PennEast Pipeline Company, LLC

PENNEAST PIPELINE PROJECT

Multi-Permit Application
for
Freshwater Wetlands Individual Permit
Special Activity Transition Area Waiver
Letter of Interpretation
Water Quality Certificate
Flood Hazard Area Individual Permit
Flood Hazard Hardship Exception Request
Flood Hazard Area Verification

ATTACHMENT R-2 – HDD Design Reports

Submitted to:
New Jersey Department of Environmental Protection
Division of Land Use Regulation

August 2019

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MOTT MACDONALD

HDD Design Report
Delaware River HDD Crossing

PennEast Pipeline Project

July 22, 2019

PennEast Pipeline Project
353754-MM-EN-CO-057 RevE

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Delaware River HDD Crossing

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July 22, 2019

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Tables

1 Introduction

Mott MacDonald has prepared this HDD design report at the request of PennEast Pipeline Company, LLC (PennEast), for their proposed HDD crossing of the Delaware River, part of the larger PennEast Pipeline Project. The proposed Project consists of 115 miles of 36-inch diameter (NPS 36) high pressure, natural gas pipeline from Luzerne County, Pennsylvania to Mercer County, New Jersey.

Specifically, this report summarizes Mott MacDonald's evaluation of the design elements and risk discussions (as determined in the information provided), and presents recommendations for enhancing the success of the Delaware River HDD Crossing.

The drawings and design elements have been prepared and evaluated with the aid of a completed geotechnical subsurface investigation performed by Mott MacDonald, and laboratory assessment and testing analysis completed by Craig Test Boring Co., Inc (CTB). The soil and rock samples were obtained during the geotechnical investigation program, and sent to CTB laboratory for testing. Additionally, a geophysical investigation was completed by Hager-Richter Geoscience, Inc. (Hager-Richter), to supplement the geotechnical borings. Discussions on the geotechnical aspects in this design report have been extracted from the information presented in the site specific Geological Data Report (GDR).

1.1 Crossing Description

The proposed plan and profile is provided in Appendix A. The horizontal length of the proposed HDD is approximately 2,836 feet (with a true length of approximately 2,863 feet). The eastern HDD entry point is located approximately 125 feet east of County Road 627, and the western HDD entry point is located approximately 950 feet west of Pennsylvania State Route 611. An elevation difference of approximately 2 feet exists between the east and west HDD entry locations, with the east HDD entry location being excavated to the lower elevation. To provide sufficient depth beneath the County Road 627, a small excavation is proposed to lower the starting elevation of the HDD bore. This excavation is also necessary to allow for the HDD installation to avoid bedrock materials with lower rock quality designations (RQD) below the horizontal tangent of the HDD profile.

The pipe staging area for the drag section is located on the west side of the crossing. It is envisioned that, due to limited workspace, this pipe string will be fabricated into three sections prior to pullback operations.

This crossing has been designed using the Drill and Intersect method to complete the pilot bore phase of the installation. To accommodate the drill and intersect method, a flat horizontal tangent of 456 feet has been incorporated into the design profile between STA 4097+59 and 4102+15.

2 Anticipated Geotechnical Conditions

The following discussions on the anticipated geotechnical conditions are based on the information provided by the site-specific geotechnical and geophysical investigation programs. Borehole logs for completed borings to support the design of the crossings by HDD methods are provided in Appendix B.

The objective of these discussions is to provide an explanation of the various construction risks identified in subsequent sections related to the geotechnical conditions.

2.1 Subsurface Investigations

A total of six (6) borings, designated as B-DEL-1, B-31, B-32, B-32A, B-33, and B-34, were completed as part of the geotechnical investigation program to support the evaluation and design of the Delaware River HDD Crossing. Due to difficult drilling conditions, Boring B-32 was abandoned and borehole B-32A was added to the program, offset approximately 10 feet from Boring B-32. More detailed discussions can be found in the site-specific GDR.

A geophysical investigation program was also completed to support the design of the Delaware River HDD Crossing and obtain geotechnical information between the borehole locations. Electrical Resistivity Imaging (ERI) was used to determine the depth and orientation of the bedrock surface beneath the Delaware River, and to determine the location and directionality of an existing thrust fault within the Delaware River. Additionally, a boring designated as B-HR-4 was completed to evaluate the presence of a potential Karst feature located approximately 1,200 feet northwest of B-DEL-1. This boring indicated a 5.0-foot thick Karst feature between an elevation of 212 and 217 feet (between depths of 30 and 35 feet below ground surface). More detailed discussions can be found in the GDR.

A summary of the subsurface materials encountered at the site is provided below.

2.2 Geotechnical Observations

The HDD entry location is anticipated to encounter soils over carbonate rock of the Allentown formation. The drill will then transition into the carbonate Leitsville formation before crossing beneath the river. At some point beneath the river the alignment is likely to encounter the Hardystone Quartzite before entering into Precambrian granite and gneiss materials for the southern section of the drill.

The elevation of rock head is seen to be highly variable with deep soils seen in B-32A and B-34.

2.2.1 Geotechnical Observations on the Pennsylvania (west) side

The HDD installation on the Pennsylvania side of the Delaware River is anticipated to encounter soils overlying bedrock materials. Based on Boring B-DEL-1, the site soils are anticipated to include the following:

- Very loose silty sand from the ground surface to a depth of 3.5 feet (from Elev. 166 to 162.5 feet).
- Medium stiff clay with sand to a depth of 8.5 feet (to Elev. 157.5 feet).
- Medium dense sand with gravel to a depth of 13.5 feet (to Elev. 152.5 feet).
- Very dense silty gravel with sand to a depth of 23.5 feet (to Elev. 142.5 feet). Grain size distribution tests indicate gravel percentages up to 64 percent of the soil particles.
- Medium dense silty brown sand with gravel to a depth of 28.5 feet (to Elev. 137.5 feet).
- Very dense, weathered dolomite fragments to a depth of 40.5 feet (to Elev. 125.5 feet). Area of no recovery from depth of 35 feet to 37 feet.

- Highly weathered to moderately weathered, weak to medium strong dolomite to a depth of 52 feet (to Elev. 114 feet). Highly fractured zones encountered near the top of the layer. RQD values ranged between 10 and 40 percent (avg. 25 percent). Recovery values ranged between 60 and 83 percent (avg. 72 percent).
- Slightly weathered, weak siltstone to a depth of 56.9 feet (to Elev. 109.1 feet). RQD value of 43 percent and recovery value of 93 percent.
- Highly weathered to moderately weathered, weak dolomite to a depth of 110 feet (to Elev. 56 feet). RQD values ranged between 0 and 73 percent (avg. 33 percent). Recovery values ranged between 47 and 100 percent (avg. 82 percent).
- Slightly weathered, medium strong dolomite to a termination depth of 120 feet (to Elev. 46 feet). RQD values ranged between 70 and 77 percent (avg. 74 percent) and recovery values of 100 percent.

