provided by the manufacturer and the other was derived using American Institute of Steel Construction (AISC) methodologies to calculate the allowable capacity of a compression member with a 10-foot and 20-foot length. For the 1.375" thick pipe, the manufacturer's capacity was the governing value.
The pipe joints were also checked to verify that the anticipated jacking forces will not exceed the manufacturer's recommended joint capacity.

- External loads
  The steel pipe was analyzed for external short term and long term loads, utilizing various combinations of soft ground, rock, and hydrostatic pressures. The interaction between the steel pipe and the surrounding ground was modeled utilizing spring constants that represent the modulus of subgrade reaction. The maximum applied external pressure was 66.7 psi.
  The maximum external pressure of 66.7 psi was used to calculate the critical buckling pressure for the steel pipe using the equations for buckling of long circular tubes subjected to uniform external pressure. The buckling pressure calculation controlled the design of the wall thickness for the pipe. To provide a required safety factor of 2 it was determined that the minimum thickness of the pipe wall should be 1.375 inch, and Grade 50 steel pipe should be used for both tunnel legs.
  In addition, after completion of microtunneling, backfill grout will be placed to fill the annular void between the outside of the pipe and the excavated ground surface. Pipe was checked for buckling caused by external pressure resulting from backfill grouting. To assure that no buckling will occur, the backfilling pressure was limited in the contract documents to 30 psi.
- Internal hydrostatic pressure
  The pipe was designed for internal hydrostatic pressure of 120 psi. The resulting tension was checked utilizing allowable stress method and allowable stress equal to 0.5 Fy.
- Seismic design
  The calculations included a closed form solution of the seismic analysis of 9'-0" pipe for both ovaling deformation and axial and curvature deformation due to S-waves during Maximum Design Earthquake (MDE). As a result of the deformation caused by the seismic event analysis the dynamic compressive and tensile stresses were generated. The dynamic stresses were superimposed on the existing static stresses in the steel pipe, however the combined stresses did not exceed the capacity of the pipe including the required safety factor of 2.
- Pipe Joint
  The length of the microtunneling runs is over 1,100 feet for the land leg tunnel and over 900 feet for the water leg tunnel. The jacking forces required to push the pipe and the MTBM over such long distances, will be significant, even with lubrication and the intermediate jacking stations. The decision was made during design not to allow welding of the steel pipe sections. Welding may result in slight bias or misalignments of the pipe string and increase the friction during jacking of the pipe. As a consequence, the jacking forces could increase and stresses in the pipe could increase as well. Instead, steel pipe with Permalok joints was specified as the only allowable option for the pipe material. The Permalok joints, after engaging, create a smooth outside surface where the risk of misalignment is minimal, which reduces the risk of overstressing the pipe during the jacking process.

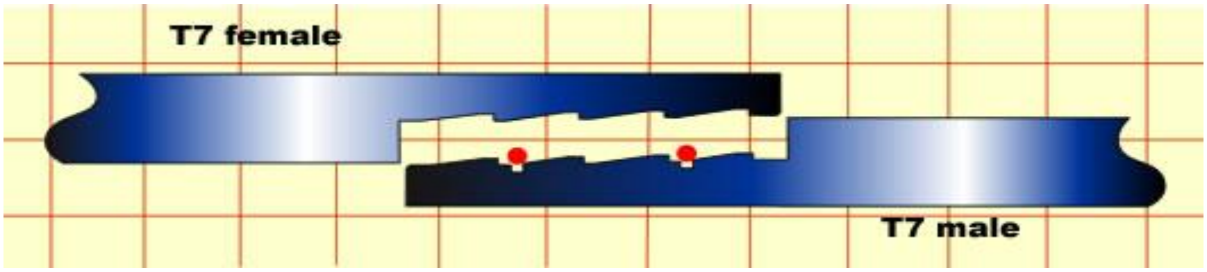

Figure 5. Permalok T7 Joint which includes two "o"-ring gaskets


Figure 6. Steel Plates Being rolled


Figure 7. Steel Plates Welded into Cylinders

Manufacture of Permalok®

Permalok is an interlocking steel casing pipe that utilizes a precision press fit joining system that eliminates the need for field butt welding of the 1 3/8" casing pipes during microtunneling. (Figure 5). The casing pipe is widely used in trenchless applications such as horizontal auger boring, microtunneling and pipe ramming. This is because costly butt welding is eliminated as the precision made joint allows expeditious joint connections and true alignment. The finished joint transmits high compressive loads and is able to withstand considerable bending forces during installation. The finished joint is designed to be flush with the inside and outside of the casing so that it will not provide joint drag or resistance to the jacking forces. The Permalok system will function as a one-pass system such that it serves as both the casing and carrier pipe for this critical application.

