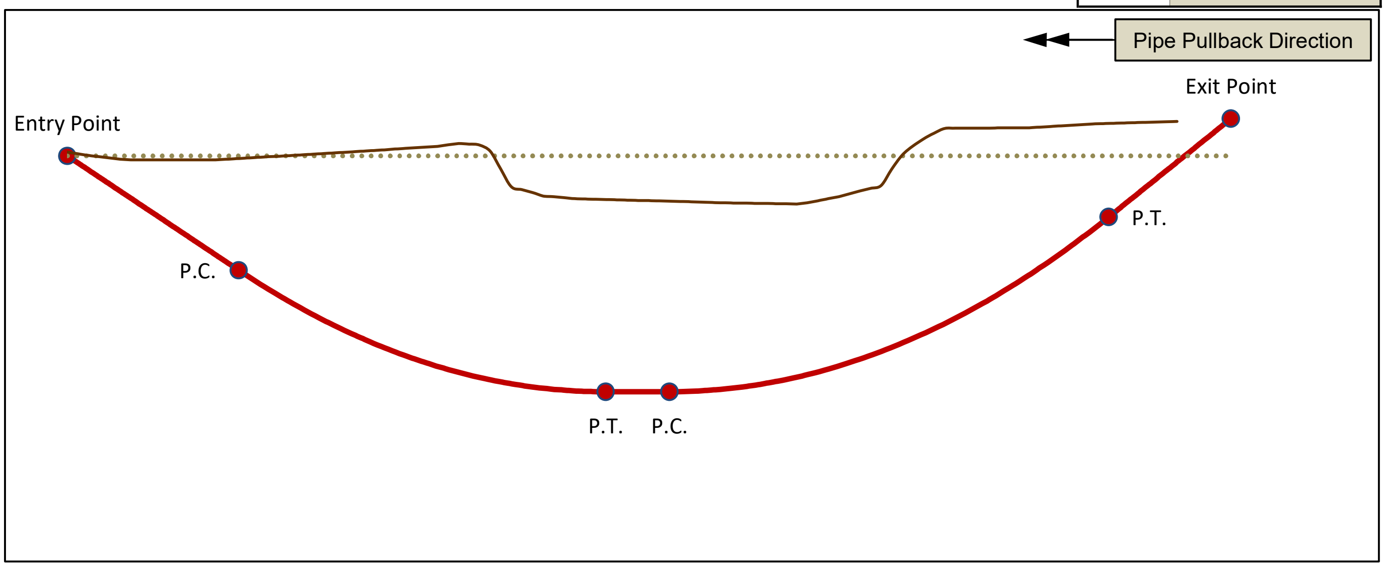
[1] Installation limits as defined by the technical report titled, *Installation of Pipelines by Horizontal Directional Drilling, An Engineering Design Guide,* prepared under the sponsorship of the Pipeline Research Committee at the American Gas Association, April 15, 1995, Revised under the sponsorship of the Pipeline Research Council International, Inc., 2015.

HDD Installation and Pipe Stress Analysis

		Station	Elevation	Angle	Radius	Length	Average Tension	Total Pull
Entry Point		0.00	95.96	10.00				43,552
Entry Tangent						164.56		
Entry Sag Bend	PC	162.06	67.38					39,594
	PI	334.38	37.00	10.00	2000	349.07	32,461	
	PT	509.36	37.00				0	25,329
Bottom Tangent				0.00		60.15		
Exit Sag Bend	PC	569.51	37.00					23,424
	PI	779.72	37.00	12.00	2000	418.88	14,089	
	PT	985.33	80.70				0	4,755
Exit Tangent						118.06		
Exit Point		1100.81	105.25	12.00	Above Ground Load			0
Drilling Mud			95.96	(Graph =)				
Ballast				(Graph =)				

No.	Station	Elevation	
1			Grade Elevation Points
2			
3			
4			
5			
6			
7			
8			
9			
10			
1			Control Point

= Cover at Control Point



Step 2, Drilled Path Input

HDD Installation and Pipe Stress Analysis

Point	Fluidic Drag	Weight & Weight Friction	Bending Friction	Total Pull	Tensile Stress		Bending Stress		External Hoop Stress		Tensile & Bending Stress		Tensile, Bending & Ext. Hoop Stress	
Entry Point	20,936	4,729	17,887	43,552	1,422	ok	0	ok	0	ok	0.02	ok	0.00	ok
					1,293	ok	0	ok	267	ok	0.02	ok	0.00	ok
PC	17,835	3,872	17,887	39,594										
					1,293	ok	12,083	ok	267	ok	0.29	ok	0.07	ok
					827	ok	12,083	ok	551	ok	0.29	ok	0.07	ok
PT	11,255	5,172	8,902	25,329										
					827	ok	0	ok	551	ok	0.01	ok	0.00	ok
					765	ok	0	ok	551	ok	0.01	ok	0.00	ok
PC	10,121	4,401	8,902	23,424										
					765	ok	12,083	ok	551	ok	0.28	ok	0.07	ok
					155	ok	12,083	ok	143	ok	0.27	ok	0.06	ok
PT	2,225	2,530	0	4,755										
					155	ok	0	ok	143	ok	0.00	ok	0.00	ok
					0	ok	0	ok	-87	ok	0.00	ok	0.00	ok
Exit Point	0	0	0	0										

*Loads and stresses associated with installation by HDD were analyzed using methods developed by J. D. Hair & Associates, Inc., for the Pipeline Research Committee International (PRCI) which can be found in Section 5 of the report titled PR-277-144507-E01, *Installation of Pipelines by Horizontal Directional Drilling* , *An Engineering Design Guide* .

HDD Installation and Pipe Stress Analysis

Pipe and Installation Properties

Based on profile design entered in 'Step 2, Drilled Path Input'.

Pipe Diameter, D =	20.000	in	Fluid Drag Coefficient, C_d =	0.025	psi	
PIpe Weight, W =	104.1	lb/ft	Ballast Weight / ft Pipe, W_b =	122.9	lb	(If Ballasted)
Coefficient of Soil Friction, μ =	0.30		Drilling Mud Displaced / ft Pipe, W_m =	146.9	lb	(If Submerged)
			Above Ground Load =	0	lb	

Exit Tangent - Summary of Pulling Load Calculations

Segment Length, L =	118.1	ft	Effective Weight, $W_e = W + W_b - W_m$ =	-42.7	lb/ft
Exit Angle, θ =	12.0	°			

Frictional Drag = W_e L μ cosθ =	1,481	lb
Fluidic Drag = 12 π D L C_d =	2,225	lb
Axial Segment Weight = W_e L sinθ =	1,049	lb
Pulling Load on Exit Tangent =	**4,755**	**lb**

Exit Sag Bend - Summary of Pulling Load Calculations

Segment Length, L =	418.9	ft	Average Tension, T =	14,089	lb
Segment Angle with Horizontal, θ =	-12.0	°	Radius of Curvature, R =	2,000	ft
Deflection Angle, α =	-6.0	°	Effective Weight, $W_e = W + W_b - W_m$ =	-42.7	lb/ft

h = R [1 - cos(α/2)] =	10.96	ft	j = [(E I) / T]$^{1/2}$ =	1,731	
Y = [18 (L)^2] - [(j)^2 (1 - cosh(U/2)$^{-1}$] =	1.5E+06		X = (3 L) - [(j / 2) tanh(U/2)] =	481.06	
U = (12 L) / j =	2.90		N = [(T h) - W_e cosθ (Y/144)] / (X / 12) =	14,836	lb
Bending Frictional Drag = 2 μ N =	8,902	lb			
Fluidic Drag = 12 π D L C_d =	7,896	lb			
Axial Segment Weight = W_e L sinθ =	1,871	lb			
Pulling Load on Exit Sag Bend =	**18,669**	**lb**			
Total Pulling Load =	**23,424**	**lb**			

Bottom Tangent - Summary of Pulling Load Calculations

Segment Length, L =	60.2	ft	Effective Weight, $W_e = W + W_b - W_m$ =	-42.7	lb/ft

Frictional Drag = W_e L μ =	771	lb
Fluidic Drag = 12 π D L C_d =	1,134	lb
Axial Segment Weight = W_e L sinθ =	0	lb
Pulling Load on Bottom Tangent =	**1,905**	**lb**
Total Pulling Load =	**25,329**	**lb**

HDD Installation and Pipe Stress Analysis

Entry Sag Bend - Summary of Pulling Load Calculations

Segment Length, L = 349.1 ft
Segment Angle with Horizontal, θ = 10.0 º
Deflection Angle, α = 5.0 º

Average Tension, T = 32,461 lb
Radius of Curvature, R = 2,000 ft
Effective Weight, $W_e = W + W_b - W_m$ = -42.7 lb/ft

$h = R\,[1 - \cos(\alpha/2)]$ = 7.61 ft

$j = [(E\,I) / T]^{1/2}$ = 1,140

$Y = [18\,(L)^2] - [(j)^2\,(1 - \cosh(U/2)^{-1}]$ = 1.3E+06

$X = (3\,L) - [\,(j / 2)\tanh(U/2)\,]$ = 505.22

$U = (12\,L) / j$ = 3.67

$N = [(T\,h) - W_e \cos\theta\,(Y/144)] / (X / 12)$ = 14,976 lb

Bending Frictional Drag = $2\,\mu\,N$ = 8,986 lb

Fluidic Drag = $12\,\pi\,D\,L\,C_d$ = 6,580 lb

Axial Segment Weight = $W_e\,L \sin\theta$ = -1,300 lb

Negative value indicates axial weight applied in direction of installation

Pulling Load on Entry Sag Bend = 14,265 lb
Total Pulling Load = 39,594 lb

Entry Tangent - Summary of Pulling Load Calculations

Segment Length, L = 164.6 ft
Entry Angle, θ = 10.0 º

Effective Weight, $W_e = W + W_b - W_m$ = -42.7 lb/ft

Frictional Drag = $W_e\,L\,\mu\cos\theta$ = 2,078 lb

Fluidic Drag = $12\,\pi\,D\,L\,C_d$ = 3,102 lb

Axial Segment Weight = $W_e\,L \sin\theta$ = -1,221 lb

Negative value indicates axial weight applied in direction of installation

Pulling Load on Entry Tangent = 3,958 lb
Total Pulling Load = 43,552 lb

Summary of Calculated Stress vs. Allowable Stress

	Tensile Stress		Bending Stress		External Hoop Stress		Combined Tensile & Bending		Combined Tensile, Bending & Ext. Hoop	
Entry Point	1,422	ok	0	ok	0	ok	0.02	ok	0.00	ok
	1,293	ok	0	ok	267	ok	0.02	ok	0.00	ok
PC										
	1,293	ok	12,083	ok	267	ok	0.29	ok	0.07	ok
	827	ok	12,083	ok	551	ok	0.29	ok	0.07	ok
PT										
	827	ok	0	ok	551	ok	0.01	ok	0.00	ok
	765	ok	0	ok	551	ok	0.01	ok	0.00	ok
PC										
	765	ok	12,083	ok	551	ok	0.28	ok	0.07	ok
	155	ok	12,083	ok	143	ok	0.27	ok	0.06	ok
PT										
	155	ok	0	ok	143	ok	0.00	ok	0.00	ok
Exit Point	0	ok	0	ok	-87	ok	0.00	ok	0.00	ok