In the vicinity of Boring B-31, the geotechnical materials are anticipated to include the following:

- Soft clayey silt with sand from the ground surface to a depth of 3.5 feet (from Elev. 152 to 148.5 feet).
- Loose sand to a depth of 8.5 feet (to Elev. 143.5 feet).
- Loose gravel with sand to a depth of 13.5 feet (to Elev. 138.5 feet).
- Very dense gravel with sand to a depth of 18.5 feet (to Elev. 133.5 feet).
- Medium dense silty gravel with sand to a depth of 23.5 feet (to Elev. 128.5 feet).
- Dense clayey sand with gravel to a depth of 28.5 feet (to Elev. 123.5 feet).
- Dense gravel with sand to a depth of 33.5 feet (to Elev. 118.5 feet).
- Very dense silty sand with gravel to a depth of 40 feet (to Elev. 112 feet).
- Moderately weathered to slightly weathered, weak to medium strong dolomite to a depth of 105 feet (to Elev. 47 feet). RQD values ranged between 38 and 100 percent (avg. 68 percent). Recovery values ranged between 88 and 100 percent (avg. 98 percent).
- Highly weathered to moderately weathered, very weak to weak dolomite to a depth of 135 feet (to Elev. 17 feet). Encountered many planar fragments at 75 – 80 degree angles near the bottom of the layer. RQD values ranged between 0 and 75 percent (avg. 31 percent). Recovery values ranged between 58 and 100 percent (avg. 75 percent).
- Moderately weathered, very weak siltstone to a depth of 140 feet (to Elev. 12 feet). Encountered planar fragments at 75 – 80 degree angles. RQD value of 17 percent and recovery value of 100 percent.
- Highly weathered to slightly weathered, very weak to weak dolomite to a termination depth of 165 feet (to Elev. -13 feet). Encountered few areas of missing rock and highly fractured zones. RQD values ranged between 10 and 32 percent (avg. 16 percent). Recovery values ranged between 22 and 100 percent (avg. 62 percent).

In the vicinity of Boring B-32, the geotechnical materials are anticipated to include the following:

- Fill described as loose to medium dense gravel from the ground surface to a depth of 18.5 feet (from Elev. 150 to 131.5 feet).
- Loose sand with silt to a depth of 23.5 feet (to Elev. 126.5 feet).
- Medium dense gravel to a depth of 31 feet (to Elev. 119 feet).
- Medium dense to very dense sand with silt and gravel to a depth of 47.5 feet (to Elev. 102.5 feet).
- Very dense gravelly sand with silt to a depth of 53.5 feet (to Elev. 96.5 feet).
- Medium stiff clayey silt to a depth of 63.5 feet (to Elev. 86.5 feet).

- Medium dense to very dense gravelly sand with silt to a depth of 73.5 feet (to Elev. 76.5 feet).
- Very dense rock fragments to a depth of 78.5 feet (to Elev. 71.5 feet). Encountered 18-inch boulder within layer.
- Stiff to very stiff clayey silt with rock fragments to a depth of 93.5 feet (to Elev. 56.5 feet).
- Medium dense decomposed rock fragments with silty sand to a termination depth of 97 feet (to Elev. 53 feet).

In the vicinity of Boring B-32A, the geotechnical materials are anticipated to include the following:

- Fill described as loose to medium dense gravel from the ground surface to a depth of 32.5 feet (from Elev. 150 to 118 feet).
- Dense gravelly sand with silt to a depth of 45 feet (to Elev. 105 feet).
- Very stiff clayey silt with sand and gravel to a depth of 85 feet (to Elev. 65 feet).
- Medium dense to very dense decomposed rock fragments to a depth of 103.5 feet (to Elev. 46.5 feet).
- Hard to very stiff clayey silt with gravel to a depth of 135 feet (to Elev. 15 feet).
- Slightly weathered, weak to medium strong dolomite with chert to a termination depth of 150 feet (to Elev. 0 feet). RQD values ranged between 23 and 88 percent (avg. 60 percent). Recovery values ranged between 42 and 92 percent (avg. 72 percent).

Along the proposed HDD alignment, the bedrock on the west side of the Delaware River appears to be of very poor to very good quality. RQD values range from 0 to 100 percent with an average value of 44.3 percent. The core recovery values on the west side ranged from 22 to 100 percent with an average value of 83.7 percent.

Laboratory testing of the Dolomite from boring B-31 indicate a Uniaxial Compressive Strength (UCS) range from 6,260 to 6,395 psi with an average of 6,328 psi. The axial point load UCS ranged from 11,593 to 20,931 psi with an average of 18,069 psi. The diametral point load UCS from boring B-31 and B-Del-1 ranged from 1,524 to 14,341 psi with an average of 7,536 psi. The splitting tensile strength ranged from 1,191 psi to 1,866 psi with an average of 1,497 psi.

Laboratory testing of the gneiss from boring B-33 indicate a UCS range from 7,101 to 44,290 psi with an average of 17,551 psi. The axial point load UCS ranged from 23,284 to 36,335 psi with an average of 30,851 psi. The diametral point load UCS ranged from 12,010 to 39,543 psi with an average of 31,577 psi. The splitting tensile strength ranged from 2,155 psi to 2,907 psi with an average of 2,561 psi.

2.2.2 Geotechnical Observations on New Jersey (east) side

The HDD installation on the New Jersey side of the Delaware River is anticipated to encounter soils overlying bedrock materials. Based on Boring B-34, the site soils are anticipated to include the following:

- Topsoil to a depth of 1 feet (from Elev. 160 to 159 feet).
- Soft to medium stiff silt to a depth of 8.5 feet (to Elev. 151.5 feet)
- Medium dense sand with trace silt to a depth of 21 feet (to Elev. 139 feet)
- Medium stiff silt to a depth of 26.5 feet (to Elev. 133.5 feet)
- Weathered Quartzite fragments (gravel) to a depth of 35 feet (to Elev. 125 feet). A possible boulder was noted between 30 and 35 feet.
- Medium dense sand with trace silt to a depth of 36 feet (to Elev. 124 feet)
- Medium dense silty gravel with trace sand to a depth of 38.5 feet (to Elev. 121.5 feet)
- Hard sandy silt with gravel to a depth of 46 feet (to Elev. 114 feet).

- Decomposed rock fragments were noted from 41 - 43.5 feet.
- Various thicknesses of dense sand, hard clay, stiff silt, hard gravelly silt to the termination depth of 110 feet (to Elev. 50 feet). Gravels were noted to be up to 18 percent of the soil, based on grain size distribution tests.

Based on Boring B-33, the site soils are anticipated to include the following:

- Topsoil to a depth of 0.5 feet (from Elev. 150 to 149.5 feet).
- Very dense gravel with silt and sand to a depth of 4 feet (to Elev. 146.0 feet).
- Slightly weathered to fresh and strong to very strong Granitic Gneiss to a depth of 112 feet (to Elev. 38 feet). RQD values ranging between 15 and 100 percent (average 78 percent). Recovery values ranging between 44 and 100 percent (average 93 percent).
- Fresh and medium strong to strong Granitic Gneiss to a termination depth of 165 feet (to Elev. -15 feet). RQD values ranging between 50 and 98 percent (average 80 percent). Recovery values ranging between 88 and 100 percent (average 97 percent).

The bedrock materials are anticipated to include predominantly slightly fresh, medium strong to strong granitic gneiss, based on information collected from Boring B-33. The granitic gneiss appears to be of very poor to good quality, with RQD values ranging from 15 to 100 percent, and an average value of 78.3 percent. The core recovery values on the east side ranged from 44 to 100 percent, with an average value of 94.1 percent.

2.3 Geophysical Observations

A geophysical survey was conducted by Hager-Richter between July 26 and August 11, 2016, to collect ERI data across the Delaware River. It was originally planned to collect data along transects perpendicular to the river. However, the swift current and depth of the river prohibited effectively laying a straight line across the river. Therefore, the survey data was collected across eight (8) transects parallel to the flow of the river and the supposed fault line.