The Gilboa project "water leg" presents a challenge with the high water level in the reservoir and the likely potential that the water will cause significant head pressure on the outside of the steel casing and joints. To address "water tightness" of the Permalok joint two O-ring gasket grooves will be precision machined into the spigot or male end of the Permalok end rings (see Figure 5). When installed with the standard silicone sealant the joint has the capability to be water tight. In anticipation of line and grade movements of the casing during installation an interior seal weld will also be provided to assure the required water tightness of the joints.

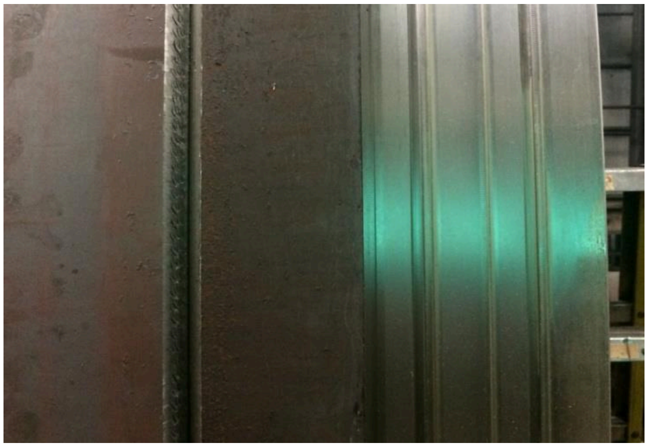

Figure 8. Permalok Joint Ring fit up (groove weld)

The Gilboa project "land leg" also has similar challenges of potential high external head plus high internal pressures caused by rapid draw down of the reservoir. To address the need to resist long term external and internal pressures on the joint, the land leg will also utilize two O-rings and be interior seal welded after installation to assure long term water tightness.

Figure 9. Butt Weld Permalok Joint To Pipe

To address the need for the Permalok casing to serve for generations, key corrosion considerations were made. It was determined that the steel casing would be provided with threaded grout ports so that the small annular space between the outside of the casing and the inside of the bore could be filled with cementious grout. The grout will chemically react with the bare steel and passivate the surface of the steel similar to what takes place when grout, mortar or concrete are placed next to any ferrous metal. On the interior of the casing a polyurethane lining per AWWA C222 is specified. The polyurethane lining has excellent corrosion and abrasion characteristics. The lining will be held back 3" on each end so that the seal weld can be performed without damaging the factory installed lining. Once complete, the joints will then be field blasted and lined with polyurethane per C222. The end product will be a completely polyurethane-lined casing with no exposed metal of any kind for maximum service life.

Permalok for this project is manufactured by rolling and welding 1 3/8" steel plates into 108" cans and butt welding of machined joint rings onto the 108" 20-foot-long cylinders.

Figure 10. Polyurethane Lining

Permalok is manufactured to ASTM A1097 standard which includes a number of steel and quality control requirements. Project specs also call out necessary physical requirements such as circumference, roundness and straightness to assure proper joint insertion and alignment of the casing. It is estimated that a field butt weld of the 1 3/8" wall thickness would have taken 16 man-hours during which time the microtunnel process would have to be idle. Not only would this have been very costly but this would also greatly increase the risk of the MTBM seizing in the bore. Through approximately 740 linear feet of mining in rock with unconfined compressive strength as high as 34,600 psi, the tunnel pipe has satisfactorily maintained alignment and grade in accordance to specification requirements.