Step 4, Pulling Load Summary

Installation Stress Scenario

20-inch O.D., 0.500-inch W.T., Grade X-65,
As-Designed Geometry, 12 ppg mud, Un-ballasted Model

J.D.Hair&Associates,Inc.
Consulting Engineers

HDD Installation and Pipe Stress Analysis

Project Information				
Project :	Enbridge Line 1 Replacement Project		User :	IDS
Crossing :	20-inch Schuylkill River Crossing		Date :	3/31/2023
Comments :	Installation stress model based on as-designed drilled path - 12 ppg drilling fluid and no buoyancy control measures			

Line Pipe Properties			
Pipe Outside Diameter =	20.000	in	
Wall Thickness =	0.500	in	
Specified Minimum Yield Strength =	65,000	psi	
Young's Modulus =	2.9E+07	psi	
Moment of Inertia =	1455.91	in^4	
Pipe Face Surface Area =	30.63	in^2	
Diameter to Wall Thickness Ratio, D/t =	40		
Poisson's Ratio =	0.3		
Coefficient of Thermal Expansion =	6.5E-06	in/in/°F	
Pipe Weight in Air =	104.13	lb/ft	
Pipe Interior Volume =	1.97	ft^3/ft	
Pipe Exterior Volume =	2.18	ft^3/ft	
HDD Installation Properties			
Drilling Mud Density =	12.0	ppg	
=	89.8	lb/ft^3	
Ballast Density =	62.4	lb/ft^3	
Coefficient of Soil Friction =	0.30		
Fluid Drag Coefficient =	0.025	psi	
Ballast Weight =	122.86	lb/ft	
Displaced Mud Weight =	195.83	lb/ft	
Installation Stress Limits[1]			
Tensile Stress Limit, 90% of SMYS, F_t =	58,500	psi	
For D/t <= 1,500,000/SMYS, F_b =	48,750	psi	No
For D/t > 1,500,000/SMYS and <= 3,000,000/SMYS, F_b =	44,460	psi	Yes
For D/t > 3,000,000/SMYS and <= 300, F_b =	43,420	psi	No
Allowable Bending Stress, F_b =	44,460	psi	
Elastic Hoop Buckling Stress, F_{he} =	15,950	psi	
For F_{he} <= 0.55*SMYS, Critical Hoop Buckling Stress, F_{hc} =	15,950	psi	Yes
For F_{he} > 0.55*SMYS and <= 1.6*SMYS, F_{hc} =	32,121	psi	No
For F_{he} > 1.6*SMYS and <= 6.2*SMYS, F_{hc} =	16,296	psi	No
For F_{he} > 6.2*SMYS, F_{hc} =	65,000	psi	No
Critical Hoop Buckling Stress, F_{hc} =	15,950	psi	
Allowable Hoop Buckling Stress, F_{hc}/1.5 =	10,633	psi	

[1] Installation limits as defined by the technical report titled, *Installation of Pipelines by Horizontal Directional Drilling, An Engineering Design Guide,* prepared under the sponsorship of the Pipeline Research Committee at the American Gas Association, April 15, 1995, Revised under the sponsorship of the Pipeline Research Council International, Inc., 2015.

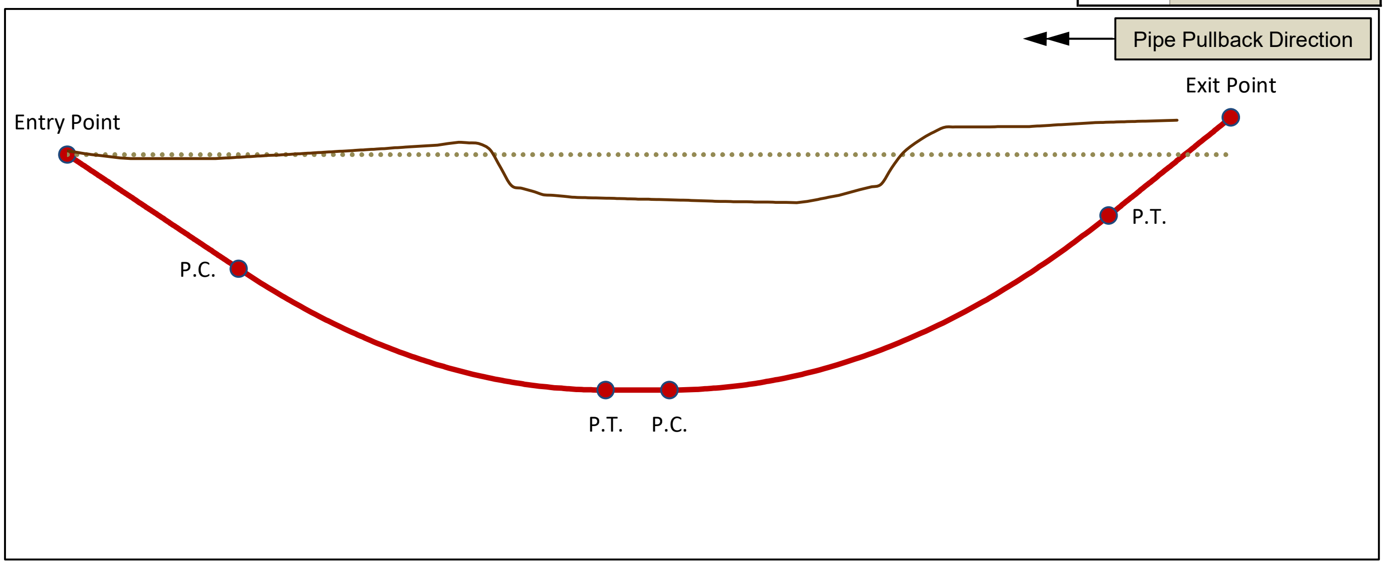
Step 1, Property Input

HDD Installation and Pipe Stress Analysis

		Station	Elevation	Angle	Radius	Length	Average Tension	Total Pull
Entry Point		0.00	95.96	10.00				64,203
Entry Tangent						164.56		
Entry Sag Bend	PC	162.06	67.38					59,263
	PI	334.38	37.00	10.00	2000	349.07	49,283	
	PT	509.36	37.00				0	39,302
Bottom Tangent				0.00		60.15		
Exit Sag Bend	PC	569.51	37.00					36,513
	PI	779.72	37.00	12.00	2000	418.88	22,083	
	PT	985.33	80.70				0	7,653
Exit Tangent						118.06		
Exit Point		1100.81	105.25	12.00			Above Ground Load	0
Drilling Mud			95.96	(Graph =)				
Ballast				(Graph =)				

No.	Station	Elevation	
1			Grade Elevation Points
2			
3			
4			
5			
6			
7			
8			
9			
10			
1			Control Point

	= Cover at Control Point



Step 2, Drilled Path Input

HDD Installation and Pipe Stress Analysis

Point	Fluidic Drag	Weight & Weight Friction	Bending Friction	Total Pull	Tensile Stress		Bending Stress		External Hoop Stress		Tensile & Bending Stress		Tensile, Bending & Ext. Hoop Stress	
Entry Point	20,936	10,145	33,121	64,203	2,096	ok	0	ok	0	ok	0.04	ok	0.00	ok
					1,935	ok	0	ok	356	ok	0.03	ok	0.00	ok
PC	17,835	8,307	33,121	59,263										
					1,935	ok	12,083	ok	356	ok	0.30	ok	0.08	ok
					1,283	ok	12,083	ok	735	ok	0.29	ok	0.08	ok
PT	11,255	11,097	16,950	39,302										
					1,283	ok	0	ok	735	ok	0.02	ok	0.01	ok
					1,192	ok	0	ok	735	ok	0.02	ok	0.01	ok
PC	10,121	9,442	16,950	36,513										
					1,192	ok	12,083	ok	735	ok	0.29	ok	0.08	ok
					250	ok	12,083	ok	190	ok	0.28	ok	0.06	ok
PT	2,225	5,427	0	7,653										
					250	ok	0	ok	190	ok	0.00	ok	0.00	ok
					0	ok	0	ok	-116	ok	0.00	ok	0.00	ok
Exit Point	0	0	0	0										

*Loads and stresses associated with installation by HDD were analyzed using methods developed by J. D. Hair & Associates, Inc., for the Pipeline Research Committee International (PRCI) which can be found in Section 5 of the report titled PR-277-144507-E01, *Installation of Pipelines by Horizontal Directional Drilling* , *An Engineering Design Guide* .

HDD Installation and Pipe Stress Analysis

Pipe and Installation Properties

Based on profile design entered in 'Step 2, Drilled Path Input'.