Interpretations of the survey results by Hager-Richter appear to indicate that the thrust fault exists just west of the centerline of the Delaware River at the crossing location. The bedrock surface appears to be relatively level beginning at approximate Elev. 100. Resistivity patterns indicate different materials on either side of the apparent thrust fault consistent with the materials encountered in the geotechnical borings.

3 Delaware River Crossing

3.1 HDD Bore Geometry and Alignment Considerations

3.1.1 Entry and Exit Angles

HDD operations are typically designed with entry angles between 8° and 16°, although steeper entry angles have been used where insufficient setback distance or steeply sloping ground exists for a given alignment. Exit angles are typically lower than the entry angle, as consideration must be given to the pipe diameter, the equipment necessary to transition the pipe into the bore, and the stresses induced as the pipe is forced over the break-over location as it enters the HDD bore.

For the Delaware River Crossing, the east entry and west entry angles have been set at 13° and 12°, respectively, relative to the horizontal.

3.1.2 Vertical and Horizontal Curvature

Vertical curvature is inherent to all HDD installations. The need for horizontal curvature is dependent on the restrictions specific to a single crossing. While horizontal curvature is feasible, it greatly increases the complexity of the scope of design and construction when required. It also increases the stress, and therefore the risk, to the pipe and the overall installation. Steering in both planes is not a standard industry practice, and can lead to complex radii and a reduction in the overall bending radius that the pipe will be subjected to. A straight alignment has been selected for this HDD crossing, thereby eliminating the risks associated with horizontal curvature.

The proposed vertical curve radius of 4,300 feet shown in Appendix A is slightly higher than the HDD industry standard of 1,200 times the 36-inch outer diameter of the pipe. This radius has been taken as the design radius for the crossing to avoid a section of bedrock materials with low RQD ratings beneath the horizontal section of the bore.

3.1.3 HDD Installation Depth

The depth of cover for a given HDD installation is dependent on several factors, including but not limited to:

- The anticipated geotechnical materials,
- The presence of preferential flow pathways,
- The design bending radius,
- The presence of existing utilities and/or structures, and
- Installation length.

Of these, the most important factors are the properties of the overlying geotechnical material, and the resistance these materials provide against the required installation-induced bore fluid pressures necessary to remove the cuttings.

Another important factor in establishing the proper installation depth is the ability to maintain bore stability over the course of the installation. This is accomplished by placing the HDD bore through geotechnical materials that are favorable to HDD operations.

The proposed HDD installation crosses beneath several surface features including wetland, waterbody, roadways, and a railroad. From a west to east orientation, the following minimum depths of cover are noted:

- Wetland 110714_JC_001_PFO: Approximately 70 feet.
- State Route 611: Approximately 140 feet.
- Waterbody 052915_JC_1002_C_IN: Approximately 141 feet.
- Delaware River: Approximately 111 feet.
- Wetland 042617_DK_1001_PSS: Approximately 126 feet.
- Old River Road: Approximately 133 feet.
- Belvidere & Delaware River Railway: Approximately 39 feet.
- Riegelsville Milford Road / County Road 627: Approximately 20 feet.

3.1.4 Bore Diameter

The diameter of the HDD bore needs to be greater than the outer diameter of the pipe. This larger bore is required to facilitate the flow of drilling fluids around the pipe, reduce the frictional force acting on the pipe as it is installed, and to help the pipe negotiate curves in the alignment.

The acceptable industry standard for the final bore diameter is generally 1.5 times larger than the pipe outer diameter for small diameter pipe (less than 24 inches), and 12 inches larger than the outer diameter for large diameter installations. However, the actual diameter of the bore is typically dependent upon the geotechnical conditions and the required bore geometry. Hence, it may be necessary to increase the diameter beyond the typical industry standard to facilitate the installation process. To increase the likelihood of success, it is highly recommended that the final bore diameter be selected by the HDD Contractor, based on their experiences with similar geotechnical materials, pipe diameters, and installation lengths, and to suit their means and methods.

Based on typical HDD industry standards, the anticipated bore diameter for the NPS 36 pipe is 48 inches.

3.2 Line and Grade Accuracy

The horizontal and vertical position of the bottom hole assembly is tracked using a downhole survey tool, consisting of a probe that utilizes Earth's gravitational and magnetic fields. These tools have a nominal accuracy of approximately:

- Inclination: ± 0.1°
- Azimuth: ± 0.3° to 0.5°
- Tool-face: ± 0.1°

The accuracy of these tools can be enhanced by using a surface wire/coil loop established over the alignment. Inducing an electrical current through the wire creates a localized magnetic field that the probe can then use to determine its location relative to the surveyed coil and magnetic field.

These enhanced guidance systems include TruTracker and ParaTrack systems. The TruTracker guidance system relies on a closed loop surveyed wire layout that is at least as wide as the depth of the HDD installation. For highways and water body crossings, individual coils are often established on each side of the crossing feature. A ParaTrack system relies on a single wire placed directly over the HDD alignment centerline, with a return wire offset several hundred feet from the alignment to form a closed loop system. When augmented with a surface coil, the lateral and vertical position of the survey probe is plus or minus two (2) percent of the depth separating the location of the probe and the surface coil. Greater inaccuracies may occur if site constraints prevent the use of an energized wire grid on the ground surface.

Fiber-optic gyroscopic guidance systems have also been used to track downhole tooling. This type of system relies on an inertial measurement unit to calculate the position of the bottom hole assembly and is not affected by magnetic interference. This tool is very effective in accurately locating the surface tool position during pilot bore drilling.

With all of these methods, survey readings can be taken at the end of each drilled joint or every half of a joint. Stand-alone surveys can be completed where the surface coils are established. Here the inaccuracy is a function of the specific depth of cover at the location in question. Where the surface coils cannot be established, such as across a highway or beneath a river, the position of the bottom hole assembly is determined based on the calculated position of the previous measurement. In this manner, any inaccuracy built into the measured position is additive as the drill length increases. However, as the bottom hole assembly re-encounters the surface coil on the opposite side of the highway or river, the inaccuracy is once again a function of a stand-alone measurement based on the specific depth of cover at the location in question.

Mott MacDonald recommends the use of a gyroscopic guidance system for the Delaware River crossing to mitigate concerns associated with laying a surface coil along the proposed alignment and across the waterway. If a ParaTrack system is proposed by the HDD Contractor, the HDD Contractor must assure adequate coverage of surveying with no gaps in coverage with a surface coil and/or beacon.

3.3 Required Workspace and Staging Areas

For the proposed HDD installation, the staging area for the east side of the crossing has been established at 230 feet by 280 feet, and the staging area for the west side of the crossing has been established at 250 feet by 250 feet (to accommodate use of the drill and intersect strategy). This area is required to stage equipment necessary for the installation, which includes the drill rig, stacks of drill pipe, operator control cabin, tooling trailers, crane or excavator, separation plant, mud tanks, mud pumps, Baker storage tanks, office trailer, and support trailers.

