An Innovative Methodology for HDD Pipeline Crossings

FINAL REPORT
APSC 480 – MULTIDISCIPLINARY INDUSTRY DESIGN PROJECT

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Executive Summary

As the energy industry continues to develop, companies are eager to innovate and revolutionize current processes to follow suit. The Young Pipeliners Association of Canada is in partnership with the Canadian Energy and Pipeline Association to optimize current Horizonal Directional Drilling (HDD) processes for river crossings.

The scope of the project was to provide recommendations to reduce risks and costs when installing an HDD crossing. The second component of the project was to design a detailed theoretical HDD crossing over the Wapiti River in Grand Prairie, Alberta. The deliverables for this project include a 2D crossing profile, a 3D model generated in AutoPIPE, an economic analysis of the proposed river crossing, and a construction plan.

Stakeholders for the project have been identified and their respective concerns and risks were documented. Major stakeholders for this project include: the clients (CEPA and YPAC), pipeline companies, regulatory bodies such as the Alberta Energy Regulator and Canadian Energy Regulator as well as contractors and landowners. These stakeholders' objectives were predominantly tied to minimizing overall construction time and cost, minimizing environmental impact, and maintaining project safety. In addition, safety and regulatory requirements were considered throughout the duration of the project to ensure the solution met all relevant standards.

After a preliminary round of idea generation and decision making it was selected to optimize the drilling and reaming processes within the construction stages. However, after meeting with industry professionals and completing a failure modes and effects analysis on HDD crossings, it was revealed that current HDD project limitations were closely tied to unknown subsurface conditions.

After this revelation, the focus of the project shifted to researching geophysical methods that could be utilized for ground investigations. It was found that electrical resistivity tomography and seismic refraction surveys were most appropriate for this application. A guide was developed to outline how the proposed solution could be applied universally to HDD projects.

This project adds values through several different mediums: environmental, safety, monetary, and social. After applying the solution back to the Wapiti River Crossing, it was determined that by investing $80,000 to $100,000 in initial ground surveying techniques, a cost reduction of between approximately 11% to 49% could be realized. For the designed crossing this ranges between $365 thousand to $3.3 million. Additional value from application of the solution includes reduced environmental impact and decreased reputational risk.

To ensure the proposed solution was accurate and feasible, validation was incorporated as a significant aspect of the project. Validation was completed using three different methods. The first method involved meeting with industry professionals to review all components of the project including pipeline design, cost estimation, and solution validity. The second technique was to apply the recommended solution back to the Wapiti River crossing model and justify through analysis. Lastly, the solution was assessed against pre-defined project metrics. When reviewing these results, the solution scored the highest ranking in all categories.

Along with the proposed solution, an implementation plan and additional recommendations were provided for the next steps to develop this solution.

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1.0 Introduction

With over 840,000 km of transmission lines, pipelines are the most prominent way to transport oil, oil fluids, and natural gases in Canada: transporting 97% of all petroleum products [1]. They are needed to span over large areas and can be installed below the ground to minimize disruption to roads, waterways, buildings, and more. These subterranean installations can result in high installation costs especially when traversing water bodies. This is a common problem in Canada, being the country with the most lakes and rivers in the world [2]. The preferred method for these underground installations is Horizontal Directional Drilling (HDD), a technique with significant installation costs [3].

The Young Pipeliners Association of Canada (YPAC) is an organization for professionals in their early years in the pipeline industry. The group aims to connect members with one another and provide both learning opportunities and support. YPAC has partnered with the Canadian Energy and Pipeline Association (CEPA) and Queen's University students to research trenchless techniques for installing pipelines across waterbodies and find innovative ways to reduce costs.

This report will discuss the existing HDD process and outline a solution to reduce the cost of HDD projects. The proposed cost reduction idea has been applied to a crossing over the Wapiti River in Grand Prairie, Alberta. In addition to the crossing application, a detailed validation plan for the design has been presented.

Section 1.0 defines the project outlining information such as the proposed scope, background research on trenchless techniques, design criteria, functional requirements and the major constraints. It also details the framework the project's evaluated against.

1.1 Problem Statement

Currently, HDD watercourse crossing methods have high construction costs and their timelines are highly susceptible to delays. These high costs are a result of expensive materials and machinery, coupled with significant labour requirements. Due to the intricacy of subsurface conditions and complications experienced with machinery, there are often delays in the construction timeline.

By the end of April 2021, a detailed river crossing will be designed to traverse Alberta's Wapiti River near Grand Prairie. The design will cater to the Grand Prairie climate and geotechnical specifications, while ensuring safety requirements are incorporated. The 315-metre crossing must be designed to be in service by April 2022. Innovative ways to improve the installation efficiency and reduce construction costs have been explored and documented. The result includes a rendered design, an economic analysis, along with a clear outline on how to apply cost reduction recommendations to any HDD crossing.

1.2 Background Research on Trenchless Techniques

Initial research was conducted on trenchless and trenched pipeline installation techniques. Three types of trenchless methods including HDD, microtunneling, and horizontal auger boring (HAB) were explored. These were compared to gain a deeper understanding of which method to use in certain situations, the costs associated with them, materials required, and more. The background research on microtunneling, HAB and the comparison table can be found in Appendix I – Background Information.

1.2.1 Trenchless vs. Trenched Crossing Techniques

There are two ways pipelines can be installed for water crossings: trenchless or trenched [4]. Trenchless techniques are methods where the pipeline is installed under the body of water without disrupting the watercourse [4]. The most common method is HDD [4]. A 2D profile of an HDD crossing is shown in Figure 1.

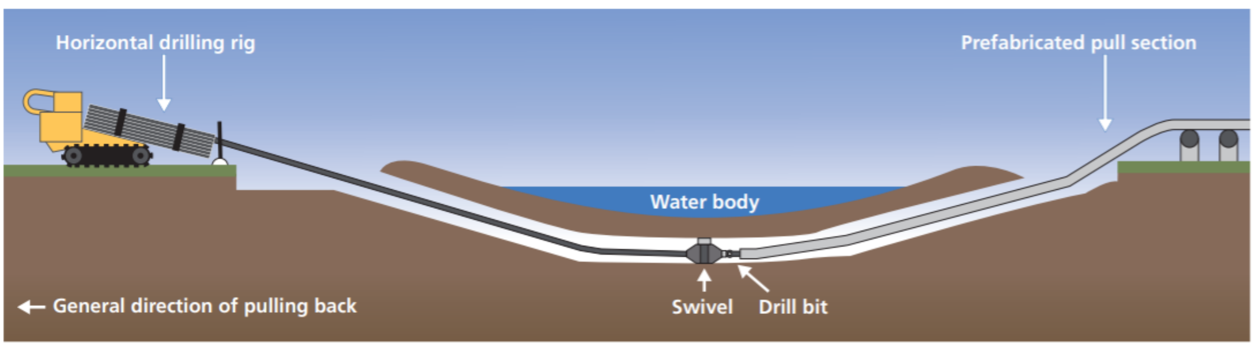


Figure 1: A 2D profile of an HDD crossing [22].

Trenched techniques, also known as open cut methods, require the excavation of a trench along the crossing [4]. To make the trench, the water flow is diverted to avoid the construction [4]. This is done by either directing the water flow around the site or over the construction using a flume [4]. Once the trench is dug out, the pipeline is placed in the trench and buried [4]. It is favourable to have the water course return to its initial conditions, but this requires a large investment and is not always successful [4]. An example of a trenched crossing is shown in Figure 2.

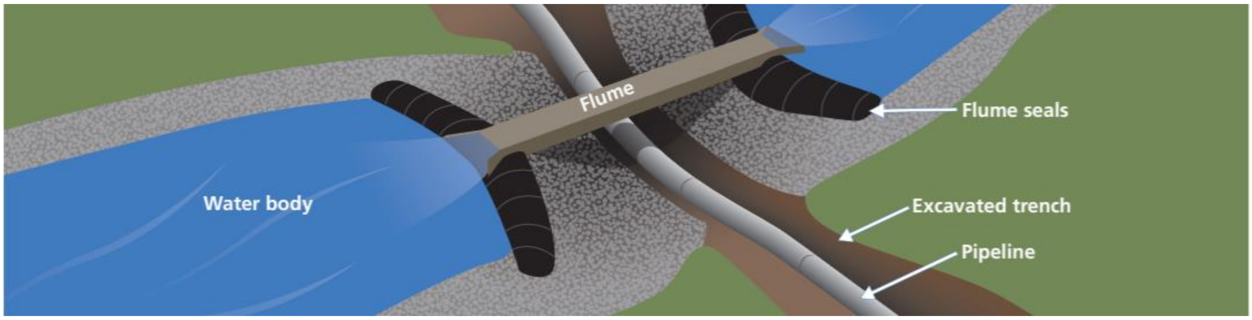


Figure 2: Example of a trenched water crossing [4].

1.2.2 Horizontal Directional Drilling

HDD is one of the primary trenchless methods used to install pipelines and underground utilities. The drilling technique was introduced in the early sixties as an innovation to handheld guided drilling. It was not until the demand for river crossings increased 20 years later that the technology was valued and commonly used [5]. Currently, HDD is a popular trenchless method as it minimizes traffic disruption, has minimal surface damage as well as an increased flexibility in where it can be installed [6]. Figure 3 outlines the major steps of the HDD construction processes.

HDD utilizes an electronic drill head which monitors the angle, depth, and exit point while drilling through the subsurface. Initially, a horizontal pilot hole is drilled beneath the river using a drill head as seen in (a) of Figure 3. A string of drill rod is attached to the drill head and left in the pilot hole to be later attached to the reamer [6]. A back reamer is then sent in the opposing direction through the pilot hole as seen in (b) of Figure 3. This process allows the hole to be enlarged to a diameter slightly larger than the pipe. The excess size is dependent on the unique conditions of the site such as soil type, soil stability, depth, drilling mud among others [6]. Typically, this results in a tunnel 20-50% larger than the diameter of the pipe [6]. A second pass is made with the back-reamer before the pipe is inserted during the pullback process as seen of (c) in Figure 3. This ensures a clear passage free of gravel and will compact the borehole walls.