Pipe Diameter, D =	20.000	in	Fluid Drag Coefficient, C_d =	0.025	psi	
PIpe Weight, W =	104.1	lb/ft	Ballast Weight / ft Pipe, W_b =	122.9	lb	(If Ballasted)
Coefficient of Soil Friction, μ =	0.30		Drilling Mud Displaced / ft Pipe, W_m =	195.8	lb	(If Submerged)
			Above Ground Load =	0	lb	

Exit Tangent - Summary of Pulling Load Calculations

Segment Length, L =	118.1	ft	Effective Weight, $W_e = W + W_b - W_m$ =	-91.7	lb/ft
Exit Angle, θ =	12.0	°			

Frictional Drag = $W_e \, L \, \mu \cos\theta$ =	3,177	lb
Fluidic Drag = $12 \, \pi \, D \, L \, C_d$ =	2,225	lb
Axial Segment Weight = $W_e \, L \sin\theta$ =	2,251	lb
Pulling Load on Exit Tangent =	**7,653**	**lb**

Exit Sag Bend - Summary of Pulling Load Calculations

Segment Length, L =	418.9	ft	Average Tension, T =	22,083	lb
Segment Angle with Horizontal, θ =	-12.0	°	Radius of Curvature, R =	2,000	ft
Deflection Angle, α =	-6.0	°	Effective Weight, $W_e = W + W_b - W_m$ =	-91.7	lb/ft

$h = R\,[1 - \cos(\alpha/2)]$ =	10.96	ft	$j = [(E\,I) / T]^{1/2}$ =	1,383	
$Y = [18\,(L)^2] - [(j)^2\,(1 - \cosh(U/2)^{-1}]$ =	1.9E+06		$X = (3\,L) - [\,(j / 2)\tanh(U/2)\,]$ =	600.81	
$U = (12\,L) / j$ =	3.64		$N = [(T\,h) - W_e \cos\theta\,(Y/144)] / (X / 12)$	28,251	lb
Bending Frictional Drag = $2\,\mu\,N$ =	16,950	lb			
Fluidic Drag = $12 \, \pi \, D \, L \, C_d$ =	7,896	lb			
Axial Segment Weight = $W_e \, L \sin\theta$ =	4,015	lb			
Pulling Load on Exit Sag Bend =	**28,861**	**lb**			
Total Pulling Load =	**36,513**	**lb**			

Bottom Tangent - Summary of Pulling Load Calculations

Segment Length, L =	60.2	ft	Effective Weight, $W_e = W + W_b - W_m$ =	-91.7	lb/ft

Frictional Drag = $W_e \, L \, \mu$ =	1,655	lb
Fluidic Drag = $12 \, \pi \, D \, L \, C_d$ =	1,134	lb
Axial Segment Weight = $W_e \, L \sin\theta$ =	0	lb
Pulling Load on Bottom Tangent =	**2,789**	**lb**
Total Pulling Load =	**39,302**	**lb**

HDD Installation and Pipe Stress Analysis

Entry Sag Bend - Summary of Pulling Load Calculations

Segment Length, L =	349.1	ft	Average Tension, T =	49,283	lb
Segment Angle with Horizontal, θ =	10.0	º	Radius of Curvature, R =	2,000	ft
Deflection Angle, α =	5.0	º	Effective Weight, $W_e = W + W_b - W_m$ =	-91.7	lb/ft

$h = R\,[1 - \cos(\alpha/2)]$ =	7.61	ft	$j = [(E\,I) / T]^{1/2}$ =	926	
$Y = [18\,(L)^2] - [(j)^2\,(1 - \cosh(U/2)^{-1}]$ =	1.5E+06		$X = (3\,L) - [\,(j / 2)\tanh(U/2)\,]$ =	594.32	
$U = (12\,L) / j$ =	4.53		$N = [(T\,h) - W_e\cos\theta\,(Y/144)] / (X / 12)$ =	26,951	lb
Bending Frictional Drag = $2\,\mu\,N$ =	16,171	lb			
Fluidic Drag = $12\,\pi\,D\,L\,C_d$ =	6,580	lb			
Axial Segment Weight = $W_e\,L\sin\theta$ =	-2,790	lb	Negative value indicates axial weight applied in direction of installation		
Pulling Load on Entry Sag Bend =	**19,961**	**lb**			
Total Pulling Load =	**59,263**	**lb**			

Entry Tangent - Summary of Pulling Load Calculations

Segment Length, L =	164.6	ft	Effective Weight, $W_e = W + W_b - W_m$ =	-91.7	lb/ft
Entry Angle, θ =	10.0	º			

Frictional Drag = $W_e\,L\,\mu\cos\theta$ =	4,458	lb	
Fluidic Drag = $12\,\pi\,D\,L\,C_d$ =	3,102	lb	
Axial Segment Weight = $W_e\,L\sin\theta$ =	-2,620	lb	Negative value indicates axial weight applied in direction of installation
Pulling Load on Entry Tangent =	**4,940**	**lb**	
Total Pulling Load =	**64,203**	**lb**	

Summary of Calculated Stress vs. Allowable Stress

	Tensile Stress		Bending Stress		External Hoop Stress		Combined Tensile & Bending		Combined Tensile, Bending & Ext. Hoop	
Entry Point	2,096	ok	0	ok	0	ok	0.04	ok	0.00	ok
	1,935	ok	0	ok	356	ok	0.03	ok	0.00	ok
PC										
	1,935	ok	12,083	ok	356	ok	0.30	ok	0.08	ok
	1,283	ok	12,083	ok	735	ok	0.29	ok	0.08	ok
PT										
	1,283	ok	0	ok	735	ok	0.02	ok	0.01	ok
	1,192	ok	0	ok	735	ok	0.02	ok	0.01	ok
PC										
	1,192	ok	12,083	ok	735	ok	0.29	ok	0.08	ok
	250	ok	12,083	ok	190	ok	0.28	ok	0.06	ok
PT										
	250	ok	0	ok	190	ok	0.00	ok	0.00	ok
Exit Point	0	ok	0	ok	-116	ok	0.00	ok	0.00	ok

Step 4, Pulling Load Summary

Installation Stress Scenario

20-inch O.D., 0.500-inch W.T., Grade X-65,
Worse-Case Geometry, 9 ppg mud, Un-ballasted Model

J.D.Hair&Associates,Inc.
Consulting Engineers

HDD Installation and Pipe Stress Analysis

Project Information			
Project :	Enbridge Line 1 Replacement Project	User :	IDS
Crossing :	20-inch Schuylkill River Crossing	Date :	3/31/2023
Comments :	Installation stress model based on worse-case scenario - 20 feet deeper, 50 feet longer, and at the minimum radius (1,333 feet) - 9 ppg drilling fluid and no buoyancy control measures		

Line Pipe Properties			
Pipe Outside Diameter =	20.000	in	
Wall Thickness =	0.500	in	
Specified Minimum Yield Strength =	65,000	psi	
Young's Modulus =	2.9E+07	psi	
Moment of Inertia =	1455.91	in^4	
Pipe Face Surface Area =	30.63	in^2	
Diameter to Wall Thickness Ratio, D/t =	40		
Poisson's Ratio =	0.3		
Coefficient of Thermal Expansion =	6.5E-06	in/in/°F	
Pipe Weight in Air =	104.13	lb/ft	
Pipe Interior Volume =	1.97	ft^3/ft	
Pipe Exterior Volume =	2.18	ft^3/ft	

HDD Installation Properties			
Drilling Mud Density =	9.0	ppg	
=	67.3	lb/ft^3	
Ballast Density =	62.4	lb/ft^3	
Coefficient of Soil Friction =	0.30		
Fluid Drag Coefficient =	0.025	psi	
Ballast Weight =	122.86	lb/ft	
Displaced Mud Weight =	146.87	lb/ft	

Installation Stress Limits[1]			
Tensile Stress Limit, 90% of SMYS, F_t =	58,500	psi	
For D/t <= 1,500,000/SMYS, F_b =	48,750	psi	No
For D/t > 1,500,000/SMYS and <= 3,000,000/SMYS, F_b =	44,460	psi	Yes
For D/t > 3,000,000/SMYS and <= 300, F_b =	43,420	psi	No
Allowable Bending Stress, F_b =	44,460	psi	
Elastic Hoop Buckling Stress, F_{he} =	15,950	psi	
For F_{he} <= 0.55*SMYS, Critical Hoop Buckling Stress, F_{hc} =	15,950	psi	Yes
For F_{he} > 0.55*SMYS and <= 1.6*SMYS, F_{hc} =	32,121	psi	No
For F_{he} > 1.6*SMYS and <= 6.2*SMYS, F_{hc} =	16,296	psi	No
For F_{he} > 6.2*SMYS, F_{hc} =	65,000	psi	No
Critical Hoop Buckling Stress, F_{hc} =	15,950	psi	
Allowable Hoop Buckling Stress, F_{hc}/1.5 =	10,633	psi	

[1] Installation limits as defined by the technical report titled, *Installation of Pipelines by Horizontal Directional Drilling, An Engineering Design Guide,* prepared under the sponsorship of the Pipeline Research Committee at the American Gas Association, April 15, 1995, Revised under the sponsorship of the Pipeline Research Council International, Inc., 2015.