Not All Projects Are Created Equal—The King County North Mercer Enatai Project Goes from 945 Alternatives to 1

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ABSTRACT

King County's Mercer and Enatai interceptors were built in the 1960s and extend over 14,000 ft from Mercer Island into the Enatai neighborhood of Bellevue, Washington. Some parts of the system are reaching the end of their useful lives, and future peak flows are projected to exceed the system's capacity. To address these deficiencies, the Mercer Enatai project team completed a complex alternatives analysis, which began its evaluation with over 945 potential pipeline alternatives and ultimately ended with one selected alternative. The alternatives analysis process began with the brainstorming of conceptual alignment options across the three distinct areas of the project: Mercer Island, East Channel (Lake Washington), and Bellevue. The existing North Mercer interceptor is primarily a subaqueous pipeline located within Lake Washington along the northern shoreline of Mercer Island. Any new pipeline on Mercer Island would have either significant challenges in constructing in the water in Lake Washington or on land that has experienced significant development since the 1960s, including the construction of Interstate 90 through the northern part of Mercer Island. The East Channel in Lake Washington is 1400 ft wide and separates Mercer Island from Bellevue. The existing Enatai siphon carries flows across the channel and traverses along the lake bottom and under the East Channel I-90 bridge. Any new pipeline across the channel would need to meet the complex constructability, hydraulic, and Army Corps 404 and WSDOT permitting requirements. The last pipeline segment is located in Bellevue in the Enatai neighborhood, a Native American term meaning "across the water". Aptly named, the existing Enatai interceptor carries flows from across the channel and from Bellevue, along the southern end of the Enatai neighborhood, and through the environmentally sensitive Mercer Slough. The last 2,000 ft of this pipeline segment is also supported on piles due to the soft ground, and runs under the I-90 corridor, which is also supported on piles in this area. A new pipeline alignment through Bellevue would have significant challenges in constructing in the water through the Mercer Slough or on land through the Enatai hillside. This presentation explores the complex challenges of this project, and the extensive alternatives analysis process that started with over 945 potential alternatives.

INTRODUCTION

King County, Washington's North Mercer and Enatai Interceptors extend nearly 3 miles underground and underwater from northern Mercer Island to the City of Bellevue. The alignment begins at the North Mercer Pump Station, enters Lake Washington along the northeast shoreline of Mercer Island, crosses the East Channel, and follows the Enatai shoreline and the Mercer Slough to the County's Sweyolocken Pump Station. Two trunk sewers on Mercer Island (the

East Trunk and the West Trunk) contribute significant flows to the interceptors; three sources in Bellevue contribute additional flow. Figure 1 shows the existing system.