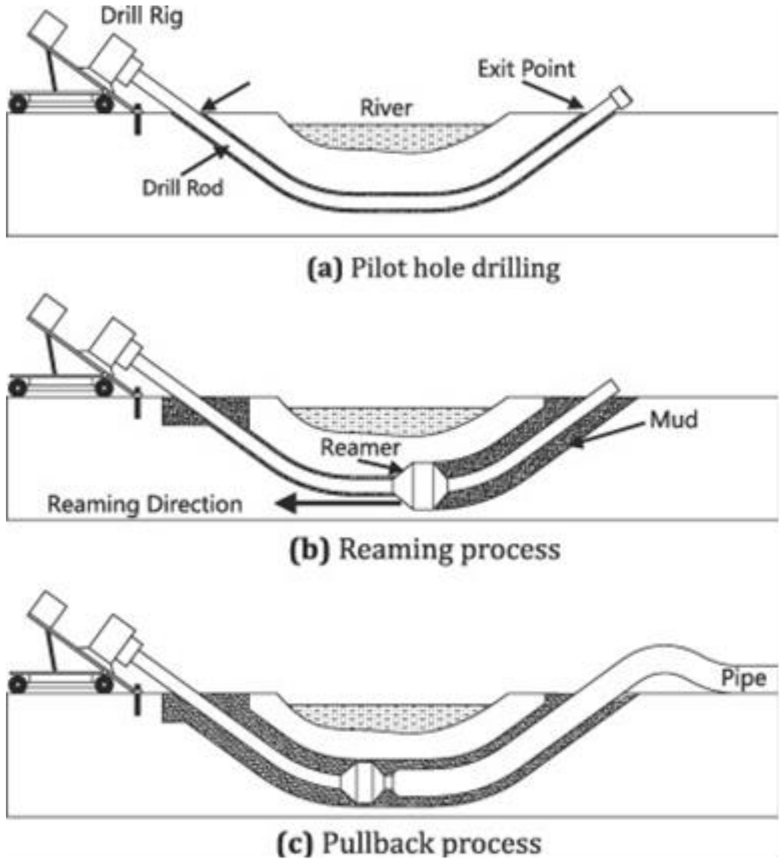


Figure 3: Cross-sectional component outlining major HDD construction process [7].

To assist in the drilling process, a mixture is used to lubricate the target areas. This is typically comprised of 95% water and 5% bentonite clay. The mud increases the efficiency of the process in several different ways [8]. Firstly, the mud assists by coating the walls of the tunnel which alleviates the drilling torque in turn increasing the stability of the boreholes. Additionally, the mud can suspend and remove drill cuttings. Another significant function of the drilling mud is to act as a lubricant when the pipe is later placed in the tunnel [9]. More details outlining the specifications of HDD can be found in Appendix I – Background Information.

1.3 Evolution of Project Scope

Initially, the scope of the project was to research multiple trenchless methods of installing pipelines including HDD, microtunneling, and auger boring, to find ways to reduce installation costs. This was defined as beginning with site clearance and ending at remediation. It was then suggested by the client to move forward focusing only on HDD. This was recommended as it is the most prominent method of installation and the project cost varies significantly between projects [3].

A pseudo project was provided by the client team to design an HDD crossing across the Wapiti River in Grand Prairie, Alberta. The purpose of this pseudo project was to understand the process of designing and implementing a pipeline installed through HDD so that areas for improvement were easier to identify and brainstorm.

The scope was updated once more to focus on the construction process with less emphasis on site clearing and remediation. This entails beginning with pilot hole drilling and ending with the pullback process.

1.4 Finalized Scope

The scope has been divided into two components: design and output. The design scope focuses on the considerations for the crossing, whereas the output scope outlines how the results will be delivered.

1.4.1 Design Scope

The selected location for the design is the Wapiti River in Grand Prairie, Alberta, however the solution should remain versatile to accommodate a wide variety of Canadian locations. This site was selected at the client's request and has been evaluated for the implementation of an HDD design. The Wapiti River is a narrow river that is surrounded by heavy forestry. It is located in northern Alberta, between Grand Prairie and Grovedale. The location is displayed in Figure 4. A requirement for the design is to operate in this area's climate conditions, such as being able to withstand the snow and ice loads. More specific information regarding the climate can be found in Section 1.6 Design Criteria and Specifications.

The design is theoretical and will not be constructed, however it will be used to identify potential cost saving opportunities that can be used in future HDD projects. As a full HDD design requires substantial personnel and resources, the scope has been limited to the construction process to avoid sacrificing depth for breadth. By limiting the scope to just the construction processes, the design solution will remain flexible for implementation at other sites. Additionally, for the same reasons the installation of the river crossing will be prioritized for the design, with the maintenance and operation being a secondary consideration. It should be noted that current maintenance and operation standards will be used; however, the economic analysis will not encompass these costs. This was decided on as maintenance costs are highly variable and dependent on the parent company [10].

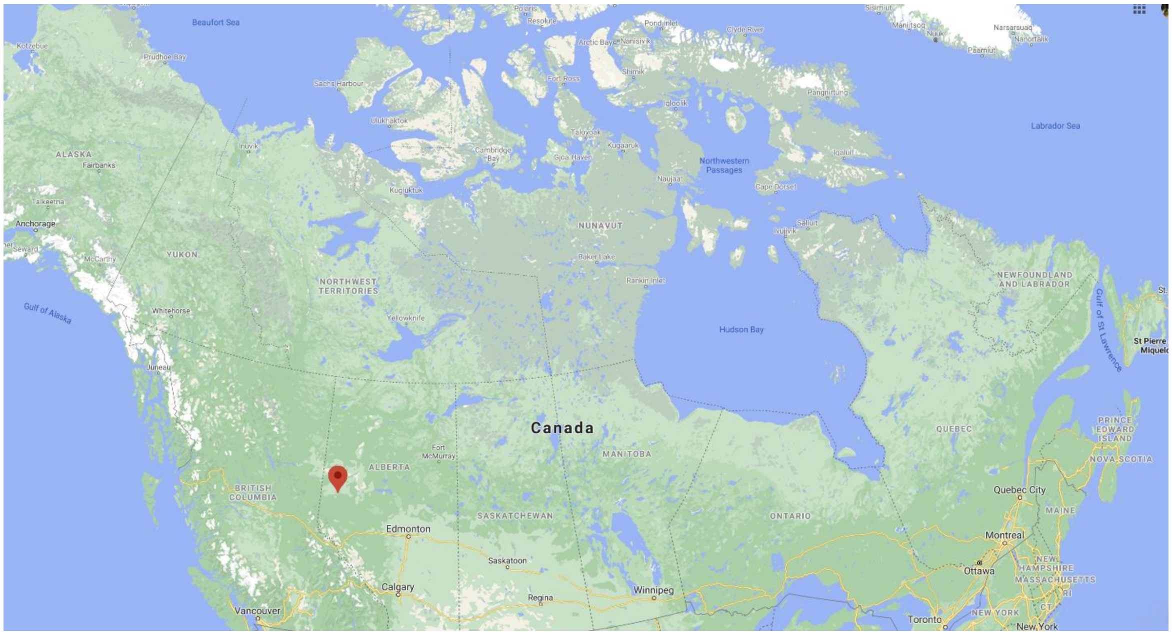


Figure 4: Wapiti River location [11].

Figure 5: Map of Alberta with Grand Prairie highlighted [12].

A view of the surrounding area can be seen below in Figure 6.

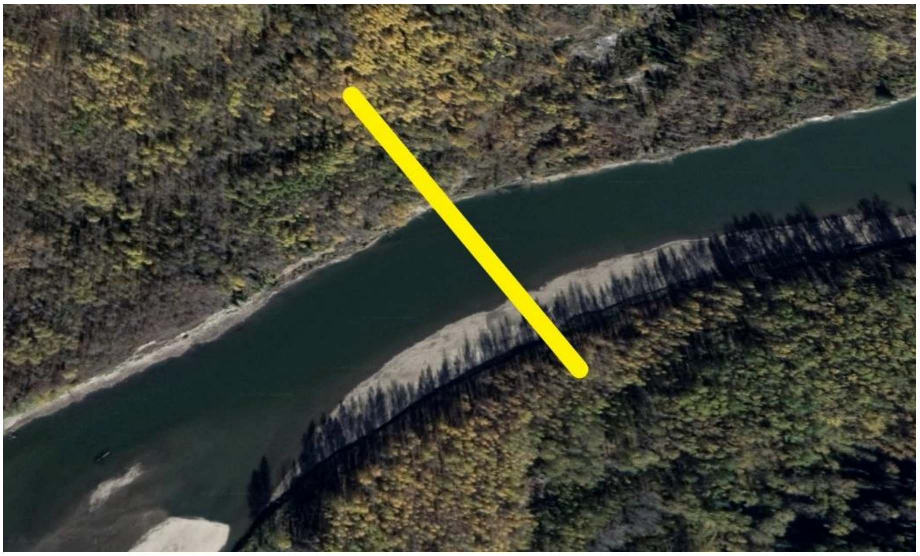


Figure 6: Photo of Wapiti River crossing and surrounding area [11].

1.4.2 Output Scope

The project encompasses a variety of unique outputs, including visuals, project plans, and an economic analysis. The first visual output is a 3D rendering of the design. This was created by leveraging AutoPIPE, a pipeline design software. The 3D visual and 2D images were constructed with AutoPIPE, which displays the pipe profile. The economic analysis has been completed for a standard HDD crossing over the Wapiti River, as well as the crossing with the optimized design. This clearly identifies the changes and allows for a side-by-side comparison outlining the cost-savings.