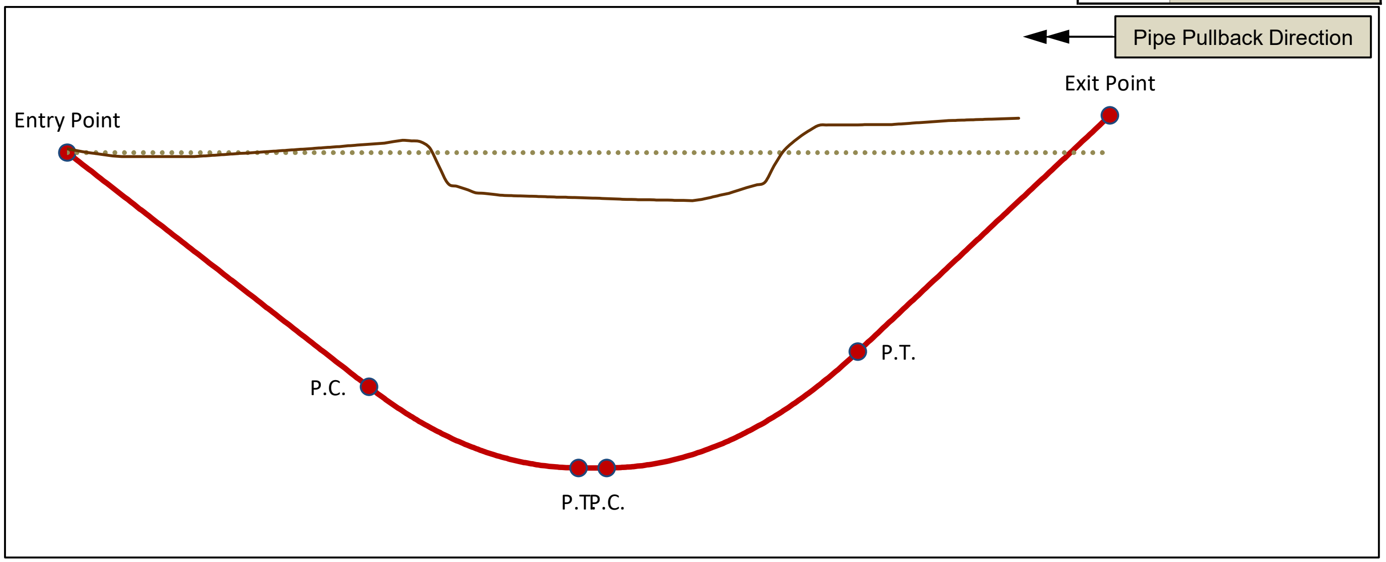
Step 1, Property Input

HDD Installation and Pipe Stress Analysis

		Station	Elevation	Angle	Radius	Length	Average Tension	Total Pull
Entry Point		-25.00	95.96	10.00				48,473
Entry Tangent						338.09		
Entry Sag Bend	PC	307.95	37.25					40,340
	PI	422.80	17.00	10.00	1333	232.65	33,981	
	PT	539.43	17.00				0	27,622
Bottom Tangent				0.00		31.10		
Exit Sag Bend	PC	570.52	17.00					26,638
	PI	710.63	17.00	12.00	1333	279.18	19,045	
	PT	847.67	46.13				0	11,453
Exit Tangent						284.36		
Exit Point		1125.81	105.25	12.00	Above Ground Load			0
Drilling Mud			95.96	(Graph =)				
Ballast				(Graph =)				

No.	Station	Elevation	
1			Grade Elevation Points
2			
3			
4			
5			
6			
7			
8			
9			
10			
1			Control Point

= Cover at Control Point



Step 2, Drilled Path Input

HDD Installation and Pipe Stress Analysis

Point	Fluidic Drag	Weight & Weight Friction	Bending Friction	Total Pull	Tensile Stress		Bending Stress		External Hoop Stress		Tensile & Bending Stress		Tensile, Bending & Ext. Hoop Stress	
Entry Point	21,967	8,632	17,873	48,473	1,582	ok	0	ok	0	ok	0.03	ok	0.00	ok
					1,317	ok	0	ok	549	ok	0.02	ok	0.00	ok
PC	15,594	6,872	17,873	40,340										
					1,317	ok	18,130	ok	549	ok	0.43	ok	0.15	ok
					902	ok	18,130	ok	738	ok	0.42	ok	0.15	ok
PT	11,209	7,739	8,675	27,622										
					902	ok	0	ok	738	ok	0.02	ok	0.01	ok
					870	ok	0	ok	738	ok	0.01	ok	0.01	ok
PC	10,622	7,340	8,675	26,638										
					870	ok	18,130	ok	738	ok	0.42	ok	0.15	ok
					374	ok	18,130	ok	466	ok	0.41	ok	0.13	ok
PT	5,360	6,093	0	11,453										
					374	ok	0	ok	466	ok	0.01	ok	0.00	ok
					0	ok	0	ok	-87	ok	0.00	ok	0.00	ok
Exit Point	0	0	0	0										

*Loads and stresses associated with installation by HDD were analyzed using methods developed by J. D. Hair & Associates, Inc., for the Pipeline Research Committee International (PRCI) which can be found in Section 5 of the report titled PR-277-144507-E01, *Installation of Pipelines by Horizontal Directional Drilling* , *An Engineering Design Guide* .

HDD Installation and Pipe Stress Analysis

Pipe and Installation Properties

Based on profile design entered in 'Step 2, Drilled Path Input'.

Pipe Diameter, D =	20.000	in	Fluid Drag Coefficient, C_d =	0.025	psi	
PIpe Weight, W =	104.1	lb/ft	Ballast Weight / ft Pipe, W_b =	122.9	lb	(If Ballasted)
Coefficient of Soil Friction, μ =	0.30		Drilling Mud Displaced / ft Pipe, W_m =	146.9	lb	(If Submerged)
			Above Ground Load =	0	lb	

Exit Tangent - Summary of Pulling Load Calculations

Segment Length, L =	284.4	ft	Effective Weight, $W_e = W + W_b - W_m$ =	-42.7	lb/ft
Exit Angle, θ =	12.0	º			

Frictional Drag = W_e L μ cosθ =	3,566	lb
Fluidic Drag = 12 π D L C_d =	5,360	lb
Axial Segment Weight = W_e L sinθ =	2,527	lb
Pulling Load on Exit Tangent =	**11,453**	**lb**

Exit Sag Bend - Summary of Pulling Load Calculations

Segment Length, L =	279.2	ft	Average Tension, T =	19,045	lb
Segment Angle with Horizontal, θ =	-12.0	º	Radius of Curvature, R =	1,333	ft
Deflection Angle, α =	-6.0	º	Effective Weight, $W_e = W + W_b - W_m$ =	-42.7	lb/ft

$h = R [1 - \cos(\alpha/2)]$ =	7.30	ft	$j = [(E I) / T]^{1/2}$ =	1,489	
$Y = [18 (L)^2] - [(j)^2 (1 - \cosh(U/2)^{-1}]$ =	4.9E+05		$X = (3 L) - [(j / 2) \tanh(U/2)]$ =	235.04	
$U = (12 L) / j$ =	2.25		$N = [(T h) - W_e \cos\theta (Y/144)] / (X / 12)$	14,458	lb
Bending Frictional Drag = 2 μ N =	8,675	lb			
Fluidic Drag = 12 π D L C_d =	5,262	lb			
Axial Segment Weight = W_e L sinθ =	1,247	lb			
Pulling Load on Exit Sag Bend =	**15,184**	**lb**			
Total Pulling Load =	**26,638**	**lb**			

Bottom Tangent - Summary of Pulling Load Calculations

Segment Length, L =	31.1	ft	Effective Weight, $W_e = W + W_b - W_m$ =	-42.7	lb/ft

Frictional Drag = W_e L μ =	399	lb
Fluidic Drag = 12 π D L C_d =	586	lb
Axial Segment Weight = W_e L sinθ =	0	lb
Pulling Load on Bottom Tangent =	**985**	**lb**
Total Pulling Load =	**27,622**	**lb**

HDD Installation and Pipe Stress Analysis

Entry Sag Bend - Summary of Pulling Load Calculations

Segment Length, L = 232.7 ft
Segment Angle with Horizontal, θ = 10.0 º
Deflection Angle, α = 5.0 º

Average Tension, T = 33,981 lb
Radius of Curvature, R = 1,333 ft
Effective Weight, $W_e = W + W_b - W_m$ = -42.7 lb/ft

$h = R\,[1 - \cos(\alpha/2)]$ = 5.07 ft

$j = [(E\,I) / T]^{1/2}$ = 1,115

$Y = [18\,(L)^2] - [(j)^2\,(1 - \cosh(U/2)^{-1}]$ = 3.9E+05

$X = (3\,L) - [\,(j / 2)\tanh(U/2)\,]$ = 224.82

$U = (12\,L) / j$ = 2.50

$N = [(T\,h) - W_e \cos\theta\,(Y/144)] / (X / 12)$ = 15,331 lb

Bending Frictional Drag = $2\,\mu\,N$ = 9,199 lb

Fluidic Drag = $12\,\pi\,D\,L\,C_d$ = 4,385 lb

Axial Segment Weight = $W_e\,L\sin\theta$ = -867 lb

Negative value indicates axial weight applied in direction of installation

Pulling Load on Entry Sag Bend = 12,717 lb
Total Pulling Load = 40,340 lb

Entry Tangent - Summary of Pulling Load Calculations

Segment Length, L = 338.1 ft
Entry Angle, θ = 10.0 º

Effective Weight, $W_e = W + W_b - W_m$ = -42.7 lb/ft

Frictional Drag = $W_e\,L\,\mu\cos\theta$ = 4,269 lb

Fluidic Drag = $12\,\pi\,D\,L\,C_d$ = 6,373 lb

Axial Segment Weight = $W_e\,L\sin\theta$ = -2,509 lb

Negative value indicates axial weight applied in direction of installation

Pulling Load on Entry Tangent = 8,133 lb
Total Pulling Load = 48,473 lb

Summary of Calculated Stress vs. Allowable Stress

	Tensile Stress		Bending Stress		External Hoop Stress		Combined Tensile & Bending		Combined Tensile, Bending & Ext. Hoop	
Entry Point	1,582	ok	0	ok	0	ok	0.03	ok	0.00	ok
	1,317	ok	0	ok	549	ok	0.02	ok	0.00	ok
PC										
	1,317	ok	18,130	ok	549	ok	0.43	ok	0.15	ok
	902	ok	18,130	ok	738	ok	0.42	ok	0.15	ok
PT										
	902	ok	0	ok	738	ok	0.02	ok	0.01	ok
	870	ok	0	ok	738	ok	0.01	ok	0.01	ok
PC										
	870	ok	18,130	ok	738	ok	0.42	ok	0.15	ok
	374	ok	18,130	ok	466	ok	0.41	ok	0.13	ok
PT										
	374	ok	0	ok	466	ok	0.01	ok	0.00	ok
Exit Point	0	ok	0	ok	-87	ok	0.00	ok	0.00	ok

Step 4, Pulling Load Summary

Installation Stress Scenario

20-inch O.D., 0.500-inch W.T., Grade X-65,
Worse-Case Geometry, 12 ppg mud, Un-ballasted Model