In addition to the entry and exit staging areas, a staging area of 75 feet wide by the length of the pipe string (greater width is required where multiple drag sections are required) is also required for welding sections of the pipe string, and preferably the entire pipe string when possible, prior to installation. The proposed staging area for the drag section is located on the west side of the crossing. The available length of the staging area is approximately 1,325 feet, resulting in the need for fabricating the pipe string into three (3) drag sections and the need for two (2) intermediate welds during pullback operations. The HDD Contractor will need to minimize delays during intermediate welding operations. To accommodate fabricating three (3) pipe strings, the staging width has been increased to 125 feet.

The temporary work space established for the Delaware River Crossing is sufficient for HDD operations.

3.4 Requirement for Temporary Surface Casing

During the geotechnical investigation, layers of gravel and isolated boulders were observed extending to various depths on both sides of the Delaware River. The gravels were observed to a depth of approximately 23.5 feet below ground surface on the west side of the crossing. These soils represent a significant risk to the overall bore stability, raveling of gravel into the bore, potential damage to the pipe string, and increased pullback loads/stresses. To support these soils and mitigate the risks associated with such deposits, a temporary conductor casing is recommended on the west side of the HDD installation. The approximate casing length required on the west side of the proposed HDD installation is 120 to 140 feet, depending on where the soil/bedrock interface is encountered with the HDD alignment and the extent of the decomposed dolomite layer above the soil/bedrock interface.

Soils containing gravels were also noted on the east side of the river to a depth of approximately 38 feet below ground surface near Boring B-34. To mitigate the presence of this material, approximately 200 feet of casing pipe is required on this side of the HDD installation.

The minimum conductor casing diameter is recommended to be 56 inches to allow for the free passage of the 48-inch reamer assembly. Any required casing pipe shall be removed once pullback operations have been completed.

The requirement for temporary conductor casings on each end of the proposed HDD installation will require a drill and intersect installation strategy for this crossing. This method involves drilling independent pilot bores from each side of the installation meeting within a target intersection location along the alignment. For the proposed profile, the intersection location is envisioned to occur along the 456-foot long horizontal tangent between STA 4097+59 and 4102+15.

3.5 Drilling Fluid Make-Up Water and Source

HDD operations require a continuous source of water to support construction activities. It is typical for contractors to make use of an onsite source or have water delivered from a nearby source. In each case, the contractor should verify that the water source is suitable for HDD operations or treat it (filtration, pH, etc.) so that it is suitable for use.

For the proposed crossing, the Delaware River has been identified as a potential source of fresh water to support construction activities. Estimates of fresh water requirements is a function of maintaining drilling fluid flow within the bore during the HDD installation, and water requirements to adjust for hole volume, minor losses to processed spoil and surrounding geotechnical materials, wash water, etc. Daily fresh water usage typically ranges from 2,650 to 5,300 ft^3, depending on the process and storage capabilities of the Contractor.

Total fresh water requirements can be estimated as a function of the final reamed diameter. Factors of between two (2) and seven (7) times the final reamed diameter have been used to estimate the fresh water requirements necessary to support HDD operations. Based on a factor of five (5), the estimated total water usage (assuming no loss in circulation) is approximately 1,500,000 gallons (200,000 ft^3). This volume estimate assumes good HDD industry practices and procedures are followed, and that no significant fluid losses occur during the installation. This volume also includes fresh water required for buoyancy control during the HDD installation (estimated at approximately 100,000 gallons).

3.6 Disposal of Excess Drilling Fluid and Processed Spoils

Excess drilling fluids and processed spoils will need to be disposed of during the installation. The direct area around the HDD is not expected to be suitable for permanent disposal of drilling fluid or processed solids (based on local, state, and federal regulations). Local temporary storage will be required either in above ground tanks or a lined burrow pit. A suitable offsite disposal site should be located for disposal of drilling fluid and processed spoil per the local, state, and federal guidelines.

Disposal volumes of excess drilling fluid and spoil are estimated at approximately 727,225 gallons (3,600 yd^3) and 50,860 ft^3 (1,885 yd^3) respectively. During pullback operations, the estimated displaced fluid volume is approximately 149,800 gallons (750 yd^3).

3.7 Schedule

The duration of the HDD installation is conservatively estimated to take a total of 161 shifts (Table 1). This estimate is based on a 12-hour shift, regardless of whether 24-hour operations are conducted to complete the crossing. No provisions have been included for pad construction and erection and tear-down of a shelter (if used) in these durations. In addition, no contingency has been provided for weather or more difficult drilling conditions.

Table 1: Estimated schedule duration for the HDD Crossing

Activity	Duration (shifts)
Mobilization	3
Rig Up / Equipment Setup	6
Casing Installation	15
Pilot Bore Drilling	30
Reaming	94
Swab Pass	2
Product Pip Pullback	3
Casing Removal	3
Rig Down and Demobilization	5
Total Number of Shifts	**161**

4 HDD Engineering Evaluation

4.1 Pipeline Properties

The pipeline properties used for the evaluation of the Delaware River Crossing have been provided by PennEast, and are summarized in Table 2 below:

Table 2: Pipeline properties and input parameters for the HDD evaluation

Evaluation Parameter	Value
Pipe Size	NPS 36
Outer Diameter	36 in
Wall Thickness	0.762 in
Pipe Grade	X-70
Maximum Allowable Operating Pressure	1,480 psig
Minimum Operating Temperature	45°F
Maximum Operating Temperature	120°F
Poisson's Ratio	0.30
Elastic Modulus	29,200,000 psi
Coefficient of Thermal Expansion	6.5×10^{-6} in/in/°F
Design Factor	0.5

4.2 Design and Minimum Allowable Bend Radii

The minimum ultimate bend radius is a function of the maximum allowable operating pressure, pipe diameter, wall thickness, design factor, location factor, and specified minimum yield strength of the pipe material. Determination of the ultimate minimum bend radius is based on determining the hoop and longitudinal stresses under operating pressure and then determining the available magnitude of stress that the product pipe can accommodate in an alignment bend/curve.

The minimum ultimate bending radius evaluation is completed in accordance with:

- ASCE Manual of Practice No. 108 Pipeline Design for Installation by Horizontal Directional Drilling
- 49 CFR 192 Transportation of Natural and Other Gas by Pipeline- Minimum Federal Safety Standards
- ASME B31.8 Gas Transmission Distribution and Piping Systems
- ASME B31.4 Pipeline Transportation Systems for Liquid Hydrocarbons and Other Liquids

Using the pipe properties presented in Table 2, the ultimate minimum bending radius is calculated for the pipe and pressure conditions. This radius represents the lowest radius that could be drilled without overstressing the pipe for the identified pipe properties and in-service loading. Based on the pipe properties provided in Table 2 and a design factor of 0.5, the ultimate minimum bending radius is approximately 2,500 feet.

The minimum allowable bending radius is the minimum radius that the HDD contractor is permitted to drill during their pilot bore to maintain the design alignment and profile. This radius is established above the calculated ultimate minimum bending radius to not overstress the pipe during the HDD installation process, and sufficiently below the design radius provided on the construction drawings. Based on an ultimate minimum bending radius of 2,500 feet, the minimum allowable bending radius has been established at 2,600 feet.

The design radius is the radius selected to develop the HDD plan and profile. This radius is greater than the minimum allowable bending radius given to the HDD contractor to complete the construction of the crossing. The design bending radius for developing the Delaware River profile has been established at 4,300 feet, which is slightly lower than the HDD industry standard of 1,200 times the outer diameter of the NPS 36 pipe.