Along with the visuals, a comprehensive construction plan has been built using Microsoft Excel to ensure all processes are accounted for and the project meets its construction deadline.

1.5 Constraints

The solution required a 48-inch (NPS 48) HDD trenchless crossing designed for a natural gas pipeline [3]. Trenchless techniques install the pipeline by drilling under the water crossing, as opposed to a trenched design where a temporary dam is used to stop the water flow [13]. The design is required to withstand the weather and overall environmental conditions in Grand Prairie, Alberta. This includes an average temperature high of 15.5°C, low of -15.5°C, and 472 cm of rain per year [14]. A theoretical construction timeline of one year has been placed on the project, meaning it must be designed by the end of April 2021, with construction completed by April 2022. This means the construction should be feasible to complete in less than one year after the design solution has been presented to the client. Ultimately, the final design is required to be cost-efficient and safe while maintaining a minimal negative impact on the wildlife and community in the surrounding area. This is outlined more specifically in Section 1.6 Design Criteria and Specifications. These constraints are summarized in Table 1. Definitions for steps referenced can be found in Appendix II – Definition and Descriptions of Construction Process Steps.

Table 1: The constraints relevant to general HDD crossings as well as the Wapiti River crossing.

Constraints	**General HDD Crossing**	**Wapiti River Crossing**
Trenchless Technique	• Design must be HDD.	• Design must be HDD.
Climate	• Design must account for all climate aspects for the specified location, such as snow loads, ice factors, temperature variances, rainfall, and terrain.	• Design must account for all climate aspects of Grand Prairie, Alberta, such as snow loads, ice factors, temperature variances, rainfall, and terrain.
Cost	• No key cost constraint has been identified; however, the economics should remain on par with typical HDD crossings and costs should be reduced for the overall project. This cost is approximately $3-5 million for the entire crossing installation [15].	• No key cost constraint has been identified; however, the Wapiti River crossing should remain on par with typical HDD crossings for the region and costs should be reduced for the overall project. This cost is approximately $3-5 million for the entire crossing installation [15].
Time	• Construction time should remain on par with typical HDD crossings for the given length and region.	• The crossing must be designed by April 2021. • The crossing must be in-service by April 2022.
Depth	• Design must be able to fit below the body of water while meeting environmental codes. This is approximately 20ft below the waterbed [16].	• Design must be able to fit below the body of water while meeting environmental codes. This is approximately 20ft below the waterbed [16].

Constraints	General HDD Crossing	Wapiti River Crossing
Land Space	• Design must be able to be implemented with the available land space adjacent to the crossing (~350 m^2 on both sides) [32].	• Design must be able to be implemented with the available land space adjacent to the crossing (~350 m^2 on both sides) [32].
Length	• Design cannot exceed maximum length limit on HDD crossings (2.95km) [17].	• Design cannot exceed maximum length limit on HDD crossings (2.95km) [17].
Field Bends	• Pipe radius of curvature must be in the limits of field bends.	• Pipe radius of curvature must be in the limits of field bends.
Environmental Impact	• Design should not interfere with the water body. • The design should aim for minimal to no permanent land destruction. • Site must be restored to its initial state or better after construction is completed.	• Design should not interfere with the water body. • The design should aim for minimal to no permanent land destruction. • Site must be restored to its initial state or better after construction is completed.

1.6 Design Criteria and Specifications

The design criteria and project specifications were outlined to develop a thorough understanding of the problem and the requirements for all project considerations. Table 2 below outlines the criteria for the design as well as their objective.

Table 2: Design criteria and specifications along with a brief description.

Criteria	
Description	**Objective**
Operable in Alberta climate conditions	
• The design must be able to operate in a range of temperatures suitable to Alberta's conditions. • Must be able to operate with snow and ice loads. • Must be functional year-round.	• The design should be operable in highs of 15.5°C, lows of -15.5°C [14]. • The design should be able to withstand high levels of rainfall such as 472 cm of rain/year [14].

Criteria	
Description	**Objective**
	• The design should be able to accommodate 1544 mm of snow annually [19].
Safe to install (no injuries due to design flaw)	
• Contractors should feel comfortable and safe during the installation.	• Zero injuries will result from improper design. • Design will not require workers to be put in a compromising situation. • The design must meet safety standards set by the province of Alberta and Canada outlined in the Pipeline Act, Pipeline Rules, Directive 077: Pipelines- Requirements and Reference Tools and Canadian Standards Association (CZA) Z662-19: Oil and Gas Pipelines [20]. • Additional standards can be found in Table 17.
Minimal construction cost	
• Material and construction costs must be minimized. • Maintenance cost is out of scope for this project.	• Have cost of project be equal to or below an average HDD project of this scale. ○ Approximately $2-7 million. ▪ Includes labour, material, and equipment costs. Note: This cost range is based off interviews with professionals. This includes Rob Purcell (PM, TC Energy), Craig Schell (Environmental Advisor, TC Energy), Mustafa Yulek (PM, TC Energy) and Paul Kelly (PE, Surerus Murphy) [15] [18] [21] [10].
Minimal installation time	
• Time required for the installation process should be minimized.	• Installment time should be minimized without adding undue risk to the HDD installation process.
Minimal environment disturbance (during construction and afterward)	

Criteria	
Description	**Objective**

• Must have little to no effect on the wildlife and biodiversity in the surrounding area.	• Zero gas leaks as a result of an implementation error.
	• Under two frac-outs/surface heaving [15].
	• Zero animals are harmed in the installation process.
	• No damage to endangered species' habitats.
	• Limit:
	  ○ Dust emitted during construction as it affects the air quality,
	  ○ Clearing of vegetation,
	  ○ Placement of structures/construction machines,
	  ○ and alterations of geology [22].

Aesthetic congruent with surrounding environment pleasing to stakeholders.	
• Design and restored site are congruent with the surrounding environment.	• 90% approval rating regarding construction set-up and site restoration plan from stakeholders [23]. • No identifiable structures after construction [15].
No effect of leaving the pipeline in-ground after service life	
• No effect of the pipeline on the environment post service lifetime. • Limit habitat destruction.	• 100% of materials used are non-harmful to the environment. • Can remain in-ground after lifetime.

1.7 Functional Requirements

The design aspects that must be achieved are summarized below in Table 3, which outlines the functional requirements. To better understand the functional requirements listed below, descriptions of the construction steps can be found in Appendix II – Definition and Descriptions of Construction Process Steps.

Table 3: Functional requirements of the design solution along with the associated specifications.

Functional Requirement	Specifications
Must Transport Gas	• Contain and transport natural gas. • Material and grade of pipe must support natural gas and be a cost-effective option.

Withstand external forces and internal pressure	• Must be able to withstand relevant pipe stresses, which include but are not limited to:
	    o Gravitational forces
	    o Forces from soil and terrain above
	    o Forces from Wapiti River above
	    o Pressure from internal gas
	    o Axial forces
	
	Note: Pipe stress calculations can be found in Section **6.1.1** Pipe Stress Calculations.

Diameter Requirement	• Diameter must be NPS 48.
Depth Requirement	• Must be installed at least 20 ft below the Wapiti River [16].
Achieve required reaming diameter Note: Reaming refers to increasing the diameter to the required size from the initial pilot hole.	• Must be able to ream a hole with a diameter of 60'' (As it is standard to ream 12'' greater than the required pipe diameter [24]).
Radius of curvature must be achievable through field bends Note: Radius of curvature refers to the radius of bends in the pipe. Field bend refers to the act of bending the pipe at the construction site.	• Required pipe curvature must be able to be achieved through field bend machinery on-site.

Functional Requirement	Specifications
Path must be feasible within the allowable bends	• The drilled hole curvature must not exceed maximum pipe bends. • The achievable cold bend for a NPS 48 pipe is 21° [25]. ○ This is according to the code ASME B31.1 Power Piping.
Construction Feasibility	• Construction must be feasible within a one-year timeframe indicating completion by April 2022. • Construction must be viable within the climate constraints of Grand Prairie, Alberta.
Pipeline must not leak or corrode	• Completed welds and coating must pass Non-Destructive Examination as described in Table 31 located in Appendix II – Definition and Descriptions of Construction Process Steps.
Pilot hole must go from entry to exit	• Designed path must be feasible for the drill to go through using standard HDD equipment.
Pullback speed should be on par with industry average Note: Pullback refers to the processing of threading the pipe through the drilled and reamed hole.	• The design should allow for the pipe to be pulled through at a speed of 1-2 ft/min [15].
Drilling Mud Composition	• Mud must be comprised of 95% water, 5% bentonite clay or other approved alternatives such as polymer mud [15].

1.8 Project Metrics

Project metrics were created to determine how the final deliverable will be assessed. Table 4 below outlines the objectives that have been used to drive the project forward and guide decisions to achieve or exceed the desired results.

Table 4: Project metrics for deliverable.