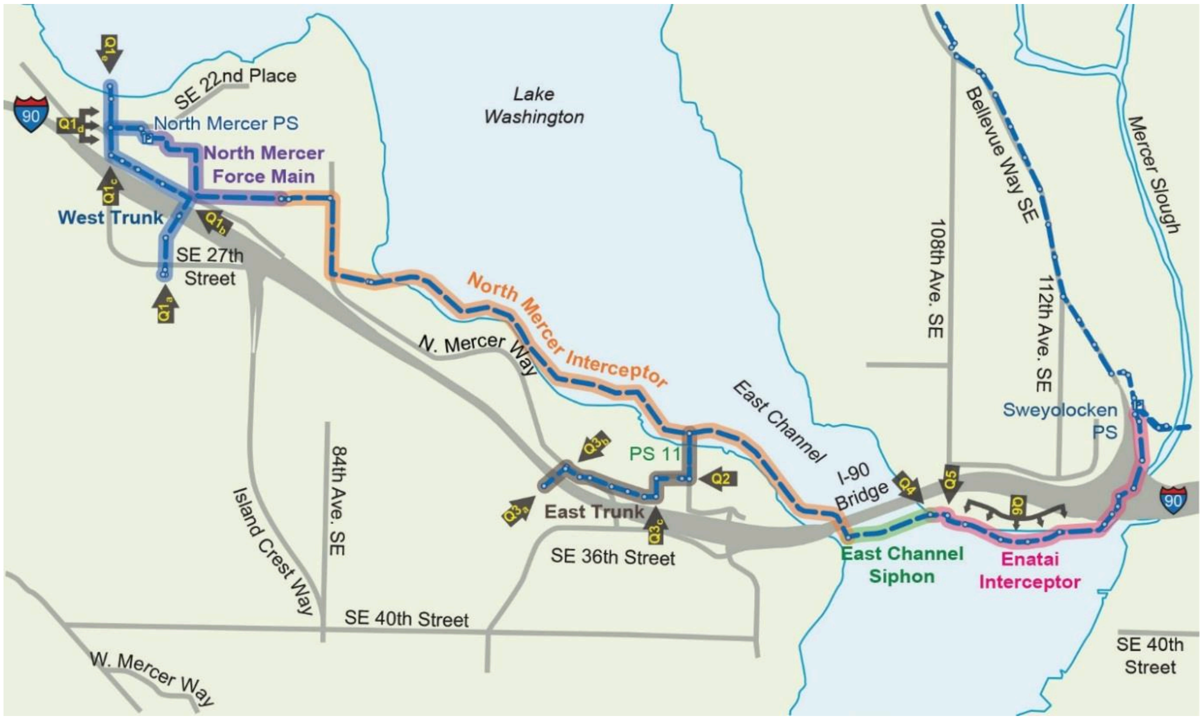

Figure 1. Existing North Mercer/Enatai Interceptor System

Some of the pipes that make up the North Mercer/Enatai system are reaching the end of their useful lives, and future peak wastewater design flows are projected to exceed the system's existing capacity. The North Mercer Island Interceptor and Enatai Interceptor Upgrade Project is developing improvements to address these deficiencies and convey projected peak wastewater flows through 2060. The project team conducted a three-Stage alternatives analysis to identify a preferred alternative to carry forward into preliminary and final design.

STAGE 1

In Stage 1 of the alternatives analysis process, initial sets of segment options were brainstormed for each of three geographic portions of the project: Mercer Island (Area A), the East Channel (Area B), and the Enatai neighborhood of Bellevue (Area C). In all, 15 options for Area A, nine options for Area B, and seven options for Area C were created. Initial segments were developed by considering all possible pipeline construction methods identified for each area, including options such as continuous trenchless construction from the North Mercer Pump Station to the Sweyolocken Pump Station. East Channel options included trenchless construction north or south of the I-90 bridge, open-cut construction, and suspension of the pipeline from the I-90 bridge. If all combinations of these initial segments options were to be considered, this would have resulted in a total of 945 preliminary alternatives for evaluation. Obviously, it became apparent that the number of segment options had to be reduced to begin a more feasible alternatives analysis process. Therefore, an initial workshop was held that eliminated numerous segment options that had "fatal flaws" characterized by prohibitive cost, excessive force main lengths, high risk trenchless crossings, extreme permitting challenges or construction complexity, or a significant increase in total dynamic head at the North Mercer Pump Station. After removing these "fatally flawed" segment options, the remaining segments were combined into 15 alternatives. Evaluation of these alternatives at the end of Stage 1 eliminated three of the 15 from consideration, as described in the following sections.

Table 1. Segment Options Retained for Consideration in Stage 1

Segment	Disposition
A1[a]	Force main from North Mercer Pump Station along N. Mercer Way to 97th Avenue SE; gravity pipeline along North Mercer Way to East Channel
A4	Generally follows existing pipeline route from North Mercer Pump Station to existing force main discharge; gravity pipeline along Mercer shoreline to East Channel
A5[a]	Force main from North Mercer Pump Station to past segment midpoint; gravity pipeline along bike path on north side of I-90. Open cut to high point at the bike path, continue gravity to Mercer shoreline (optional open cut portion along North Mercer Way)
A10-1[b]	Divert flows at Manhole S-10, trenchless construction on SE 24th Street from 78th Avenue SE to 84th Avenue SE, trenchless construction south on 84th Avenue SE to meet grade at south end of Luther Burbank Park, then in lake
A10-2[b]	Same as A10-1, except trenchless construction from SE 24th Street / 78th Avenue SE directly to south end of Luther Burbank Park
B3[c]	Trenchless crossing of East Channel, south of I-90
B4[c]	Trenchless crossing of East Channel, north of I-90
B5	Trenchless crossing on north side of I-90, straight from west side of East Channel to Sweyolocken Pump Station
B6	Parallel the existing pipeline across East Channel, laying or trenching along bottom of lake.
C1	Trenchless crossing under Enatai from the vicinity of Enatai Beach Park to Sweyolocken Pump Station
C6	Gravity pipe parallel to existing pipeline along Enatai shoreline, through Mercer Slough, to Sweyolocken Pump Station

[a]Segments A1 and A5 were combined as A1/A5 for alternatives analysis due to significant similarities.
[b]Segments A10-1 and A10-2 were combined as A10 for alternatives analysis due to significant similarities.
[c]Segments B3 and B4 were combined as B3/B4 for alternatives analysis due to significant similarities.