4.3 Operating Stress Evaluation

Evaluation of operating loads for pipelines installed by HDD methods is generally similar to the evaluation for pipelines installed by open-cut construction methods. The main difference between the two scenarios is that the condition of elastic bending (as a result of the curved HDD alignment profile) must be considered for the HDD installation. Elastic bending stresses occur as the pipe takes on the final shape of the HDD bore. As a rule, the bending stresses induced are not a critical stress condition on their own, but must be considered in a combined loading condition with other stress conditions such as hoop stress and longitudinal stress.

An operating stress evaluation has been completed in compliance with the American Society of Mechanical Engineers B31.4 and B31.8. The input parameters for this analysis are provided in Table 2. The results of the evaluation are provided in Table 3 below, and are based on the minimum allowable bending radius of 2,600 feet (based on the allowable bend radius provided to the HDD contractor). As observed in Table 3, the operating stresses are below the maximum allowable limits. Hence, the pipe properties (wall thickness and grade) are sufficient to meet the operating stresses within the HDD alignment.

Table 3: Summary of operating stress evaluation

Stress Condition	Estimated Stress (psi)	Percent of SMYS[1] (%)	Maximum Allowable Percent of SMYS[1] (%)
Longitudinal Bending Stress	16,846	24.1	--
Hoop Stress	34,961	49.9	50[2]
Longitudinal Tensile Stress from Hoop Stress	10,488	15.0	--
Longitudinal Stress from Thermal Expansion	-14,235	20.3	90[3]
Net Longitudinal Stress (Compression Side of the Curve)	-20,593	29.4	90[4]
Net Longitudinal Stress (Tension Side of the Curve)	13,099	18.7	90[4]
Maximum Shear Stress	27,777	39.7	45
Combined Biaxial Stress	55,553	79.4	90[4]

Notes: [1] Specified Minimum Yield Stress
[2] Limited by design factor
[3] Limited by ASME B31.4
[4] Limited by ASME B31.8

4.4 HDD Installation Load and Stress Evaluation

A total of six (6) pull load evaluations were completed for the HDD bore profile. These calculations are based on the installation load calculation method provided in American Society of Civil Engineer MREP 108 (2015), and the Pipeline Research Committee at the American Gas Association publication, entitled "Installation of Pipelines by Horizontal Directional Drilling, an Engineering Guide."

The pull load evaluation includes assumptions for final bore diameter, soil, and pipe roller friction coefficients, drilling fluid yield point, plastic viscosity, drilling fluid pumping rate, and other installation parameters such as buoyancy control measures (i.e. whether or not the pipe will be filled with water during pullback operations). In addition, the evaluation accounts for the capstan effect induced by curves in the alignment, fluidic drag, buoyancy of the pipe string within the bore, and the weight of the tail string at start-up and throughout the installation process.

Six (6) installation evaluations have been completed to investigate the effects of varying mud weights and buoyancy control measures during the installation of the pipe. The six (6) scenarios evaluated include:

- Case 1: Drilling Fluid Weight 10 ppg (Specific Gravity of 1.20)
  Pipe No buoyancy control (pipe empty of water)
- Case 2: Drilling Fluid Weight 10 ppg (Specific Gravity of 1.20)
  Pipe Full buoyancy control (pipe full of water)
- Case 3: Drilling Fluid Weight 11 ppg (Specific Gravity of 1.32)
  Pipe No buoyancy control (pipe empty of water)
- Case 4: Drilling Fluid Weight 11 ppg (Specific Gravity of 1.32)
  Pipe Full buoyancy control (pipe full of water)
- Case 5: Drilling Fluid Weight 12 ppg (Specific Gravity of 1.44)
  Pipe No buoyancy control (pipe empty of water)
- Case 6: Drilling Fluid Weight 12 ppg (Specific Gravity of 1.44)
  Pipe Full buoyancy control (pipe full of water)

A summary of the maximum anticipated pull load for each case scenario is provided in Table 4 below. Detailed calculations are provided in Appendix C. The anticipated installation loads shown in Table 4 are well below the ultimate allowable load of the pipe of approximately 3,542,953 lbs, based on a tensile stress equivalent to 60 percent of the yield stress for the given wall thickness and pipe grade provided in Table 2. It is important to note the difference in pull loads when buoyancy control measures are implemented and water is added to the pipe during pullback, as the estimated installation loads are typically lower when buoyancy control measures are used. Mott MacDonald recommends the use of buoyancy control measures to lower the overall installation loads and stresses for this installation.

A start-up factor of 1.5 has been applied to the estimated pullback forces to replicate the higher installation loads observed during stoppages and recommencing of pullback operations. This is referred to as the initial start-up pullback force in Table 4.

Table 4: Summary of anticipated pullback loads

Drilling Fluid Weight (ppg)	Product Pipe Buoyancy Condition	Estimated Pullback Force (lbs)	Initial Start-Up Force String 1 (lbs)	Initial Start-Up Force String 2 (lbs)	Initial Start-Up Force String 3 (lbs)
10 (Case 1)	Empty	487,716	18,084	170,415	469,513
10 (Case 2)	Full	278,750	18,084	138,372	277,740
11 (Case 3)	Empty	564,254	18,084	178,335	524,490
11 (Case 4)	Full	232,700	18,084	137,021	250,100
12 (Case 5)	Empty	642,908	18,084	186,256	582,637
12 (Case 6)	Full	210,918	18,084	135,670	222,901

Results of the corresponding installation stresses (based on the design bending radius of 4,300 feet) are summarized in Table 5.

Table 5: Summary of installation stress evaluation

Stress Condition	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Maximum Tensile Stress (Percent of Allowable)	5,782 psi (8.3%)	3,304 psi (4.7%)	6,689 psi (9.6%)	2,965 psi (4.2%)	7,621 psi (10.9%)	2,642 psi (3.8%)
Maximum Bending Stress (Percent of Allowable)	10,116 psi (14.5%)	10,116 psi (14.5%)	10,116 psi (14.5%)	10,116 psi (14.5%)	10,116 psi (14.5%)	10,116 psi (14.5%)
Maximum Hoop Stress (Percent of Allowable)	1,966 psi (2.8%)	326 psi (0.5%)	2,163 psi (3.1%)	523 psi (0.8%)	2,359 psi (3.4%)	719 psi (1.0%)
Maximum Unity Check – Tensile and Bending	0.33	0.28	0.34	0.28	0.36	0.27
Maximum Unity Check – Tensile, Bending, and Hoop	0.17	0.06	0.19	0.06	0.21	0.07

As observed in this Table, the results of the HDD installation stress evaluation are within the allowable limits for all cases.

4.5 Hydraulic Fracture Evaluation

The hydraulic fracture evaluation for this crossing has been completed in general accordance with the Delft Geotechnics Method outlined in Appendix B of the Army Corps of Engineers 1998 Report CPAR-GL-98 and 2002 Report ERDC/GSL TR-02-9 (Guidelines for Installation of Utilities Beneath Corp of Engineers Levees Using Horizontal Directional Drilling). This method is used to estimate the maximum effective pressure (i.e. drilling fluid pressure) that can be induced during an HDD operation within a particular soil horizon. This pressure is then compared with the fluid pressure required to induce slurry flow within the HDD bore to determine the potential for a hydraulic fracture for a given HDD alignment. The required fluid pressure for an HDD installation is governed by the drilling fluid weight (commonly referred to as the mud weight), installation length and depth, and drilling fluid flow properties (plastic viscosity, yield point, etc.).