Feature	Level 3	Level 2	Level 1
External Design Metrics			
Construction Cost Reduction	>8% reduction	8-3% reduction	<3% reduction
Safety	All codes and standards will be met throughout the design and implementation of this project.		
Solution Versatility	Adaptable to any HDD or pipeline construction project.	Design is only successful with Wapiti River crossing	Not feasible
Robustness of Design	Designs considers possible delays and provides prevention strategies	Design considers possible delays and provides solution strategies	Design does not consider delays
Validation from Professionals	Validated by more than three industry professionals	Validated by three or less industry professionals	Validated by no industry professionals
Risk Mitigation	>8% reduction	8-3% reduction	<3% reduction
Internal Project Metrics			
Project Timelines	Deliverables completed on time or early	Deliverable two days late	Deliverable > two days late
Provide proof of concept by project end	Detailed design of crossing	High-level overview of design and crossing	No deliverable accompanying project
Stakeholder Requirements	Design meets all design criteria and constraints	Design meets some design criteria and constraints	Design meets no design criteria and constraints
Client Satisfaction	Design exceeds expectations	Design meets expectations	Design does not meet expectations
Clarity of Design	Delivery of project is clear, easy to interpret and is straight-forward to apply from an external perspective with no prior knowledge on HDD	Delivery of project is partially clear, can be interpreted but is difficult to apply from an external perspective with no prior knowledge on HDD	Delivery of project is not clear, difficult to interpret and is difficult to apply from an external perspective with no prior knowledge on HDD

2.0 Stakeholder Analysis

The nature of this project has the potential to impact a wide variety of stakeholders. When installing pipelines, many different groups must be considered from regulatory bodies to Indigenous Nations. For the scope of this project, the identified stakeholders have been classified as one of three types: primary, secondary, and tertiary. Primary stakeholders have been defined as those who are heavily involved with the installation of the project. Secondary stakeholders include those impacted by the installation of the crossing. Lastly, tertiary stakeholders are those considered in the construction process, however, have little input on the construction process. The breakdown can be found in Table 5 below.

Table 5: Outline of primary, secondary, and tertiary stakeholders.

Primary	
YPAC and CEPA (Client)	Young Pipeliners Association of Canada and Canadian Energy and Pipeline Association are the clients for this project.
Pipeline Companies	Companies who own the pipeline and crossing. These companies will be responsible for the cost of the HDD installation as well as the project management.
Regulatory Bodies	Organizations which govern the pipelines such as the Canadian Energy Regulator and the Alberta Energy Regulator. These organizations approve the design, permits and construction for pipeline projects.
Environmental Groups	Environmental groups advocate for the environment and against projects which may cause harm to the earth, waterways, and vegetation. Environmental groups are typically opposed to pipelines, especially ones which traverse rivers and lakes.
Landowners	Landowners are residents whose land will be impacted by the installation of a crossing. This is usually those whose land backs on to the crossing or where drilling waste will be disposed.
Contractors	Contractors are contract managers or construction companies hired by the pipeline companies for the installation. They will complete the crossing using their respective equipment or hire other companies as required.
Secondary	
Indigenous Nations	Indigenous Nations must be consulted before pipelines and crossings can be installed on their land. They have an important role in the approval process of projects.
Pipe Manufacturers	Pipe manufacturers create and distribute the pipe that will be used for the crossing.
Operations Groups	Operations groups are those who manage the pipeline and complete the maintenance once the installation is complete.
Tertiary	
Surrounding Communities	Those who will not directly interact with the pipeline, but live nearby and may benefit from the installation.

Throughout the project multiple stakeholders including pipeline companies, YPAC, contractors and regulatory bodies were contacted to discuss their concerns and respective considerations. Contact with primary stakeholders was prioritized as their values and inputs should be considered most heavily.

A table of all interviewed stakeholders, the point of contact, as well as the discussion topics from each meeting can be found in Appendix IV – Stakeholder Interviews. These interviews spanned topics such as apprehensions with current trenched and trenchless designs, environmental concerns, regulatory considerations, as well as important outcomes. The results of these interviews and stakeholder research have been used to populate Table 6 to Table 11. These tables outline stakeholders' concerns, their associated design criteria, project value, as well as project risk.

2.1 Primary Stakeholders

The most immediate stakeholders to the project entails groups directly involved in the research, design, and construction phases of the project. Primary stakeholders include YPAC & CEPA, pipeline companies, regulatory bodies, environmental groups, landowners, and contractors. These are the stakeholders whose concerns, and needs were prioritized. The pressing concerns associated with each stakeholder impacted the project by influencing the priority of design criteria.

Table 6: Primary stakeholders and their pressing concerns and relevant design criteria.

Stakeholder	Pressing Concerns	Design Criteria to Address Concerns
YPAC and CEPA (Interviewed)	• Minimize the cost of solution (capital and maintenance). • Improve/maintain the safety of design. • Minimize construction time. • Minimize negative environmental impacts. • Improve efficacy of designs.	• Time efficiency • Cost efficiency • Safe to operate • Environmentally responsible • Limited land destruction • Scalability • Versatility • Long lifespan
Pipeline Companies (Interviewed)	• Minimize the cost of solution (capital and maintenance). • Improve/maintain the safety of design. • Minimize construction time. • Minimize negative environmental impacts. • Improve efficacy of designs. • Maximize pipeline lifespan.	• Time efficiency • Cost efficiency • Safe to operate • Environmentally responsible • Limited land destruction • Scalability • Versatility • Long lifespan
Regulatory Bodies (Interviewed)	• Improve/maintain the safety of design. • Minimize negative environmental impacts.	• Safe to operate • Environmentally responsible • Limited land destruction
Environmental Groups (Interviewed)	• Minimize negative environmental impacts.	• Environmentally responsible • Limited land destruction
Construction companies (Interviewed)	• Improve/maintain the safety of design. • Ease of implementation. • Maximize job creation. • Minimize construction time.	• Environmentally Responsible • Limited land destruction • Safe to operate

Stakeholder	Pressing Concerns	Design Criteria to Address Concerns
		• Time efficiency
Landowners	• Minimize negative environmental impacts.	• Environmentally responsible • Limited land destruction

Table 7 below outlines the value and the risks of the of the project for each primary stakeholder.

Table 7: Primary stakeholders and their respective project values, risks, and impact.

Stakeholder	Project Value/Impact	Project Risks
YPAC and CEPA (Interviewed)	• Innovate pipeline industry and improve old methods. • Introduce talent and young engineers to the pipeline industry.	• No new solutions are developed. • New design solutions are not widely adopted.
Pipeline Companies (Interviewed)	• A decrease in construction costs means a larger profit margin for companies. • Improved efficiency. • Reduced environmental impact. • Safer installation and work environment may lead to an increase in workers.	• New design is not feasible in practice or fails. • New design does not alleviate environmental impact. • Cost increase in construction or equipment.
Regulatory Bodies (Interviewed)	• Reduced environmental impact. • Safer installation methods.	• New design is not feasible in practice or fails. • New design does not improve environmental impact.
Environmental Groups (Interviewed)	• Reduced environmental impact.	• New design does not alleviate environmental impact.
Construction companies (Interviewed)	• Creation of new projects/jobs. • Improved construction efficiency. • Safer installation methods.	• New design solutions are not safe. • Installation may become more difficult.
Landowners	• Improved trenchless methods could increase the number of projects. • Monetary value from new projects.	• New design is not feasible in practice or fails. • New design does not alleviate environmental impact.

2.2 Secondary Stakeholders

The secondary stakeholders include Indigenous Nations, pipe manufacturers, and operation groups. These groups have valuable insight on the project and will be affected by the outcome, however, it will be to a much lesser extent than the primary stakeholders. Table 8 outlines the pressing concerns and design criteria for the secondary stakeholders.

Table 8: Secondary stakeholders and their pressing concerns and relevant design criteria.

Stakeholder	Pressing Concerns	Design Criteria to Address Concerns
Indigenous Nations	• Minimize negative environmental impacts. • Maximize job creation for individuals belonging to Indigenous Nations. • Improve/maintain the safety of design.	• Environmentally responsible • Limited land destruction • Safe to operate • Time efficiency
Pipe Manufacturers	• Improve/maintain the safety of design.	• Safe to operate • Long lifespan
Operations (maintenance) Groups	• Improve/maintain the safety of design.	• Safe to operate • Long lifespan

Please note: Due to the political sensitivity of the project no indigenous communities were contacted. Their concerns instead were thoroughly researched through several mediums including national news sources, blog posts, and an interview with an Indigenous Relations Manager for InterPipeline (Michelle Goodkey) [23].

Table 9 below outlines the value of the project to each secondary stakeholder as well as the risks that it poses.

Table 9: Secondary stakeholders and their respective project values, risks, and impact.

Stakeholder	Project Value/Impact	Project Risks
Indigenous Nations	• Increased number of jobs through new projects. ◦ Many companies aim to hire 20% Indigenous staff [21]. • Safer installation methods.	• New design is not feasible in practice or fails. • New design does not alleviate environmental impact.
Pipe Manufacturers	• Decreased cost of installation. • Creation of new projects.	• Reputational risk in cases of pipe failure.
Operations (maintenance) Groups	• Safer installation methods. • Improved planning for appropriate subsurface conditions may increase pipe lifespan and reduce wear.	• New design solutions are not safe.

2.3 Tertiary Stakeholders

Surrounding communities were identified as a tertiary level stakeholder. For the Wapiti River crossing this would include the residents of Grand Prairie and Grovedale. These communities were considered from a general unbiased point of view. Table 10 outlines the tertiary stakeholders along with their project concerns and relevant design criteria to address their concerns.

Table 10: Tertiary stakeholders and their pressing concerns and relevant design criteria.

Stakeholder	Pressing Concerns	Design Criteria to Address Concerns
Surrounding Communities	• Minimize negative environmental impacts. • Minimize construction time. • Minimize noise disturbance during and after construction. • Minimize traffic from construction.	• Environmentally responsible • Limited land destruction • Time efficiency

Table 11 below outlines the value of the project to each tertiary stakeholder as well as the risks that it poses.

Table 11: Tertiary stakeholders and their respective project values, risks, and impact.

Stakeholder	Project Value/Impact	Project Risks
Surrounding Communities	• Decreased time of installation. • Less disruption to surrounding land.	• Efficient trenchless crossings may lead to new projects resulting in more affected communities. • Unsuccessful design solutions may lead to contaminated land and water bodies. • Project failures may lead to increased construction times.

2.4 Stakeholder Analysis Summary

Meeting stakeholder's needs and requirements has been a top consideration throughout the project. All primary stakeholders – with the exception of landowners – for this project have been interviewed to better understand their concerns and goals for pipeline projects. Landowners were not contacted as the Wapiti River crossing will not be constructed, in lieu landowners needs and values were explored through interviews with contractors.