J.D.Hair&Associates,Inc.
Consulting Engineers

HDD Installation and Pipe Stress Analysis

Project Information				
Project :	Enbridge Line 1 Replacement Project	User :	IDS	
Crossing :	20-inch Schuylkill River Crossing	Date :	3/29/2023	
Comments :	Installation stress model based on worse-case scenario - 20 feet deeper, 50 feet longer, and at the minimum radius (1,333 feet) - 12 ppg drilling fluid and no buoyancy control measures			
Line Pipe Properties				
	Pipe Outside Diameter =	20.000	in	
	Wall Thickness =	0.500	in	
	Specified Minimum Yield Strength =	65,000	psi	
	Young's Modulus =	2.9E+07	psi	
	Moment of Inertia =	1455.91	in^4	
	Pipe Face Surface Area =	30.63	in^2	
	Diameter to Wall Thickness Ratio, D/t =	40		
	Poisson's Ratio =	0.3		
	Coefficient of Thermal Expansion =	6.5E-06	in/in/°F	
	Pipe Weight in Air =	104.13	lb/ft	
	Pipe Interior Volume =	1.97	ft^3/ft	
	Pipe Exterior Volume =	2.18	ft^3/ft	
HDD Installation Properties				
	Drilling Mud Density =	12.0	ppg	
	=	89.8	lb/ft^3	
	Ballast Density =	62.4	lb/ft^3	
	Coefficient of Soil Friction =	0.30		
	Fluid Drag Coefficient =	0.025	psi	
	Ballast Weight =	122.86	lb/ft	
	Displaced Mud Weight =	195.83	lb/ft	
Installation Stress Limits[1]				
	Tensile Stress Limit, 90% of SMYS, F_t =	58,500	psi	
	For D/t <= 1,500,000/SMYS, F_b =	48,750	psi	No
	For D/t > 1,500,000/SMYS and <= 3,000,000/SMYS, F_b =	44,460	psi	Yes
	For D/t > 3,000,000/SMYS and <= 300, F_b =	43,420	psi	No
	Allowable Bending Stress, F_b =	44,460	psi	
	Elastic Hoop Buckling Stress, F_{he} =	15,950	psi	
	For F_{he} <= 0.55*SMYS, Critical Hoop Buckling Stress, F_{hc} =	15,950	psi	Yes
	For F_{he} > 0.55*SMYS and <= 1.6*SMYS, F_{hc} =	32,121	psi	No
	For F_{he} > 1.6*SMYS and <= 6.2*SMYS, F_{hc} =	16,296	psi	No
	For F_{he} > 6.2*SMYS, F_{hc} =	65,000	psi	No
	Critical Hoop Buckling Stress, F_{hc} =	15,950	psi	
	Allowable Hoop Buckling Stress, $F_{hc}/1.5$ =	10,633	psi	

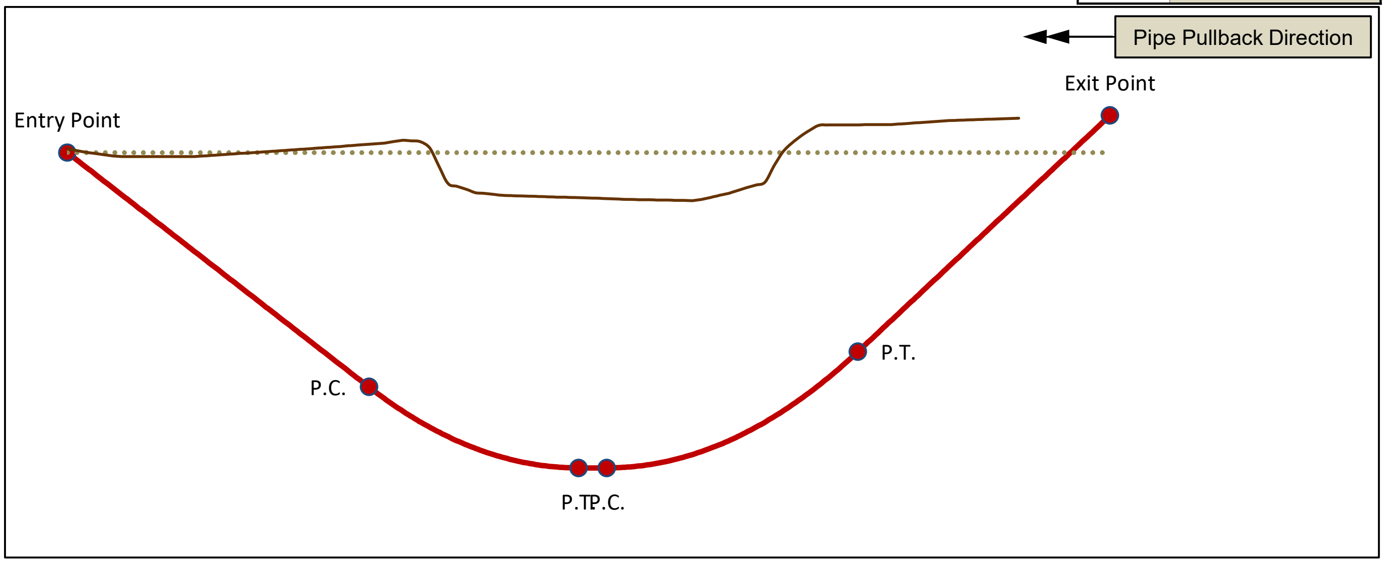
[1] Installation limits as defined by the technical report titled, *Installation of Pipelines by Horizontal Directional Drilling, An Engineering Design Guide,* prepared under the sponsorship of the Pipeline Research Committee at the American Gas Association, April 15, 1995, Revised under the sponsorship of the Pipeline Research Council International, Inc., 2015.

HDD Installation and Pipe Stress Analysis

		Station	Elevation	Angle	Radius	Length	Average Tension	Total Pull
Entry Point		-25.00	95.96	10.00				69,381
Entry Tangent						338.09		
Entry Sag Bend	PC	307.95	37.25					59,232
	PI	422.80	17.00	10.00	1333	232.65	50,762	
	PT	539.43	17.00				0	42,292
Bottom Tangent				0.00		31.10		
Exit Sag Bend	PC	570.52	17.00					40,851
	PI	710.63	17.00	12.00	1333	279.18	29,642	
	PT	847.67	46.13				0	18,432
Exit Tangent						284.36		
Exit Point		1125.81	105.25	12.00	Above Ground Load			0
Drilling Mud			95.96	(Graph =)				
Ballast				(Graph =)				

No.	Station	Elevation	
1			Grade Elevation Points
2			
3			
4			
5			
6			
7			
8			
9			
10			
1			Control Point

= Cover at Control Point



Step 2, Drilled Path Input

HDD Installation and Pipe Stress Analysis

Point	Fluidic Drag	Weight & Weight Friction	Bending Friction	Total Pull	Tensile Stress		Bending Stress		External Hoop Stress		Tensile & Bending Stress		Tensile, Bending & Ext. Hoop Stress	
Entry Point	21,967	18,520	28,894	69,381	2,265	ok	0	ok	0	ok	0.04	ok	0.00	ok
					1,934	ok	0	ok	732	ok	0.03	ok	0.01	ok
PC	15,594	14,744	28,894	59,232										
					1,934	ok	18,130	ok	732	ok	0.44	ok	0.16	ok
					1,381	ok	18,130	ok	984	ok	0.43	ok	0.16	ok
PT	11,209	16,604	14,480	42,292										
					1,381	ok	0	ok	984	ok	0.02	ok	0.01	ok
					1,334	ok	0	ok	984	ok	0.02	ok	0.01	ok
PC	10,622	15,748	14,480	40,851										
					1,334	ok	18,130	ok	984	ok	0.43	ok	0.16	ok
					602	ok	18,130	ok	621	ok	0.42	ok	0.14	ok
PT	5,360	13,072	0	18,432										
					602	ok	0	ok	621	ok	0.01	ok	0.00	ok
					0	ok	0	ok	-116	ok	0.00	ok	0.00	ok
Exit Point	0	0	0	0										

*Loads and stresses associated with installation by HDD were analyzed using methods developed by J. D. Hair & Associates, Inc., for the Pipeline Research Committee International (PRCI) which can be found in Section 5 of the report titled PR-277-144507-E01, *Installation of Pipelines by Horizontal Directional Drilling* , *An Engineering Design Guide* .

HDD Installation and Pipe Stress Analysis

Pipe and Installation Properties

Based on profile design entered in 'Step 2, Drilled Path Input'.

Pipe Diameter, D =	20.000	in	Fluid Drag Coefficient, C_d =	0.025	psi	
PIpe Weight, W =	104.1	lb/ft	Ballast Weight / ft Pipe, W_b =	122.9	lb	(If Ballasted)
Coefficient of Soil Friction, μ =	0.30		Drilling Mud Displaced / ft Pipe, W_m =	195.8	lb	(If Submerged)
			Above Ground Load =	0	lb	

Exit Tangent - Summary of Pulling Load Calculations

Segment Length, L =	284.4	ft	Effective Weight, $W_e = W + W_b - W_m$ =	-91.7	lb/ft
Exit Angle, θ =	12.0	º			

Frictional Drag = $W_e\ L\ \mu\ \cos\theta$ =	7,651	lb
Fluidic Drag = $12\ \pi\ D\ L\ C_d$ =	5,360	lb
Axial Segment Weight = $W_e\ L\ \sin\theta$ =	5,421	lb
Pulling Load on Exit Tangent =	**18,432**	**lb**

Exit Sag Bend - Summary of Pulling Load Calculations

Segment Length, L =	279.2	ft	Average Tension, T =	29,642	lb
Segment Angle with Horizontal, θ =	-12.0	º	Radius of Curvature, R =	1,333	ft
Deflection Angle, α =	-6.0	º	Effective Weight, $W_e = W + W_b - W_m$ =	-91.7	lb/ft