The hydraulic fracture evaluation method described above and used in the HDD industry was developed for soil installations. Currently, no accepted method is available to model/predict the maximum allowable drilling fluid pressure within bedrock materials. While bedrock tensile strength and unconfined compressive strength evaluations have been used to estimate the allowable drilling fluid pressure within bedrock materials, these methods tend to provide results that are not considered suitably conservative and greatly over-predict the true maximum allowable drilling fluid pressures. These over-predictions are a result of laboratory testing on sound or high quality bedrock samples that are not representative of the strengths of the weaker bedrock materials that contain natural fractures/joints that are washed out or impacted by the geotechnical coring process. Hence, for bedrock hydraulic fracture evaluation, Mott MacDonald has elected to model the dolomite and gneiss bedrock materials as strong soils. This conservative approach has been used by Mott MacDonald to successfully complete several HDD installations in similar bedrock materials.

The Delft Geotechnics Method assumes a uniform column of soil above any point of interest along the alignment. Where an increased risk of hydraulic fracture is identified, it does not necessarily mean that a hydraulic fracture will occur. A proper HDD execution plan, based on HDD industry standard construction practices, can reduce the risk of a hydraulic fracture from occurring.

In order to complete the hydraulic fracture evaluation, it is necessary to make several assumptions relative to the bore diameter, drilling fluid pumping rate, and drilling fluid properties. Parameters used in Mott MacDonald's evaluation are provided in Table 6 below. These parameters have been selected based on Mott MacDonald's experience in drilling within similar anticipated geotechnical materials.

Table 6: Assumptions used for hydraulic fracture evaluation

Evaluation Parameter	Value
Pilot Bore Diameter	12-¼ in
Drill Pipe Diameter	6-⅝ in
Drilling Fluid Pumping Rate	600 gal/min
Drilling Fluid Weight (Specific Gravity)	11 ppg (1.32)
Yield Point	24 lb./100 ft^2
Plastic Viscosity	16 cP

In addition to the assumptions provided in Table 6, assumptions are also required for the anticipated soil formation(s) and their properties including, but not limited to, geotechnical material strength, unit weight, cohesion, friction angle, and shear modulus. These assumptions are provided in Tables 7 through 11 for the varied subsurface materials that are anticipated for this crossing. For this evaluation, Mott MacDonald assumes that the encountered subsurface material will be similar to that described in Section 2.0, namely, a mixture of silt, sand, and gravel overlying dolomite and gneiss bedrock. For this evaluation, it has also been assumed that the Drill and Intersect method will be used to complete the pilot bore.

Table 7: Material property assumptions for the silt and sand

Evaluation Parameter	Value
Soil Unit Weight Above / Below Water Table	125 lb./ft^3 / 135 lb./ft^3
Effective Cohesion	0 psf
Internal Friction Angle	30°
Young's Modulus	522,136 psf
Poisson's Ratio	0.33

Table 8: Material property assumptions for the silty clay

Evaluation Parameter	Value
Soil Unit Weight Above / Below Water Table	120 lb./ft^3 / 135 lb./ft^3
Effective Cohesion	2,600 psf
Internal Friction Angle	0°
Young's Modulus	730,990 psf
Poisson's Ratio	0.35

Table 9: Material property assumptions for the sand and gravel

Evaluation Parameter	Value
Soil Unit Weight Above / Below Water Table	130 lb./ft^3 / 135 lb./ft^3
Effective Cohesion	0 psf
Internal Friction Angle	31°
Young's Modulus	835,417 psf
Poisson's Ratio	0.33

Table 10: Material property assumptions for the gneiss bedrock

Evaluation Parameter	Value
Soil Unit Weight Above / Below Water Table	135 lb./ft^3 / 140 lb./ft^3
Effective Cohesion	2,000 psf
Internal Friction Angle	28°
Young's Modulus	960,730 psf
Poisson's Ratio	0.33

Table 11: Material property assumptions for the dolomite bedrock

Evaluation Parameter	Value
Soil Unit Weight Above / Below Water Table	130 lb./ft^3 / 135 lb./ft^3
Effective Cohesion	2,000 psf
Internal Friction Angle	28°
Young's Modulus	898,073 psf
Poisson's Ratio	0.33

The results of the preliminary hydraulic fracture evaluation for the proposed crossing are provided in Figure 1 for the pilot bore phase of the installation process. More detailed results are provided in Appendix D. A safety factor has been incorporated into the hydraulic fracture evaluation for the allowable bore pressure within the bedrock, to account for assumptions incorporated into the design and heterogeneity of the geotechnical materials. The graph also displays the total soil/bedrock overburden stress representing the equivalent unit weight of the overlying soil without consideration of any soil strength. Mott MacDonald recommends holding discussions with the HDD contactor if the actual bore pressures trend higher than those values estimated in Appendix D during actual construction, especially if the observed bore pressures spike during the installation.

As shown in the graph, the required bore pressure to facilitate the installation process is well below the allowable bore pressure for the installation.

Once the pilot bore is completed, the hydraulic fracture risk associated with the reaming, swab, and pullback phase of the installation typically decreases, assuming the bore is reamed to its full extent and a subsequent swab pass is completed through the bore prior to installing the pipe. However, it is important to note that although the hydraulic fracture potential is significantly reduced, a hydraulic fracture event may still occur during the reaming pass if the bore becomes plugged or blocked such that the required drilling fluid pressure increases in magnitude to the point where it exceeds the estimated allowable mud pressure for the overlying soils. HDD industry standard construction practices, such as pumping sufficient drilling fluids, maintaining drilling fluid returns, monitoring and maintaining drilling fluid and returning slurry properties, etc., should reduce any potential loss of drilling fluids.