Completing the stakeholder analysis allowed for the identification of relevant design criteria for all parties involved in an HDD project. Understanding which stakeholders were most impacted by the project along with their respective concerns allowed for the prioritization of design criteria. As YPAC and CEPA were identified as the most immediate stakeholder, a House of Quality, as seen in Appendix VI—B House of Quality, was completed from their perspective to further develop the design criteria. Additionally, the early identification of the project risks shaped the decisions made throughout the project. The analysis helped to drive the project forward by guiding decisions to ensure they aligned with stakeholders' needs.

3.0 Idea Generation

Idea generation techniques were used for several purposes, from mapping and developing an HDD project, to identifying possible project outputs. Methods used include Mind Maps generated in Coggle, an online mind mapping software, the Post-It Note method using MS Word, and Reverse Solution Breakdown in MS Word.

A variety of processes were used to optimize the output of each idea generation technique. A plan of which techniques would be used was created, and from there, individuals each generated their output to avoid groupthink and to maximize the number of unique ideas produced. Following individual completion, the outputs were then combined and discussed together, and often conversation sparked new additions. As a result, the idea generation process identified areas where further research should be conducted to examine possible time or cost-saving opportunities. Additionally, several promising ideas were generated and were further examined to determine their feasibility.

3.1 Construction Process Timeline Analysis

A timeline analysis was conducted on the construction process of implementing an HDD crossing. The data used in the analysis was gathered through a stakeholder interview previously conducted with a project manager at TC Energy, Rob Purcell [15]. It should be noted that the data being used is from a previously constructed 1km, NPS 48 river crossing in a similar climate to Grand Prairie [15].

This process was completed to understand the distribution of construction times and identify opportunities to reduce time. As with any construction project, time is equal to money; therefore, reducing the overall project cost will be strongly influenced by reducing the number of processes and improving their efficiencies.

3.1.1 Process for Completing the Timeline Analysis

The timeline analysis was a straightforward examination which had a significant impact in later idea generation techniques. After receiving the data from Rob Purcell, it was entered into Excel and transformed into a bar chart [15]. This allowed for an understanding of the ordering of tasks and their respective timeline. Processes with large time requirements were noted as they were considered tasks where improvements or alterations will have the most considerable effect. Smaller processes were additionally analyzed as their elimination or amalgamation may also have an enormous impact. The purpose of this analysis was used as a steppingstone for idea generation techniques, as discussed in Section 3.1.2 Outcome and Value from Completing the Timeline Analysis . In Figure 7, the blue timeline represents the construction completed by the HDD contractor and the green timeline represents work completed by the pipeline construction contractor. The table outlining the steps and descriptions can be found in Appendix II – Definition and Descriptions of Construction Process Steps.

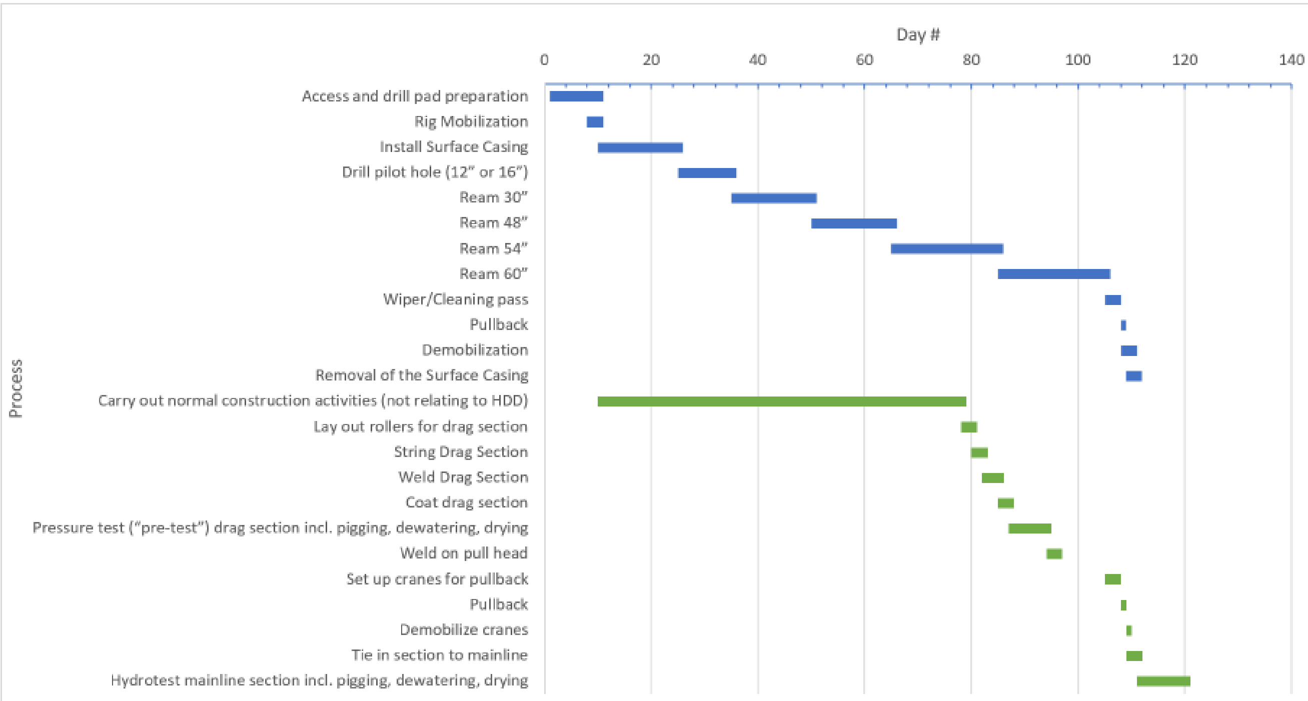


Figure 7: Timeline analysis generated to review the construction processes and their respective time requirements. Note these times are for a 1000 m HDD crossing completed by TransCanada Energy [15].

3.1.2 Outcome and Value from Completing the Timeline Analysis

Having the data in graphical form allowed it to be more accessible and more apparent which processes require the most time. For example, even with a strong understanding of the reaming process, it was not clear how time-consuming it was. The reaming process required four passes and 74 days to be complete on this project. It was determined that reaming spanned 62% of the project timeline.

Another outcome of the analysis was discovering the significant amount of time spent on what has been deemed "normal construction activities". These 69 days encompass a wide variety of pipe preparing activities early in the project; as it is a long process, there is the potential for significant time reduction.

A realization from this activity was that it is not necessarily one timely process that must be altered to bear an impact; multiple smaller processes can be merged or eliminated to reduce times and costs.

The timeline analysis did not result in any significant design ideas; however, it was invaluable in terms of processing information. The processes used in this analysis (Y-axis of Figure 7) became necessary inputs in future idea generation techniques such as the Post-It Note method below. Additionally, the time-consuming processes were identified through this method and used as a focal point in the later techniques such as Section 3.4 Time-Intensive Processes Ideation.

3.2 Construction Step Ideation

One of the idea generation methods used was the Post-It Note method. The results from completing this method are in Appendix V—A Construction Step Ideation Results. The steps outlined in Table 34 were drawn from the timeline analysis described above in Section 3.1 Construction Process Timeline Analysis. The Post-It Note method was selected as there are many different steps in the construction process, and with that, lots of opportunities for cost reduction. By going through each step systematically, possible cost-saving ideas were brainstormed and documented.

3.2.1 Process of Completing the Construction Step Ideation

The Post-It Note method began by identifying the construction process steps and creating a clear description for each one. Once all the steps were documented, team members individually brainstormed ways to reduce each step's costs. This was done individually to reduce groupthink and encourage more diverse and eccentric proposals. After preliminary passes on cost reduction, tables were merged, and new ideas were generated through conversation and challenging ideas. A more detailed description of the steps can be found in Appendix II – Definition and Descriptions of Construction Process Steps.

3.2.2 Outcome and Value of Completing the Construction Step Ideation

This method produced many outputs and ideas. There were a wide variety of idea types, from evident to outlandish and feasible to nearly impossible. Therefore, showcasing a successful idea generation session.

It was found that there exist lots of opportunities in the drilling process to reduce costs. This encompasses pilot hole drilling, reaming, and the pullback process. Additionally, it was revealed that drilling mud creates an array of substantial expenses leaving many possible process adjustments.

This brainstorming method was beneficial for documenting the ideas that had been coming up throughout the project. Viewing the steps alongside one another and comparing the processes allowed for seeing similar procedures and potential opportunities to merge multiple steps.

The outcomes of this analysis were further researched to determine their feasibility and implementation value. Having the steps documented systematically and each described exhibited a more comprehensive understanding, therefore laying out several upcoming vital tasks. The idea generation technique gave way to some strong design ideas, as mentioned above. These ideas were further analyzed, and the results can be found in Section 4.2 Narrowing Down Ideas for Cost Reduction Solutions.

3.3 Horizontal Directional Drilling Ideation

Minds maps were used to brainstorm the aspects of an HDD project, significant costs, and time-consuming processes (Figure 24, Figure 8, and Figure 9). The first mind map was used to ideate on all facets related to an HDD project. The results of completing this mind map are shown in Appendix V—B Horizontal Directional Drilling Ideation Results.

3.3.1 Process of Completing Horizontal Directional Drilling Ideation

The HDD mind map depicted in Figure 24 is the final product of multiple iterations and a conglomeration of multiple maps. To begin the process three individual mind maps were created to organize each individuals' thoughts and record all processes related to HDD projects. This was completing early in the project when initial research was being conducted on HDD. This mind map helped to further define the problem as it compartmentalized the topics which frame the problem. Once the three maps were finalized, the outputs were merged into a final map to exhibit all the ideation conducted.

3.3.2 Outcome and Value of Completing Horizontal Directional Drilling Ideation

A considerable outcome from this process was seeing all the project research previously completed mapped out and organized. This included research on stakeholders, stresses, processes, and design criteria.