$h = R\ [1 - \cos(\alpha/2)]$ =	7.30	ft	$j = [(E\ I) / T]^{1/2}$ =	1,193	
$Y = [18\ (L)^2] - [(j)^2\ (1 - \cosh(U/2)^{-1}]$ =	6.4E+05		$X = (3\ L) - [\ (j / 2)\ \tanh(U/2)\ ]$ =	308.77	
$U = (12\ L) / j$ =	2.81		$N = [(T\ h) - W_e\ \cos\theta\ (Y/144)] / (X / 12)$	24,133	lb
Bending Frictional Drag = $2\ \mu\ N$ =	14,480	lb			
Fluidic Drag = $12\ \pi\ D\ L\ C_d$ =	5,262	lb			
Axial Segment Weight = $W_e\ L\ \sin\theta$ =	2,676	lb			
Pulling Load on Exit Sag Bend =	**22,418**	**lb**			
Total Pulling Load =	**40,851**	**lb**			

Bottom Tangent - Summary of Pulling Load Calculations

Segment Length, L =	31.1	ft	Effective Weight, $W_e = W + W_b - W_m$ =	-91.7	lb/ft

Frictional Drag = $W_e\ L\ \mu$ =	855	lb
Fluidic Drag = $12\ \pi\ D\ L\ C_d$ =	586	lb
Axial Segment Weight = $W_e\ L\ \sin\theta$ =	0	lb
Pulling Load on Bottom Tangent =	**1,442**	**lb**
Total Pulling Load =	**42,292**	**lb**

HDD Installation and Pipe Stress Analysis

Entry Sag Bend - Summary of Pulling Load Calculations

Segment Length, L =	232.7	ft	Average Tension, T =	50,762	lb
Segment Angle with Horizontal, θ =	10.0	º	Radius of Curvature, R =	1,333	ft
Deflection Angle, α =	5.0	º	Effective Weight, $W_e = W + W_b - W_m$ =	-91.7	lb/ft

$h = R\,[1 - \cos(\alpha/2)]$ =	5.07	ft	$j = [(E\,I) / T]^{1/2}$ =	912	
$Y = [18\,(L)^2] - [(j)^2\,(1 - \cosh(U/2)^{-1}]$ =	4.9E+05		$X = (3\,L) - [\,(j / 2) \tanh(U/2)\,]$ =	282.76	
$U = (12\,L) / j$ =	3.06		$N = [(T\,h) - W_e \cos\theta\,(Y/144)] / (X / 12)$ =	24,023	lb
Bending Frictional Drag = $2\,\mu\,N$ =	14,414	lb			
Fluidic Drag = $12\,\pi\,D\,L\,C_d$ =	4,385	lb			
Axial Segment Weight = $W_e\,L \sin\theta$ =	-1,859	lb	Negative value indicates axial weight applied in direction of installation		
Pulling Load on Entry Sag Bend =	**16,940**	**lb**			
Total Pulling Load =	**59,232**	**lb**			

Entry Tangent - Summary of Pulling Load Calculations

Segment Length, L =	338.1	ft	Effective Weight, $W_e = W + W_b - W_m$ =	-91.7	lb/ft
Entry Angle, θ =	10.0	º			

Frictional Drag = $W_e\,L\,\mu \cos\theta$ =	9,159	lb	
Fluidic Drag = $12\,\pi\,D\,L\,C_d$ =	6,373	lb	
Axial Segment Weight = $W_e\,L \sin\theta$ =	-5,383	lb	Negative value indicates axial weight applied in direction of installation
Pulling Load on Entry Tangent =	**10,149**	**lb**	
Total Pulling Load =	**69,381**	**lb**	

Summary of Calculated Stress vs. Allowable Stress

	Tensile Stress		Bending Stress		External Hoop Stress		Combined Tensile & Bending		Combined Tensile, Bending & Ext. Hoop	
Entry Point	2,265	ok	0	ok	0	ok	0.04	ok	0.00	ok
	1,934	ok	0	ok	732	ok	0.03	ok	0.01	ok
PC										
	1,934	ok	18,130	ok	732	ok	0.44	ok	0.16	ok
	1,381	ok	18,130	ok	984	ok	0.43	ok	0.16	ok
PT										
	1,381	ok	0	ok	984	ok	0.02	ok	0.01	ok
	1,334	ok	0	ok	984	ok	0.02	ok	0.01	ok
PC										
	1,334	ok	18,130	ok	984	ok	0.43	ok	0.16	ok
	602	ok	18,130	ok	621	ok	0.42	ok	0.14	ok
PT										
	602	ok	0	ok	621	ok	0.01	ok	0.00	ok
Exit Point	0	ok	0	ok	-116	ok	0.00	ok	0.00	ok

Step 4, Pulling Load Summary

Appendix 3

Operating and Testing Stress Calculations

J.D.Hair&Associates,Inc.
Consulting Engineers

Operating Stress Analysis

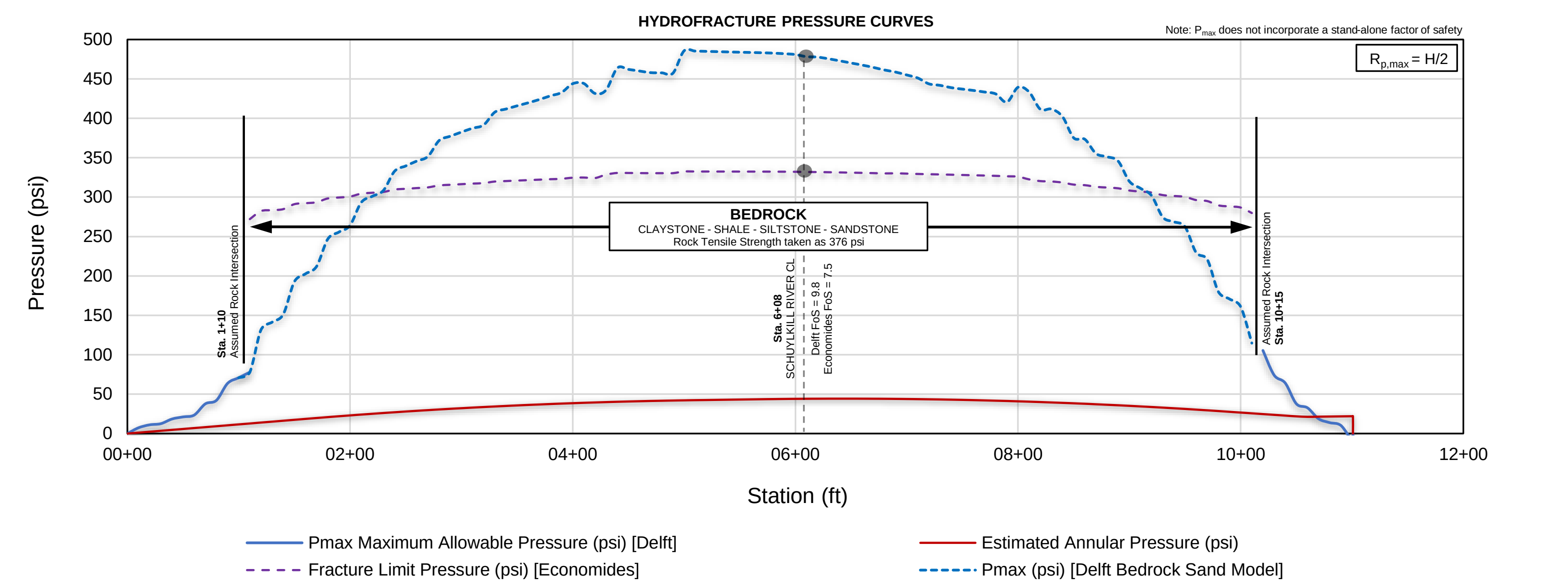
PROJECT: Audubon/Enbridge Line 1 Replacement Project
20-inch Schuylkill River Crossing