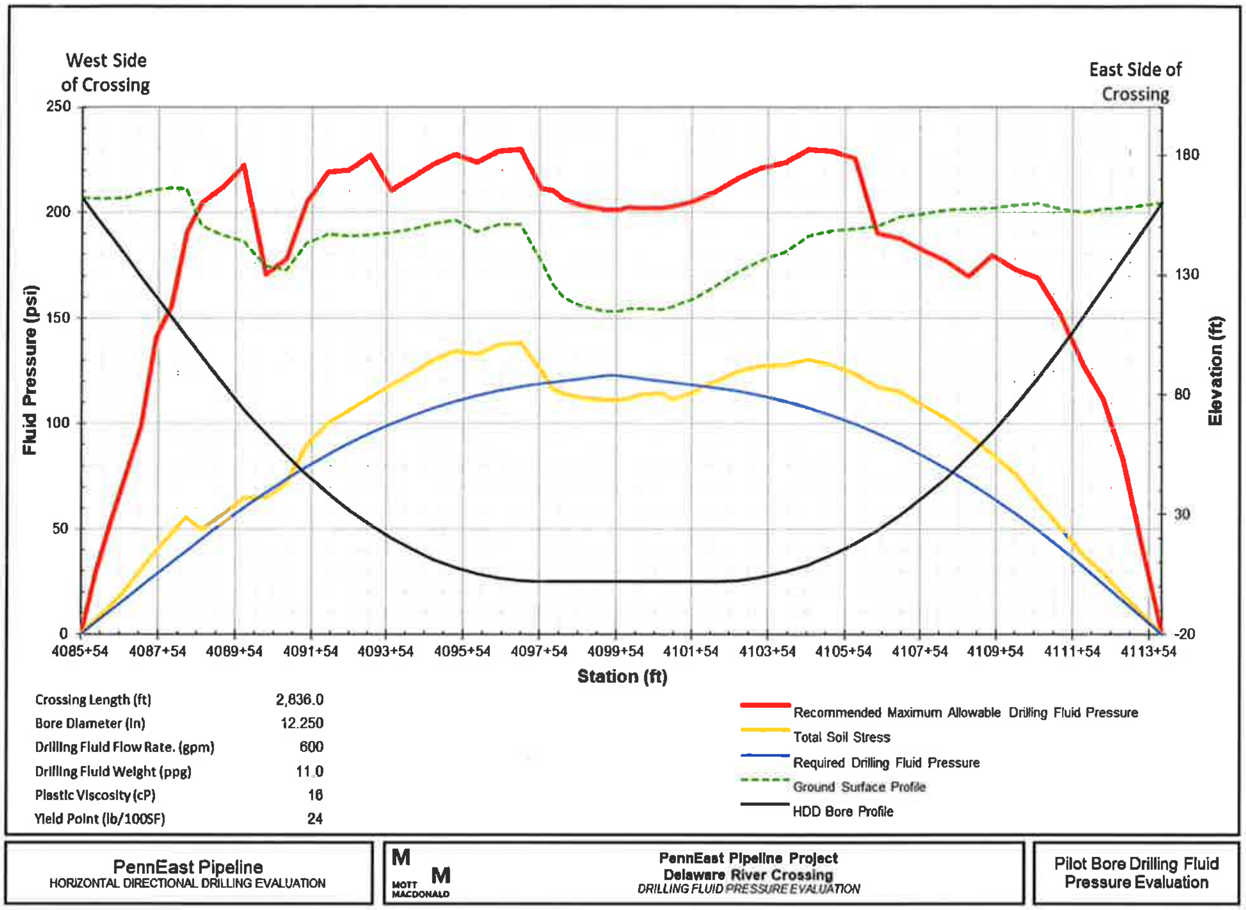

Figure 1: Calculated, recommended, and allowable drilling fluid pressures

5 HDD Risk Discussions

5.1 HDD Risk Characterization

Risk identification and mitigation is paramount to successfully completing the Delaware River Crossing. Discussions of the general risks associated with these crossings are presented below.

5.2 HDD Industry – State of Practice

Mott MacDonald maintains an up-to-date database of successfully completed HDD installations based on pipeline diameter and installation length, as shown in Table 12 below. This database is used to quickly and uniquely assess the achievable installation length for a given pipeline diameter. The green shaded cells indicate the common range of HDD industry experience/capability, and was established with the requirement that several contractors have successfully completed similar installation lengths at the specific diameter. The yellow shaded cells identify the installation lengths and diameters that are considered feasible with an experienced contractor in favorable ground conditions. The red shaded cells are considered to be at the limits of, or beyond, the current state-of-the-practice for the HDD industry.

Table 12: State of the HDD Industry

Product Pipe Diameter	Installation Length												
	1,000 m	1,200 m	1,400 m	1,600 m	1,800 m	2,000 m	2,200 m	2,400 m	2,600 m	2,800 m	3,000 m	3,500 m	3,750 m
	3,281 ft	3,937 ft	4,593 ft	5,249 ft	5,905 ft	6,562 ft	7,218 ft	7,874 ft	8,530 ft	9,186 ft	9,842 ft	11,483 ft	12,303 ft
200 mm (8 inch)	16	9	14	4	5	10	5	0	0	0	1	0	1
250 mm (10 inch)	9	9	4	11	1	0	3	1	0	0	0	0	0
300 mm (12 inch)	14	10	9	4	3	1	0	1	1	0	0	1	0
350 mm (14 inch)	3	5	3	0	1	0	0	0	0	0	0	0	0
400 mm (16 inch)	9	4	4	6	4	1	3	0	0	0	2	0	0
450 mm (18 inch)	0	0	0	2	0	0	0	0	0	0	0	0	1
500 mm (20 inch)	8	10	9	1	0	1	2	1	0	0	0	0	0
600 mm (24 inch)	29	30	9	12	9	4	1	2	0	0	1	0	0
750 mm (30 inch)	23	10	10	11	8	3	1	3	0	0	1	0	0
900 mm (36 inch)	23	21	21	6	2	1	2	0	1	0	0	0	0
1050 mm (42 inch)	29	21	11	5	1	1	0	0	0	0	0	0	0
1200 mm (48 inch)	1	2	1	0	0	0	0	0	0	0	0	0	0

Colour Coding:

- (Green) Within typical capabilities of industry. Multiple experienced contractors.
- (Yellow) Zone of limited industry application. Considered feasible with an experienced contractor and favourable ground conditions.
- (Red) Exceeds current capabilities of industry. Considered risky even with an experienced contractor and favourable ground conditions.

NOTE: Current State of the HDD Industry shown above is based solely on the reported installation lengths and diameters. Site-specific geotechnical and installation based risks have not been considered in developing this chart.

It is very important to note that the state of the HDD industry shown above includes crossings with similar elevations between HDD entry/exit locations and the crossing feature, good soils/bedrock materials, and adequate staging area for fabricating the pipe string. These completed projects mostly reflect those with low risk profiles (especially for larger and longer HDD installations). As such, when comparing a specific crossing to those completed projects within the HDD industry, the site-specific geotechnical and crossing risks need to be thoroughly considered and evaluated to verify the completed project listings are comparable and deemed to be adequate. If the current proposed crossing carries a low risk profile, then the comparison can serve as a guide to what has been successfully completed within the HDD industry. However, if the current proposed crossing carries a high risk profile, then the comparison to the completed projects may not be applicable.

As observed in Table 12, several HDD installations have been successfully completed at a diameter of NPS 36 for lengths considerably longer than the horizontal installation length of approximately 2,836 feet, with a true pipe length of approximately 2,863 feet, required for the Delaware River crossing. Therefore, from a constructability standpoint, the Delaware River Crossing falls within the zone of typical experience of what has been accomplished to date within the HDD industry.

5.3 Geotechnical Risk Discussions

Sands, silts, and clays typically present no significant challenge to an HDD installation. These materials are often described as good to excellent materials in terms of feasibility. However, when these soils exist in a soft or loose state, they may not provide sufficient strength to resist the required fluid pressures necessary to complete an HDD installation. Within these materials, the required drilling fluid pressures can exceed their strength, resulting in the formation of a hydraulic fracture through the overlying soils and ponding of drilling fluids at the ground surface. This risk can only be mitigated by placing the HDD bore within more favorable geotechnical materials that provide greater resistance to induced drilling fluid pressures, or through the use of conductor casings to provide an open pathway for drilling fluid flow.

Soils containing gravels and larger size particles (cobbles) range from marginally acceptable to unacceptable in terms of feasibility, depending upon the percentage of gravels by weight and particle size. Only those particles that can be suspended within the drilling fluid can be removed from the bore. Generally speaking, gravel-sized particles less than approximately 0.5 to 0.75 inches can be removed from the bore, provided good HDD practices are followed. Particles greater in size typically cannot be suspended by the drilling fluid and tend to settle out and accumulate along the bottom of the bore. The risks associated with accumulation of larger particles within the bore increase with greater bore diameter, due to the greater exposed soil materials in the crown of a larger bore.

To mitigate risks associated with the anticipated soils, temporary conductor casings have been incorporated into the design of the profile on each end of the installation.