The value in completing this mind map was acknowledging the breadth of an HDD project and the sheer quantity of steps that influence time and cost. The process of working top-down on the map identified which sections required further research. These were areas where difficulty occurred breaking down thoughts or it was found to be unclear. For example, the stresses in the pipe were unable to be broken down further. The internal and external forces on the pipe required a more in-depth analysis which included calculating the longitudinal compressional, hoop, combined, and max allowable stress. These forces can be found in Section 6.1 Modeling.

3.4 Time-Intensive Processes Ideation

A mind map was generated to brainstorm time-intensive processes related to HDD construction. This was completed to identify key steps in the process that require the most resources, which are time and money. By identifying these steps, ideation could then be completed on ways to reduce their costs.

Time-consuming steps can be defined as any step that takes 6% or more of the project timeline to complete. These steps were built on those from Section 3.1 Construction Process Timeline Analysis.

3.4.1 Process of Completing Time-Intensive Processes Ideation

This mind map was developed by using a top-down approach. The time-consuming processes were identified and further divided into their specific construction steps. Figure 8 displays the mind map created to outline time generating steps of the construction of an HDD water crossing.

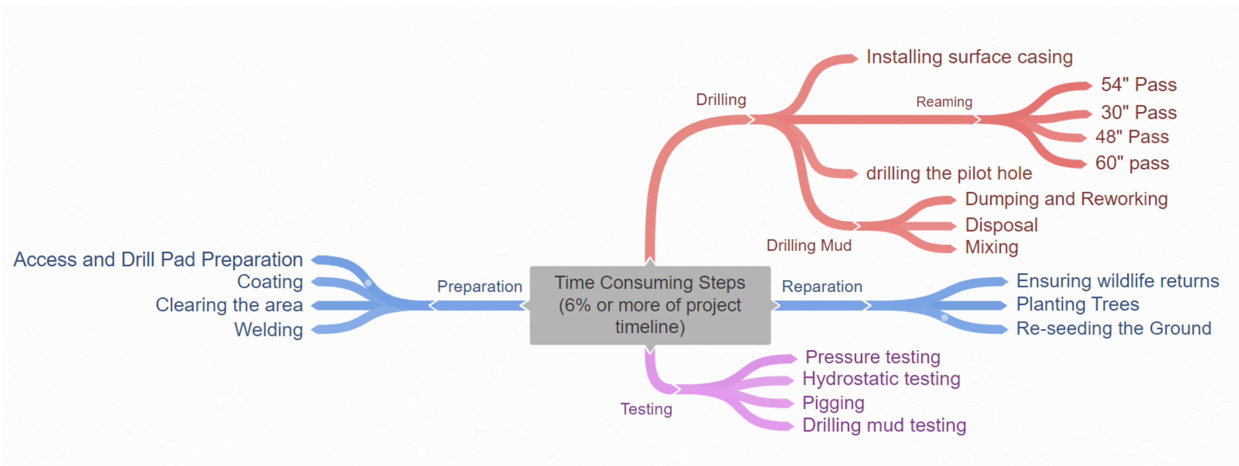


Figure 8: Mind map used to outline time-consuming steps construction of the project using coggle.

3.4.2 Outcome and Value of Completing Time-Intensive Processes Ideation

As seen above, time-consuming steps exist in every construction step, therefore there is not one key section to hone-in on. Although the specific times for each step are not displayed on the map, they can be found in Figure 7.

Figure 8 visually conveys the significant time requirements of the drilling process, meaning there may be a noteworthy opportunity for time reduction in this stage. Every sub-step of the four major processes were further divided. These new steps were then explored and researched more in-depth.

The value from this mind map can be drawn from the identified key steps. These are the ones where significant time is spent and there exists an opportunity to propose alternative steps. These steps are the ones present in Figure 8 as smaller ones were not included. This provided direction in areas to prioritize for cost reduction.

This mind map is presented to the client and possible stakeholders to demonstrate the thought process and path to the final solution. It also relates directly to Figure 9 as time and cost have a strong positive correlation with one another.

3.5 High-Level Costs Ideation

A mind map breaking down the sources of the high-level costs associated with the HDD process was completed. This was done to outline areas producing higher costs and where the costs come from within the process. The mind map technique was chosen for this topic to visually organize the costs and break them down into their sub-groups within the construction process. It should be noted that this process was completed prior to finalizing the detailed cost estimate for the Wapiti River crossing. Therefore, this mind map was a preliminary idea of what would be included in an estimate. The detailed cost estimate for the Wapiti River is included in Section 6.4 Original Economic Analysis for Wapiti River Crossing.

3.5.1 Process of Completing High-Level Costs Ideation

The mind map was generated to include the costs associated with HDD and how they could be grouped. It was decided that the main three branches for the mind map would be the costs associated with the equipment (purple), raw material (red), and labour (yellow). These were then used as a guide for the remaining branches on the map. The mind map generated is shown in Figure 9.

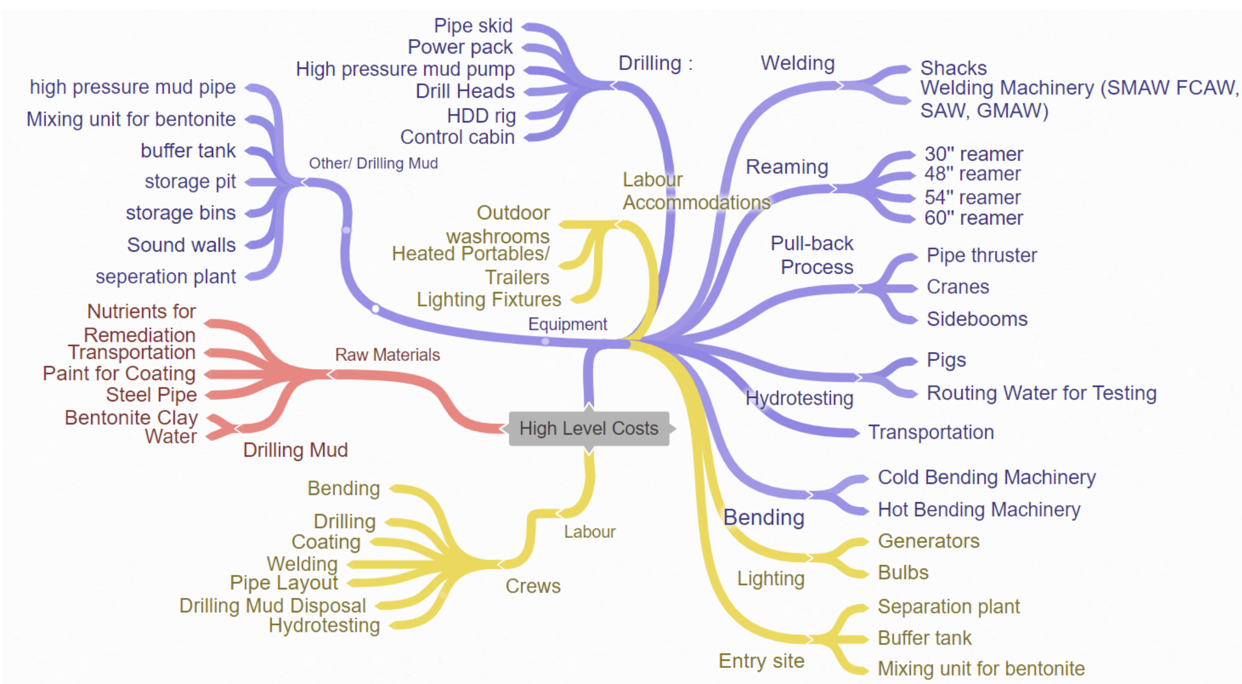


Figure 9: Mind map for the high-level costs associated with HDD.

3.5.2 Outcome and Value of Completing High-Level Costs Ideation

Completing this exercise aided in breaking the problem down and outlining the main costs associated with HDD's different processes. This also helped highlight which costs affect the different steps in HDD.

The value in completing this process was that this mind map was referred to when completing the economic analysis found in Section 6.4 Original Economic Analysis for Wapiti River Crossing. This ensured all costs were included to produce a more accurate analysis.

Additionally, by outlining the main costs associated with HDD, identifying cost saving opportunities was more straightforward. Expanding on this idea, this mind map was used when completing Section 3.2 Construction Step Ideation. The costs outlined in this mind map helped generate ideas to reduce costs.

3.6 Extreme Conditions Ideation

The Reverse Solution idea generation method was used to think of the problem in extreme conditions to generate unique, innovative ideas. The results of completing this ideation method are shown in Appendix V—C Extreme Conditions Ideation Results.

3.6.1 Process of Completing the Extreme Conditions Ideation

The worst-case scenarios in essential steps in the HDD process were identified. Methods to avoid these scenarios from happening or ways to fix them if they did occur were recorded. This process was completed to gather more ideas, build on each other's ideas, and view the scenario from multiple perspectives.

3.6.2 Outcome and Value of Completing the Reverse Solution Breakdown Method

This method encouraged creative thinking and to look at the problem from a new perspective. Potential problem areas were highlighted, and unique ideas were generated. This process helped create new topics for research that had not been previously discussed.

This idea generation method highlighted key aspects of the process that need to be done with precision and accuracy, such as welding and coating, to avoid significant issues later in the project. Additionally, this exercise helped identify problems that could occur, which was valuable for future steps in the project such as when completing the Failure Modes and Effects Analysis (FMEA) which is discussed in Section 6.3 Failure Modes and Effects Analysis for Wapiti River Crossing.