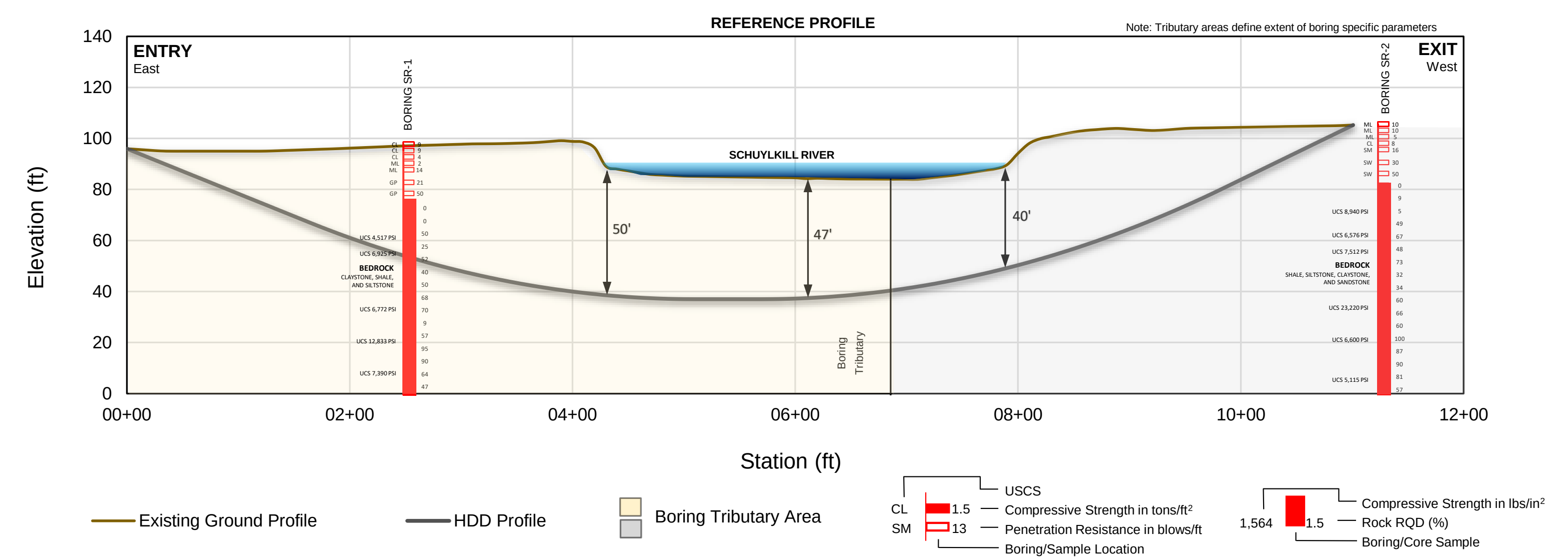
Pipe Properties	Operation: MAOP Design Radius Check		Operation: MAOP Minimum Radius Check		Operation: MAOP Absolute Minimum Radius Check		Hydrostatic Testing: (2 x MAOP) Absolute Minimum Radius Check	
Scenario	Scenario 1		Scenario 2		Scenario 3		Scenario 3	
Pipe Outside Diameter =	20.000	in	20.000	in	20.000	in	20.000	in
Wall Thickness =	0.500	in	0.500	in	0.500	in	0.500	in
Specified Minimum Yield Strength =	65,000	psi	65,000	psi	65,000	psi	65,000	psi
Young's Modulus =	2.9E+07	psi	2.9E+07	psi	2.9E+07	psi	2.9E+07	psi
Moment of Inertia =	1455.91	in^4	1455.91	in^4	1455.91	in^4	1455.91	in^4
Pipe Face Surface Area =	30.63	in^2	30.63	in^2	30.63	in^2	30.63	in^2
Diameter to Wall Thickness Ratio, D/t =	40		40		40		40	
Poisson's Ratio =	0.3		0.3		0.3		0.3	
Coefficient of Thermal Expansion =	6.5E-06	in/in/°F	6.5E-06	in/in/°F	6.5E-06	in/in/°F	6.5E-06	in/in/°F
Pipe Weight in Air =	104.13	lb/ft	104.13	lb/ft	104.13	lb/ft	104.13	lb/ft
Pipe Interior Volume =	1.97	ft^3/ft	1.97	ft^3/ft	1.97	ft^3/ft	1.97	ft^3/ft
Pipe Exterior Volume =	2.18	ft^3/ft	2.18	ft^3/ft	2.18	ft^3/ft	2.18	ft^3/ft
Operating Parameters[1]								
Maximum Allowable Operating Pressure =	656	psig	656	psig	656	psig	1,312	psig
Radius of Curvature =	2,000	ft	1,333	ft	602	ft	602	ft
Installation Temperature =	42	°F	42	°F	42	°F	42	°F
Operating Temperature =	80	°F	80	°F	80	°F	42	°F
Groundwater Table Head =	0	ft	0	ft	0	ft	0	ft
Operating Stress Check[2,3]								
Hoop Stress =	13,120	psi	13,120	psi	13,120	psi	26,240	psi
% SMYS =	20%		20%		20%		40%	
Longitudinal Stress from Internal Pressure =	3,936	psi	3,936	psi	3,936	psi	7,872	psi
% SMYS =	6%		6%		6%		12%	
Longitudinal Stress from Temperature Change =	-7,106	psi	-7,106	psi	-7,106	psi	0	psi
% SMYS =	11%		11%		11%		0%	
Longitudinal Stress from Bending =	12,083	psi	18,125	psi	40,127	psi	40,127	psi
% SMYS =	19%		28%		62%		62%	
Net Longitudinal Stress (taking bending in tension) =	8,913	psi	14,955	psi	36,956	psi	47,999	psi
Limited to 90% of SMYS by ASME B31.8 (2010) B31.4 (2012) =	14%	**Pass**	23%	**Pass**	57%	**Pass**	74%	**n/a**
Net Longitudinal Stress (taking bending in compression) =	-15,254	psi	-21,295	psi	-43,297	psi	-32,255	psi
Limited to 90% of SMYS by ASME B31.8 (2010) B31.4 (2012) =	23%	**Pass**	33%	**Pass**	67%	**Pass**	50%	**n/a**
Combined Stress (NLS w/bending in tension) - Max. Shear Stress Theory =	4,207	psi	1,835	psi	23,836	psi	21,759	psi
Limited to 90% of SMYS by ASME B31.8 (2010) B31.4 (2012) =	6%	**Pass**	3%	**Pass**	37%	**Pass**	33%	**n/a**
Combined Stress (NLS w/bending in compression) - Max. Shear Stress Theory =	28,374	psi	34,415	psi	56,417	psi	58,495	psi
Limited to 90% of SMYS by ASME B31.8 (2010) B31.4 (2012) =	44%	**Pass**	53%	**Pass**	87%	**Pass**	90%	**n/a**
Combined Stress (NLS w/bending in tension) - Max. Distortion Energy Theory =	11,603	psi	14,127	psi	32,451	psi	41,629	psi
Limited to 90% of SMYS by ASME B31.8 (2010) B31.4 (2012) =	18%	**Pass**	22%	**Pass**	50%	**Pass**	64%	**n/a**
Combined Stress (NLS w/bending in compression) - Max. Distortion Energy Theory =	24,596	psi	30,084	psi	51,136	psi	50,747	psi
Limited to 90% of SMYS by ASME B31.8 (2010) B31.4 (2012) =	38%	**Pass**	46%	**Pass**	79%	**Pass**	78%	**n/a**

[1] Installation temperature taken as 10% worse than the region's mean average earth temperature (Collins, 1925)
[2] Calculations assume pipe is restrained
[3] Pass/Fail/NA relatable to applicable ASME Code

Appendix 4

Hydrofracture Evaluation





J.D.Hair&Associates,Inc.
Consulting Engineers

HYDROFRACTURE EVALUATION
CONFINING CAPACITY VS. ESTIMATED ANNULAR PRESSURE
SCHUYLKILL RIVER CROSSING
BY HORIZONTAL DIRECTIONAL DRILLING

Date: 3/29/2023 Revision: IFB

Project: Enbridge Line 1 Replacement Project
20-inch Schuylkill River Crossing
Hydrofracture Tabular Output

Drilled Path & Grade Information														
Distance from Entry Point (ft)	0.0	50.0	100.0	150.0	200.0	250.0	300.0	350.0	400.0	450.0	500.0	550.0	600.0	650.0
Grade Elevation (ft)	96.0	95.0	95.0	95.4	96.2	97.1	97.7	98.1	98.8	87.3	85.2	84.9	84.6	84.1
Path Elevation (ft)	96.0	87.1	78.3	69.5	61.1	53.9	48.0	43.4	40.0	37.9	37.0	37.0	37.2	38.6
Water Table Elevation (ft)	89.00	89.00	89.00	89.00	89.00	89.00	89.00	89.00	89.00	87.27	85.23	84.88	84.57	84.07
Depth of Path Below Grade (ft) (h_{tot})	0.00	7.86	16.67	25.89	35.12	43.19	49.73	54.77	58.84	49.39	48.21	47.88	47.34	45.45
Depth of Path Below Entry Point (ft)	0.00	8.82	17.63	26.45	34.89	42.07	47.97	52.60	55.97	58.08	58.94	58.96	58.73	57.34
Depth of Submerged Soil Column Below Groundwater (ft) (h_w)	0.00	1.86	10.67	19.49	27.93	35.11	41.01	45.64	49.01	49.39	48.21	47.88	47.34	45.45
Depth of Soil Column Above Groundwater (ft)	0.00	6.00	6.00	6.40	7.19	8.08	8.72	9.13	9.83	0.00	0.00	0.00	0.00	0.00
River Surface Elevation (ft)	89.00	89.00	89.00	89.00	89.00	89.00	89.00	89.00	89.00	89.00	89.00	89.00	89.00	89.00
Depth River (ft)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.73	3.77	4.12	4.43	4.93
Annular Pressure Properties														
Unit Weight of Drilling Fluid (pcf)	78.54	78.54	78.54	78.54	78.54	78.54	78.54	78.54	78.54	78.54	78.54	78.54	78.54	78.54
Friction Loss Gradient (psi/ft)	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Pressure from Mud Column (psi)	0.00	4.81	9.62	14.43	19.03	22.95	26.16	28.69	30.53	31.68	32.15	32.16	32.03	31.27
Frictional Head Loss (psi)	0.00	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00	11.00	12.00	13.00
Estimated Annular Pressure (psi) [Bingham Plastic Model]	0.00	5.81	11.62	17.43	23.03	27.95	32.16	35.69	38.53	40.68	42.15	43.16	44.03	44.27
Soil Properties														
c = Cohesion (psf)	500.0	425.0	219.8	675.0	792.9	950.0	1005.0	1050.0	1087.5	1195.2	1220.0	1220.0	1220.0	1220.0
ϕ = Angle of Internal Friction (degrees)	1.3	1.1	20.2	27.3	29.1	31.5	32.4	33.0	33.6	38.3	40.1	40.1	40.1	40.1
ϕ (radians)	0.0	0.0	0.4	0.5	0.5	0.5	0.6	0.6	0.6	0.7	0.7	0.7	0.7	0.7
G = Shear Modulus (psf)	104138	79045	612346	631660	636661	643329	645663	647572	649163	733057	763187	763187	763187	763187
Weighted γ_{soil} = Soil Unit Weight (pcf)	110.3	108.9	117.9	125.8	127.8	130.5	131.5	132.2	132.9	136.8	137.7	137.7	137.7	137.7
γ_{sub} = Submerged Unit Weight (pcf)	47.9	46.5	55.5	63.4	65.4	68.1	69.1	69.8	70.5	74.4	75.3	75.3	75.3	75.3
V Poissons	0.5	0.4	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
P_{max} Maximum Allowable Mud Pressure (psi) [Delft]	0.0	21.1	70.8	-	-	-	-	-	-	-	-	-	-	-
P_{max} (psi) [Delft Bedrock Sand Model]	-	-	-	194.1	245.1	305.0	338.3	364.8	387.7	410.0	433.0	431.7	429.5	421.9
Rock Properties (if applicable)														
Overburden Pressure (psi)	-	-	-	22.6	31.2	39.1	45.4	50.3	54.3	46.9	46.1	45.8	45.3	43.5
Effective Horizontal Stress (psi)	-	-	-	13.6	18.8	23.0	26.6	29.3	31.4	28.6	28.4	28.4	28.2	27.3
Assumed Rock Strength (psi)	-	-	-	376.0	376.0	376.0	376.0	376.0	376.0	376.0	376.0	376.0	376.0	376.0
Fracture Limit Pressure (psi) [Economides]	-	-	-	291.1	300.7	310.6	316.4	321.0	324.6	330.6	332.5	332.4	332.1	331.1