Process

Stage 1 began with the development of evaluation criteria in the following categories: North Mercer Pump Station capacity and total dynamic head; Technical considerations; Constructability; Operation and maintenance; Permitting; Rights of way, easements and rights of entry; Environment; Community; and Cost.

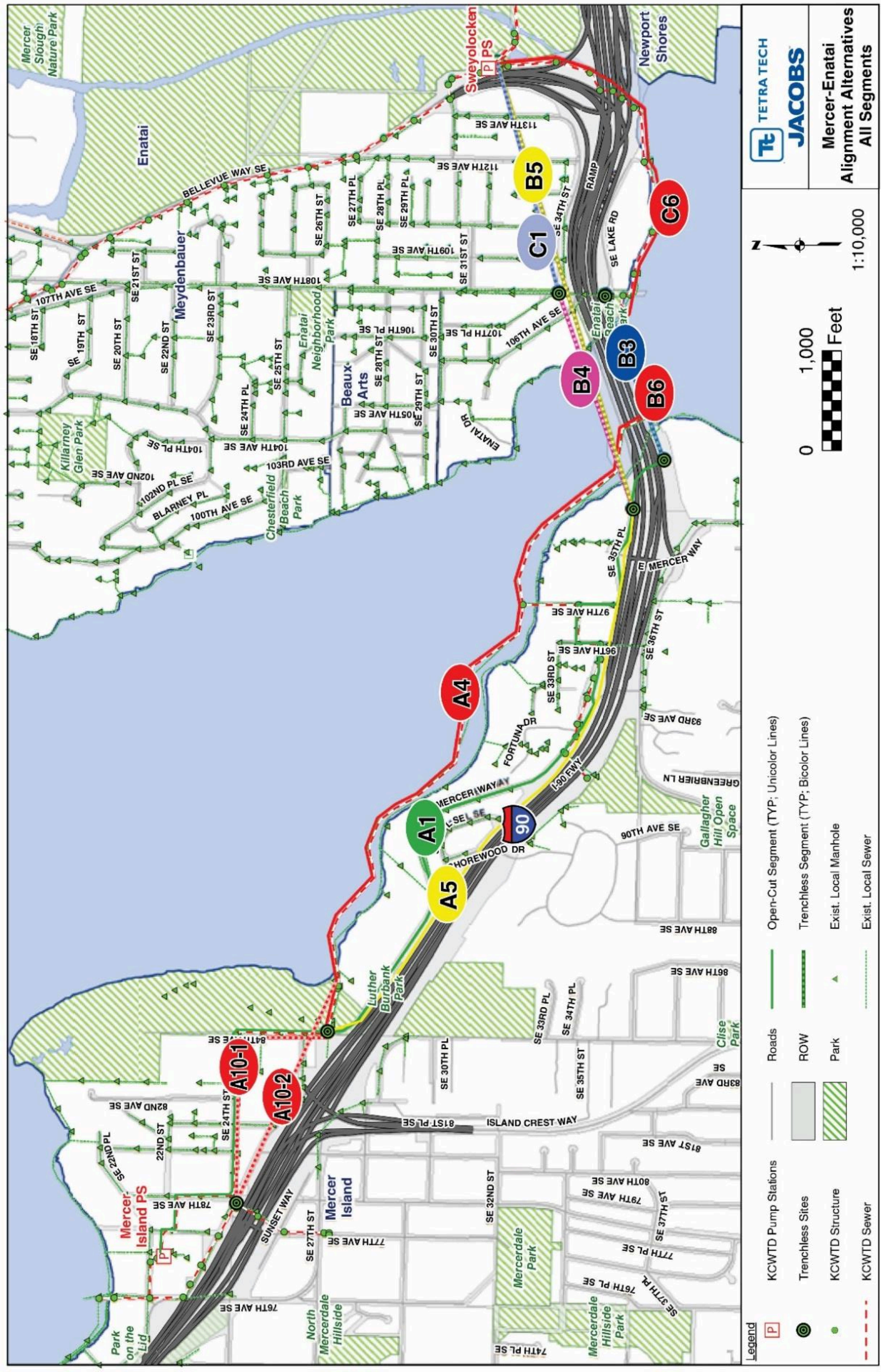

Figure 2. Segment Options Retained for Consideration in Stage 1

Alternative development began with identification of pipe segment options for the three project areas as follows:

- “A” segments are options for the system on Mercer Island (15 options were identified).
- “B” segments are options for the system as it crosses the East Channel (nine options were identified).
- “C” segments are options for the system in Bellevue (seven options were identified).