Controlling and maintaining fluid flow within the bore is critical to the success of an HDD installation. Installation risks significantly increase when slurry circulation is not maintained within the HDD bore. The flow of drilling fluid follows the path of least resistance. As long as the bore is located within favorable geotechnical materials at a sufficient installation depth and properly drilled by the HDD contractor, a stable flow pathway can be created between the drill bit and the HDD entry or exit locations, and maintaining drilling fluid flow within the bore should not be an issue. As observed in the hydraulic fracture evaluation, loss of drilling fluids through the overlying soil is not anticipated for this crossing.

The drill and intersect method was chosen to mitigate risks associated with the geotechnical data provided during the investigation, such as drilling through cobbles and gravel at the entry and exit points, and hydraulic fracture through the overburden materials above the alignment. However, drill and intersect method provides an added level of complexity and technical proficiency to the drilling process. Mott MacDonald recommends that an intersection plan be discussed with the contractor and that they demonstrate that they are technically proficient using the drill and intersect method.

Bedrock can be highly variable and can be classified as being excellent to unacceptable with respect to HDD feasibility. Competent bedrock is well suited for HDD as the bore tends to remain open for extended periods of time. However, heavily weathered, jointed, fractured or fissured bedrock can present challenges with respect to bore stability. In fact, poor quality bedrock can present the same challenges as coarse granular (gravel) deposits where fracturing and jointing is extensive and present an unacceptable risk in terms of constructability to an HDD installation. The risk associated with these materials arises from the inability to support and maintain stability within the bore.

This risk increases with RQD ratings below 60 percent. For the Delaware River Crossing, the bedrock exhibits a wide range of ratings, with an average of 64.4 percent overall, and several isolated areas below 60 percent. The areas of lower rock quality are not anticipated to significantly increase risks associated with this installation.

Karst features have been identified within 0.5 miles of the HDD alignment on the Pennsylvania side. The potential for Karst features in dolomite formations should also be considered with respect to drilling fluid management and steering control. These features pose a risk for significant drilling fluid losses and an inability to maintain design line and grade/loss of downhole tooling. As stated earlier, Mott MacDonald recommends that this issue be discussed with the respective HDD contractor and requests that a contingency plan be provided by the contractor to deal with this potential condition if it is encountered.

The strength of the bedrock can impact construction duration, with higher strength leading to more frequent trips out of the bore to replace worn tooling. The laboratory tests completed to date on the dolomite bedrock indicate unconfined compressive strengths ranging from 11,593 to 20,931 psi, with an average value of 18,070 psi. The unconfined compressive strength of the chert bedrock ranged from 23,284 to 39,543 psi, with an average value of 30,677 psi. The unconfined compressive strength of the granitic gneiss bedrock ranged from 31,152 to 33,531 psi, with an average value of 32,093 psi.

High angle fractures were observed throughout the geotechnical borings. The presence of these fractures increases the risk to bore stability, as the vertical and intersecting fracture planes will be less likely to bridge the crown of the bore and maintain an open annular space for fluid flow. Bore collapse that occurs during the pilot bore and reaming phases of the installation can lead to spikes in drilling fluid pressure, lost circulation and hydraulic fracture, increased force on the downhole tooling, decreased steering control, and loss or damage of downhole tooling. A swab pass is recommended to determine the condition of each bore prior to pullback operations. If areas of higher drill rig effort (torque or thrust/pullback) are experienced, the HDD Contractor should complete additional passes with a hole opener to clear the bore of any debris within the bore.

Preferential flow pathways may occur where heavily weathered, jointed, fractured or fissured bedrock exists. If interconnected, preferential flow pathways may exist for drilling fluid losses into the rock mass or upwards towards the ground surface. Fortunately, the presence of the drilling fluid slurry within the bore often is capable of sealing fractures and/or joints as drilling fluids migrate into these features, resulting in low potential for inadvertent returns of drilling fluids at the ground surface.

Based on the anticipated geotechnical materials, the HDD installation has been designed within favorable geotechnical materials to the extent possible.

5.4 Crossing-Specific Risk Discussions

The length of the pipe staging area for the proposed crossing is insufficient to fabricate the pipe into a single string prior to pullback operations, and intermediate welds will be required. Intermediate welds will require stoppage of pullback operations each time a new pipe segment is welded on. These stoppages represent a significant risk to the installation because the bore is required to remain open much longer than would be required for the installation of a single pipe string. Stoppages for the intermediate welds also provide downtime, while welding occurs, that allows the drilling fluids to "gel" and making it harder to resume pullback operations due to the increased friction between the gelled fluids and the pipe. Start-up loads will increase each time pullback operations are resumed. In some cases, the gel strength of the fluids is too great and the resulting loads lead to damage to the pipe, or the pipe may become stuck at its current position in the bore. This risk increases with each additional intermediate weld. Prior to pullback operations, a swab pass should be completed to gauge whether the bore has been conditioned to accept the pipe.

Areas of high torque and/or pull force should be re-reamed to lower the drill rig effort to pass tools through this portion of the bore. The pipe should be installed with the shortest sections of pipe first and the longest pipe section last to decrease the startup loads on the pipe required to resume drilling operations.

The geological conditions encountered by this HDD installation will vary considerably along the alignment and each condition has an associated risk profile.

At the western end of the crossing, with in the carbonate Allentown and Leitsville formations, there is potential for karst features to be encountered which included pinnacled rock head and dissolution features within the formations and a potential for high strength chert layers.

In the central area of the crossing the alignment will transition out of the carbonates, across the Muscenetcong Fault before entering into Precambrian granite and gneiss materials. At this fault location there is an increased probability of fractured rock and potentially higher weathering grades. A secondary risk item within the central crossing location is the unknown top of rock profile; previous channel erosion elevations may have deepened the top of rock to lower elevations than observed in B-32A.

The Eastern end of the profile may transition out of the Precambrian bedrock into deep soils stratum. B-34 did not hit bedrock and was drilled to 110ft through thick silt and clay materials with occasional sand and gravel layers which is consistent with river alluvial deposits.

6 Summary

For the Delaware River Crossing, geotechnical risks have been acknowledged, but no fatal deterrents have been identified within the alignment. Based on the required installation length and diameter, the HDD contracting community in North America has successfully completed a large number of HDD installations of similar lengths.

While not anticipated, if an attempted HDD installation is unsuccessful, the proposed HDD alignment could be modified using the same HDD entry/exit locations to accommodate an additional HDD attempt, depending on the condition that resulted in the HDD failure. Prior to attempting a second HDD crossing, a risk mitigation workshop should be held with all parties to determine the cause of the initial failure and any mitigation measures that could be adopted to reduce the risk(s) during the second HDD attempt.

7 Limitations

This report is intended to be used in its entirety. The data, interpretations, conclusions, and recommendations contained within this report are provided for informational purposes for PennEast, and pertain specifically to the Delaware River Crossing. The data and conclusions presented herein do not and should not be applied to any other project site or HDD installation. Interpretations of the subsurface conditions are based on the information obtained from the geotechnical borings. The subsurface conditions presented between the geotechnical borings are interpretations and may vary from the actual conditions encountered.

It is recommended that Mott MacDonald provide construction monitoring services to verify the subsurface conditions encountered during construction, provide field design services, and evaluate contractor performance in accordance with the contract and the approved contractor supplied work plan.

Appendix A

HDD Plan and Profile