3.7 Idea Generation Summary

Using these different methods to generate ideas allowed the problem to be approached and broken down in a new way. The Reverse Solution Breakdown method caused extreme situations to be considered that forced the project to be viewed from a different perspective. The mind maps helped break down the problem in multiple ways and increased the understanding of the scope. This method effectively visualized the problem, compartmentalizing the aspects to make them more manageable and to see how the different areas tie into one another. It helped determine the areas that were considered at the time and was used as a guide for the different paths for investigation. The Post-It Note method was effective in documenting all the ideas that were generated throughout the process. Its lack of structure was beneficial for the first round of ideation since it helped determine groupings and areas where a better understanding of the process was required.

Through these exercises, working together and discussing ideas as a team was found to be very beneficial for idea generation along with a cohesive understanding of the problem. A method that was determined to be effective was to ideate individually, then come together to share ideas and generate more. When this was done, ideas were combined, altered, and built off one another to produce creative, innovative ideas. This functional approach as a cohesive team was practiced for the remainder of the project to ensure the best ideas were formulated.

4.0 Decision Making

After conducting a comprehensive idea generation process, several preliminary decisions were necessary to advance the project. These include specifying a Wapiti River crossing location, selecting the top processes for improvement, determining important functional requirements, and defining the project metrics. Various decision tools were utilized to carry out this process such as a comparison table, a benefits and challenges table, a House of Quality, and an evaluation matrix. Section 4.0 outlines the decision, process, outcome and value from each decision tool.

4.1 Wapiti River Crossing Location

A specific river crossing location was required to commence the project design and understand the project costs. To make this decision, key features of the viable crossings were compared and then evaluated against the objective. The results of this process can be found in Table 13 in Section 4.1.1 Process of Choosing the Crossing Location.

4.1.1 Process of Choosing the Crossing Location

Google Earth was utilized to determine three feasible crossing locations between Grand Prairie and Grovedale on the Wapiti River. An illustration of the three crossing options can be seen below in Figure 10. The elevation profiles of the crossings are illustrated in Appendix VI—A Possible Crossing Location Profiles.

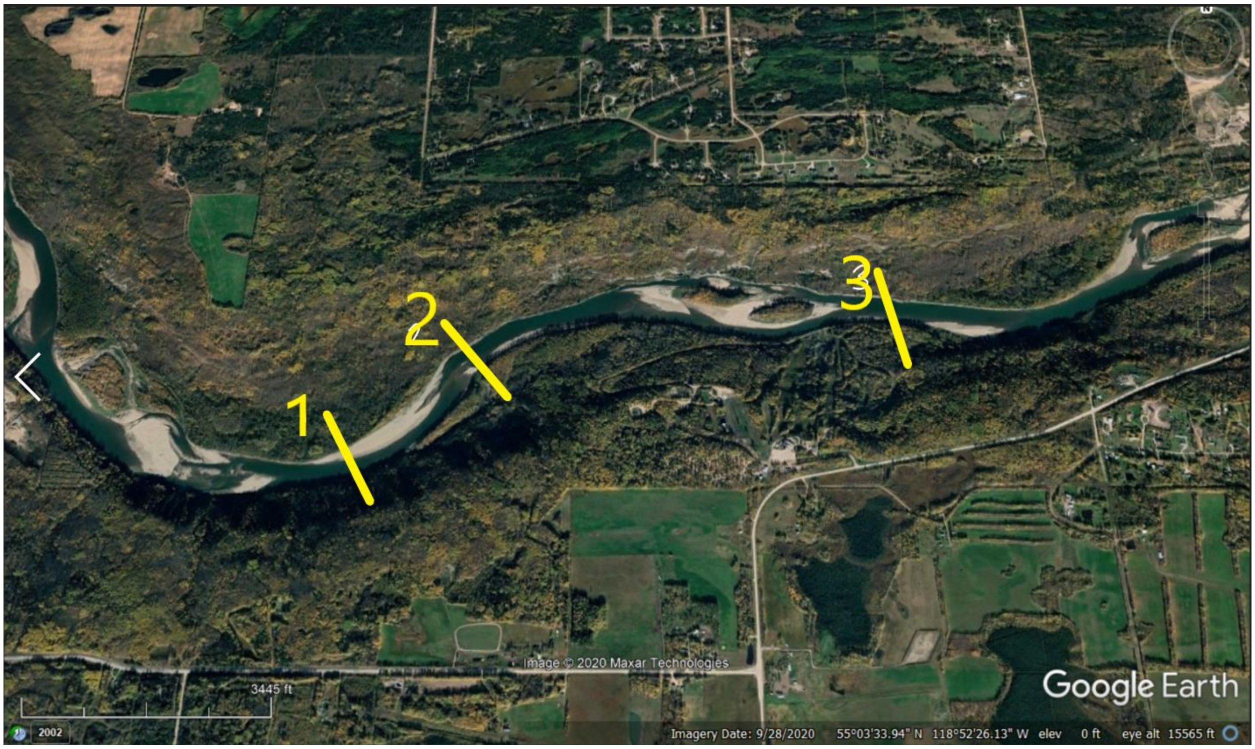


Figure 10: Overview of three considered Wapiti River crossings between Grand Prairie and Grovedale [11].

The practicality of these crossings was determined by seven predetermined feature requirements. The objective of each feature was identified before collecting statistics on each crossing to remove bias. Research to identify these critical elements was completed by interviewing professionals such as HDD Project Managers and Geotechnical Engineers. These traits were the main considerations when selecting crossing location as they have the largest impact on project feasibility, cost, and time. The information on each crossing was gathered using Google Earth to analyze the crossing's elevation profile. Table 12 provides a brief description of each of the features used to describe and evaluate a crossing.

Table 12: Descriptions of features used to determine the ideal crossing location.

Feature	Description
Length [m] (river width)	The width of the river at the designated crossing location.
Elevation Change [m]	The change in elevation across the width of the river.
Max Slope [%]	The maximum rate of elevation change along the crossing length.
Surrounding Area Type	The forestry and terrain of the area surrounding the crossing. This is the area within 200m of the entry and exit points.
Enough room for drilling pad	There must be enough space surrounding the entry and exit points for the equipment required to install the HDD crossing. This is defined as 350 m^2 [32].

Feature	Description
Distance from highway [m]	A measure of how far the entry point is from the nearest highway. This is essential for delivering equipment and materials therefore proximity is highly desired.
Direction of installation	The designated installation direction between the entry and exit points. The direction will move from the entry point (higher elevation) to the exit point (lower elevation) as it is most efficient [3].

Table 13 was created to analyze all of the aforementioned features for each crossing for comparison, all data was gathered using Google Earth.

Table 13: Comparison of crossing location options. Note: The direction of installation bears no impact on the selected crossing but is important to designate the crossing's entry and exit points, and therefore the relevant distance to the highway.

Feature	Objective	Crossing 1	Crossing 2	Crossing 3	Crossing that Best Meets Requirement
Length [m] (river width)	Minimized	146	115	131	2
Elevation Change [m]	Minimized	38.0	2.1	6.6	2
Max Slope [%]	Minimized	59.3	N/A (too small)	N/A (too small)	2,3
Surrounding Area Type	Easily cleared and not farmland	Heavy forestry and sand	Heavy forestry	Heavy forestry	2,3
Enough room for drilling pad	~350 m^2 [32]	Yes	Yes	Yes	1,2,3
Distance from highway [m]	Minimized	887	1427	683	3
Direction of installation	N/A	South to North	South to North	South to North	N/A
Final Selection					**2**

4.1.2 Outcome and Value of Choosing the Crossing Location

Crossing 2 was selected as the designated path for several reasons. This route was most efficient with respect to length being 16 metres and 31 metres shorter than the alternatives. This implies that it will be cheaper to install as the drilling and reaming processes will be completed faster. The HDD technique also requires less material on shorter crossings, which will reduce costs. Elevation changes can be problematic when installing pipes using HDD as it can lead to pipe slides, therefore crossings that minimize these changes are favoured [18].

As the second crossing had the smallest elevation change, it was deemed preferable for the installation. Crossing 2 and 3 ranked the same regarding the max slope and surrounding area type. The max slopes for the two paths were not registered by Google Earth as they were too small, therefore no distinction was made between the two. All three paths satisfied the minimum space requirements; this space is crucial for the rig equipment, and to lay the welded pipe before the pullback process. It should be noted that crossing 3 ranked higher than crossing 2 based on distance from the highway as it is just under half the length. This was decided to not be as large a factor as the length of crossing and elevation change, as an extra 500 metres from the highway to the crossing will not have a significant impact on the construction time.

Establishing a crossing point was required to proceed with the design process. By selecting a specific route, critical information such as the distance, elevation profile, and surrounding limitations was defined. This ultimately had an impact on the economic analysis and construction timelines. Additionally, after selecting the crossing location, the profile was modelled in AutoPIPE. Modelling the river pass outlined areas that required more technical knowledge and further research.

Another important result of pin-pointing the crossing location was a better understanding of the relevant stakeholders. This included the surrounding landowners, local contractors, and regulatory bodies. As the final path did not cross provincial boundaries, the only provincial regulations needed to be considered were within Alberta [20]. This impacted the design as well as the restrictions applied to the design.

4.2 Narrowing Down Ideas for Cost Reduction Solutions

To provide the client with an optimized construction design and overall cost reduction, the areas of focus within the construction process had to be narrowed down to one or two procedures. To make this decision, the five construction steps were outlined with possible ideas for cost and time reduction. The results of this process can be found in Table 14 and Table 16.

4.2.1 Process to Narrow Down Areas for Cost Reduction

The five major construction processes considered in this decision and their respective opportunities were developed in the idea generation phase. For each step or area of focus, the top cost reduction ideas were used. Following idea compilation, the benefits of focusing on each process were documented alongside the challenges each may incur. This was necessary to understand the logistics of moving forward with each step as all areas will impact the feasibility, cost, and timeline of the project.