Project: Enbridge Line 1 Replacement Project
20-inch Schuylkill River Crossing
Hydrofracture Tabular Output

Drilled Path & Grade Information									
Distance from Entry Point (ft)	700.0	750.0	800.0	850.0	900.0	950.0	1000.0	1050.0	1100.0
Grade Elevation (ft)	84.0	86.0	94.2	102.5	103.6	103.9	104.4	104.7	105.2
Path Elevation (ft)	41.3	45.2	50.3	56.8	64.5	73.5	83.8	94.5	105.1
Water Table Elevation (ft)	83.96	86.03	89.00	89.00	89.00	89.00	89.00	89.00	89.00
Depth of Path Below Grade (ft) (h_{tot})	42.70	40.87	43.84	45.70	39.15	30.37	20.53	10.27	0.16
Depth of Path Below Entry Point (ft)	54.70	50.80	45.64	39.20	31.47	22.44	12.14	1.51	0.00
Depth of Submerged Soil Column Below Groundwater (ft) (h_w)	42.70	40.87	38.68	32.24	24.51	15.48	5.18	0.00	0.00
Depth of Soil Column Above Groundwater (ft)	0.00	0.00	5.16	13.46	14.64	14.89	15.35	10.27	0.16
River Surface Elevation (ft)	89.00	89.00	89.00	89.00	89.00	89.00	89.00	89.00	89.00
Depth River (ft)	5.04	2.97	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Annular Pressure Properties									
Unit Weight of Drilling Fluid (pcf)	78.54	78.54	78.54	78.54	78.54	78.54	78.54	78.54	78.54
Friction Loss Gradient (psi/ft)	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Pressure from Mud Column (psi)	29.83	27.71	24.89	21.38	17.16	12.24	6.62	0.82	0.00
Frictional Head Loss (psi)	14.00	15.00	16.00	17.00	18.00	19.00	20.00	21.00	22.00
Estimated Annular Pressure (psi) [Bingham Plastic Model]	43.83	42.71	40.89	38.38	35.16	31.24	26.62	21.82	22.00
Soil Properties									
c = Cohesion (psf)	1500.0	1349.4	1153.2	1007.7	881.4	790.4	494.8	500.0	500.0
ϕ = Angle of Internal Friction (degrees)	40.0	40.3	40.0	34.0	32.5	31.4	27.8	8.3	1.3
ϕ (radians)	0.7	0.7	0.7	0.6	0.6	0.5	0.5	0.1	0.0
G = Shear Modulus (psf)	666667	666667	621447	533141	498904	474233	394052	119278	79104
Weighted γ_{soil} = Soil Unit Weight (pcf)	140.0	140.0	138.3	133.5	131.9	130.7	126.8	110.2	110.3
γ_{sub} = Submerged Unit Weight (pcf)	77.6	77.6	75.9	71.1	69.5	68.3	64.4	47.8	47.9
V Poissons	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.4	0.3
P_{max} Maximum Allowable Mud Pressure (psi) [Delft]	-	-	-	-	-	-	-	-	-
P_{max} (psi) [Delft Bedrock Sand Model]	407.9	395.2	395.1	334.7	290.1	247.6	167.5	41.5	20.0
Rock Properties (if applicable)									
Overburden Pressure (psi)	41.5	39.7	42.1	42.4	35.8	27.6	18.1	7.9	0.1
Effective Horizontal Stress (psi)	25.9	24.2	23.3	22.6	18.6	13.5	8.0	4.3	0.1
Assumed Rock Strength (psi)	376.0	376.0	376.0	376.0	376.0	376.0	376.0	376.0	376.0
Fracture Limit Pressure (psi) [Economides]	329.8	328.1	325.9	315.9	308.4	300.4	286.8	0.0	0.0

Appendix 5

HDD Construction Estimates

Construction Duration Estimate

Project: Enbridge Line 1 Replacement Project
20-inch Schuylkill River Crossing

General Data		Comments
Work Schedule, hours/shift =	10.0	20-inch Schuylkill River Construction Duration Estimate
days/week =	6.0	Estimate Assumptions:
Drilled Length, feet =	1,111	- Assumes crossing length of 1,111-feet based on IFB design
Pilot Hole		- Assumes Contractor drills conventionally sized pilot hole (9-15 inches) - Assumes Contractor enlarges bore up to 30-inches (1.5 * Pipe O.D.)
Production Rate, feet/hour =	15	- Assumes moderate strength bedrock
shifts/day =	1	
Drilling Duration, hours =	74.1	
shifts =	7.4	
Trips to change/inspect tools, shifts =	1.0	Note: The pilot hole and reaming production rates were estimated by JDH&A based on information contained within the Pipeline Research Council International's "Installation of Pipelines by Horizontal Directional Drilling" , as well as past experience in similar subsurface conditions.
Pilot Hole Duration, days =	8.4	

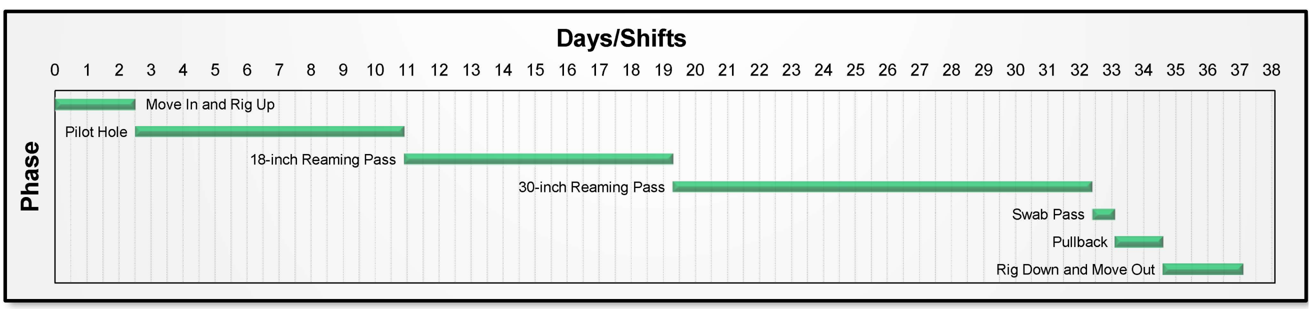
Ream and Pull Back

Pass Description =	18-inch	30-inch				Swab	Pull Back	Total
Production Rate, feet/minute =	0.25	0.16				8.0	6.7	
shifts/day =	1	1				1	1	
Reaming Duration, hours =	74.1	115.7				2.3	2.8	194.9
shifts =	7.4	11.6				0.2	0.3	19.5
Rig up, shifts =	0.5	0.5				0.5	0.5	2.0
Trips to change/inspect tools, shifts =	0.5	1.0				0.0		1.5
Pull Back Weld Duration, shifts =	0.0	0.0				0.0	0.8	0.8
Pass Duration, days =	8.4	13.1				0.7	1.5	23.7

Summary

HDD Duration Total, days =	**37.1**

Site Establishment	Move in	Rig Up	Rig Down	Move Out
shifts/day =	1.0	1.0	1.0	1.0
shifts =	1.0	1.5	1.5	1.0
days =	1.0	1.5	1.5	1.0



J.D.Hair&Associates,Inc.
Consulting Engineers

HDD Drilling Fluid and Spoil Estimate

Project: Enbridge Line 1 Replacement Project
20-inch Schuylkill River Crossing

ESTIMATE INFORMATION:

Pipe Diameter:	**20.0**	inches
Drilled Length:	**1,111**	feet
Subsurface Conditions:	Estimate assumes moderate strength bedrock	
Drilling Fluid Mix Ratio:	Calculations assume typical bentonite mix ratio of approximiately 25 lbs. per 100 gal (water)	

PILOT HOLE DRILLING: Assumes Conventionally Sized Pilot Hole (9-14-inches)

Production Rate:	15	feet per hour	Drilling Fluid Consumed =	4,960	barrels
Pumping Factor:	45	minutes per hour	Bentonite Consumed =	992	sacks (50 lb)
Loss Factor Assumption:	25%		Water Consumed =	208,313	gallons
Drilling Mud Flow Rate:	250	gallons per minute			

PREREAMING: Assumes two (2) Reaming Passes and one (1) Swab Pass

PASS #2: 18-inch Ream Pass

Penetration Rate:	0.25	feet per minute	Drilling Fluid Consumed =	9,258	barrels
Loss Factor Assumption:	25%		Bentonite Consumed =	1,852	sacks (50 lb)
Drilling Mud Flow Rate:	350	gallons per minute			

PASS #3: 30-inch Ream Pass

Penetration Rate:	0.16	feet per minute	Drilling Fluid Consumed =	24,799	barrels
Loss Factor Assumption:	25%		Bentonite Consumed =	4,960	sacks (50 lb)
Drilling Mud Flow Rate:	600	gallons per minute	Water Consumed =	1,041,563	gallons

PASS #4: Swab Pass

Penetration Rate:	8.00	feet per minute	Drilling Fluid Consumed =	248	barrels
Loss Factor Assumption:	50%		Bentonite Consumed =	50	sacks (50 lb)
Drilling Mud Flow Rate:	150	gallons per minute	Water Consumed =	10,416	gallons

PULLBACK: 20-inch Product Pipe

Penetration Rate:	6.70	feet per minute	Drilling Fluid Consumed =	592	barrels
Loss Factor Assumption:	100%		Bentonite Consumed =	99	sacks (50 lb)
Drilling Mud Flow Rate:	150	gallons per minute	Water Consumed =	24,873	gallons

DRILLING FLUID ESTIMATE:

Drilling Fluid Consumed =	39,857	barrels	Total Water Consumed =	**1,674,014**	gallons
Bentonite Consumed =	7,952	sacks (50 lb)			

SPOIL ESTIMATE: Assumes 30-inch Final Hole Diameter

Reamed Hole Size	30	inches	Spoils Removal Assumption	75%	
Reamed Hole Volume	5,454	cubic feet	Volume of Spoil Removed	4,090	cubic feet
	40,793	gallons		**151**	cubic yards