After the initially identified segment options were evaluated to eliminate fatal flaws (described above), 11 segment options remained, as listed in Table 1 and shown in Figure 2. Fifteen pipeline alignment alternatives for the full project length were created from the identified segments, each including one of the segments for each project area, as listed in Table 2. A screening process then evaluated the pipeline alternatives based on the established criteria.

Table 2. Pipeline Alignment Alternatives by Segment

	Segments				Segments		
	Mercer Island	**Each Channel**	**Bellevue**		**Mercer Island**	**Each Channel**	**Bellevue**
Alternative 1	A1/A5	B3/B4	C1	Alternative 9	A4	B6	C1
Alternative 2	A1/A5	B3/B4	C6	Alternative 10	A4	B6	C6
Alternative 3	A1/A5	B5		Alternative 11	A10	B3/B4	C1
Alternative 4	A1/A5	B6	C1	Alternative 12	A10	B3/B4	C6
Alternative 5	A1/A5	B6	C6	Alternative 13	A10	B5	
Alternative 6	A4	B3/B4	C1	Alternative 14	A10	B6	C1
Alternative 7	A4	B3/B4	C6	Alternative 15	A10	B6	C6
Alternative 8	A4	B5					

Key Findings

The sections below describe key findings from investigations performed during Stage 1.

Hydraulics

Based on a preliminary hydraulic analysis, alternatives were categorized into one of three hydraulically similar scenarios:

- **Upland Pipeline Option**—Alternatives 1 through 5 include a long force main on Mercer Island, which would require improvements to the North Mercer Pump Station.
- **In-Water Option**—Alternatives 6 through 10 include an in-water pipeline along the north side of Mercer Island. Hydraulics for these alternatives would closely match the existing system, with most of the in-water portion of the interceptor surcharged during most flow conditions.
- **Diversion Option**—Due to the elevation of a gravity diversion to bypass the North

Mercer Pump Station, Alternatives 11 through 15 work only with an in-water section along Mercer Island. For these alternatives, the entire interceptor would be surcharged from the diversion point to the East Channel.

Trenchless Construction

The use of trenchless technologies was evaluated using criteria such as trenchless length, compatibility with geotechnical conditions, need for conductor casings and intersect drilling, and ability to handle potential obstructions along the bore path. Ultimately, six segments involving trenchless construction were retained for further evaluation: A10-1, A10-2, B3, B4, B5 and C1.

Results

Through the Stage 1 evaluation, three of the 15 alternatives were eliminated from consideration:

- Alternative 2—Redundant with other alternatives, since Alternative 1 provided a fully “dry land” alternative (including segments A1/A5 and B3/B4), whereas other remaining Alternatives also included segment C6 that Alternative 2 included.
- Alternatives 3 and 8—High risk associated with long trenchless crossing for Segment B5; insufficient benefit relative to other alternatives including Segment B5 (Alternative 13).

The remaining 12 alternatives were carried forward for evaluation in Stage 2.

STAGE 2

Process

Initial Work Plan

The remaining Stage 1 alternatives and the Stage 1 matrix of evaluation criteria were the starting point for Stage 2. The initial work plan for Stage 2 was as follows:

- Further develop the 12 remaining alternatives.
- Update the criteria categories and questions based on updated design information.
- Define numerical weighting to indicate the relative importance of each criterion.
- Use this updated information for a second-round evaluation to reduce the number of alternatives from 12 to six.

At the beginning of this process, the project team deleted the North Mercer Pump Station category of evaluation criteria, as the issues related to it were integrated into the other categories. All other Stage 1 categories of criteria were retained. A workshop on May 12, 2015 was held to establish a numerical weight for each category, indicating its relative importance, as follows:

Operations & Maintenance (19); Technical (16); Cost (16); Constructability (15); Environment (11); Permitting (10); Rights of way and easements (8); Community (5)

Revised Work Plan

Ongoing technical investigations performed during Stage 2 identified additional fatal flaws that reduced the number of feasible alternatives, without performing the initially planned formal criterion-based evaluation. Therefore, no evaluation workshop was held, and all alternatives that remained following the findings of the investigation were carried forward to Stage 3. The findings and results are summarized below.