An evaluation matrix was then used to rank each step in various categories. These categories were designed to equally encompass all critical areas of consideration, meaning there is no associated weight between the attributes. As seen in Table 16, the traits were evaluated on average time, impact on future processes, quality of ideas, feasibility of implementation, and potential cost savings. The processes with the highest rankings were then selected as the areas to continue innovating. At the time this exercise was completed, geophysical surveys were not considered to be within the scope of the project. Therefore, it was not seen as a viable cost reduction area until more information was gathered from industry professionals.

This process was completed as a team as ideas were generated from multiple points of view and gaining others' feedback was critical to finding the most efficient outcome.

Table 14: Benefits and challenges for process improvement ideas.

<table>
<tr><th>Process Step</th><th>Areas of Focus</th><th>Impacts</th></tr>
<tr><td>Pilot Hole Drilling</td><td>

Research how curvature of drill hole effects cost.
Will reducing the curvature of the hole be more cost-effective in the long run compared to a hole with large bends?
Research methods to reduce collapsing of hole.
Research design technology to not lose drill head or locate it when it falls off.
Research into how to minimize depth of the hole.
</td><td>
Benefits:

Improvements have ability to enhance following steps
Setbacks at this stage have the ability to impact the project timeline significantly, therefore minimizing the possibility of setbacks can be cost-saving.

The estimated cost per person per day is between $400-$600 [33].
A single day delay at this stage can result in $45,000 in lost labour wages as the pipeline construction crew must wait until the pilot hole is completed before they can weld the strung pipe [34].
This does not include the cost of the equipment on site.

A critical component in this step is to ensure the drill hole does not collapse, which can result in significant financial expenses.
</td></tr>
</table>

Process Step	Areas of Focus	Impacts
		Challenges: • Difficult to get data on radius' impact on reaming and pullback to justify the improvements. • Minimal data on occurrence of losing drill heads, therefore unsure of realized value in these improvements. • Information regarding drill hole collapsing will rely strongly on contractor's experience.
Reaming	• Research how to eliminate setbacks (when changing ream heads). • Research how to select optimal ream head. • Research impact of increasing ream size too quickly.	*Benefits:* • Currently is the longest step in process, therefore room for improvement. • Similar to drilling, delays in reaming can have a significant effect on other steps in the process. • Delays are common in this stage. • A critical component in this step is to ensure the drill hole does not collapse, which can result in significant financial expenses.
		Challenges: • The success of these improvements will be determined by information from contractors. • Improvements depend largely on subsurface knowledge or ability to attain substantial data on subsurface.

Drilling Mud	• Research into reducing volume of drilling mud prior to transportation.
	    o Reduce water content in mud.
	    o Look into polymer mud feasibility.
	• Research ways to reduce the volume required in construction.
		Benefits:
		• Drilling mud creates significant costs for a project.
		• Execution of disposing large volumes can be unfeasible.
		• Drilling mud exists for every HDD project and therefore a solution could provide significant cost savings.

Process Step	Areas of Focus	Impacts
	• Research ways to reuse mud in surrounding area.	*Challenges:* • It is a competitive market to solve this problem. There are many groups working to find alternatives or find ways to reduce costs. • Limited data on the cost of this facet for comparison.
Pullback Process	• Research feasibility to increase maximum force that drill string can withstand. • Research alternative ways for the drill string to be attached to the pipe when pulling the pipe through. • Research ways to reduce equipment needed in process. • Research ways to reduce the time machinery is on-site.	*Benefits:* • Many opportunities to improve the efficiency of this step. • Aspects of this process could cause significant time delays as the pipe may get stuck and solutions must be determined. *Challenges:* • This step in the process is relatively fast compared to the other steps. For a 1 km crossing, this can be completed in one day [25].
Coating and Welding	• Research methods to increase efficiency of crew overlap. • Research method that could achieve coating and welding simultaneously. • Optimize types of welds required (Gas Metal Arc Welds are preferred). • Research alternative electrodes to reduce weld time (non-cellulosic). • Research automated welding and coating techniques. • Research alternative corrosion protection methods.	*Benefits:* • Improvements can be applied throughout all pipeline projects, not just specific to HDD. • Appears to be many inefficiencies in the processes. *Challenges:* • These processes only take seven days for a 1 km pipeline. • No quantification on how often problems occur, although it does not appear to be frequent. • Automating these processes may be impractical.

Table 15 below details the attributes used to evaluate the various cost reduction opportunities.

Table 15: Attributes used in the evaluation matrix and their respective decisions.

Attribute	Definition
Average time spent on process	The amount of time spent on construction for each process from set up to completion.
Impacts the most succeeding processes	The number of future processes a step has the ability to impact. Impacts are defined to encompass time and cost. Therefore, it is a measure of how many processes a time delay, design, or change in the given step will influence.
Quality of improvement ideas	A measure of strength of preliminary design ideas. This refers to how unique and innovative ideas for each process were.
Feasibility of improvement ideas (implementation)	A measure of how viable ideas from each step were found to be. Viable is defined to encompass cost, time, materials and labour.
Potential cost savings if implemented	A measure of potential cost and time reductions from each step if implemented.

Table 16 is the evaluation matrix that was used to rank the steps according to each attribute.

Table 16: Evaluation matrix to select areas of focus for cost reduction.

Attribute	Ranking	Drilling	Reaming	Pullback	Drilling Mud	Welding/Coating
Average time spent on process	5 = most 1 = least	4	5	1	3	2
Impacts the most succeeding processes	5 = most 1 = least	5	4	2	1	3
Quality of improvement ideas	5 = most 1 = least	4	3	5	2	1
Feasibility of improvement ideas (implementation)	5 = most 1 = least	5	4	1	2	3
Potential cost savings if implemented	5 = most 1 = least	3	5	2	4	1
Total		**21**	**21**	**11**	**12**	**10**

4.2.2 Outcome and Value of Narrowing Down Areas for Cost Reduction

As a result of this decision, the areas for focus and future consideration were identified. Drilling and reaming were chosen to innovate for cost reduction opportunities at that time. These were selected as they incurred the most benefit and promise to further evaluate. As there was a large discrepancy between the 2nd and 3rd options, it was decided to only move forward with the top two highest scoring attributes.

Minimizing the scope for areas of research allowed for a more in-depth look at drilling and reaming. As the previous scope was more general, there was a sacrifice to the depth in order to accommodate the coverage required given the project timeline. Classifying the areas for further consideration identified the required resources to help drive the project forward. It should be noted that substantial ideas outside of the drilling and reaming realm were still explored following the completion of this exercise and are discussed in later sections.

4.3 Ranking Functional Requirements for the Project

To understand stakeholder's priorities and how they were applied to the design, a House of Quality was completed. The customer requirements and functional requirements were analyzed against one another and their relationship was defined. The results of this process can be found in Appendix VI—B House of Quality.

4.3.1 Process of Ranking Functional Requirements

The House of Quality was selected as it visually demonstrated the correlation between the functional and customer requirements and their magnitudes. The customer requirements were geared towards the needs and wants of the client (YPAC and CEPA). From the results in the House of Quality, the two highest scoring functional requirements were selected as the priority for solution development.

4.3.2 Outcome and Value of Ranking Functional Requirements

The House of Quality made evident that optimizing the reaming time and crossing path should be prioritized in the design process. These requirements had an equal score of 728.6; this was because they were highly correlated, and both had a meaningful impact on other design aspects. Optimizing the reaming time may include choosing the correct reaming head, ensuring a safe procedure, avoiding the collapse of the hole, and researching new technology that may exist to speed up the process. Optimizing the crossing path implied determining the relationship between length, depth, and bend radius which minimizes cost. Despite lower scores, other functional requirements were still considered throughout the design process even if they were not prioritized.

The client's needs included a low-profile design, and a pipeline with no effect on the environment post-service life. Neither had any correlation to the functional requirements nor were ranked high in importance, however, both were be kept in mind during the design process. Completing the House of Quality from the client's perspective allowed for the influence of their needs to be deeply understood and incorporated into the design process.

Research was conducted on reaming heads, how to efficiently increase diameter size, the impact of radius of curvature on reaming times, and the relationship between length and reaming time. Ultimately this path was not selected, however, it was still valuable to learn more about the overall HDD process and make connections that led to the selected solution.

4.4 Defining Project Metrics

Levels of success and goals for the final project solution were defined. This was completed in multiple iterations to determine how the final deliverable would be assessed and to clearly outline targets that drove the project. The final results of this process can be found in Section 1.8 Project Metrics.

Initially, features that were important to assess the final solution against were outlined and recorded. Next, the success levels of these features were determined. It was decided to have three levels, with level three being the most successful and level one being the least. The goal for each of the features was determined, along with its counterpart levels.

Although this is not a typical decision-making tool, decisions were made to determine how the final solution would be evaluated. It helped quantify and identify goals as well as aspects that needed to be considered for the remainder of the project.

4.4.1 Outcome and Value of Defining the Project Metrics

Generating these decisions helped to define all the aspects required to complete a successful project. It outlined the objectives to achieve a solution that is valued by the client. The typical project costs for an HDD crossing were analyzed and the reduced cost percentages were estimated. These numbers were selected as they provided significant cost reductions while remaining realistic. The feasibility of the values was reviewed and confirmed by professionals [10]. These success levels were updated throughout the project as more knowledge was attained, or if these goals were surpassed.

While completing this process, areas that had not been considered previously were discovered. It was found that contingency planning should be completed to have the most robust solution. Planning for delays ensured a more accurate cost estimate and timeline. It was also realized that the final deliverable must be realistic to be used by the client. As there are often discrepancies between research and real-life applications, a goal was to have the final design reviewed by at least three professionals. This ensured that the design, cost estimate, and construction plan were practical and could be implemented.

The value in defining project metrics was that they could be referred to throughout the project to strive for the highest standard. Additionally, it was valuable to outline what makes the project successful before completion to eliminate bias. If these metrics were defined once the solution was completed, they would not assess the solution as effectively.

4.5 Decision Making Summary

Finalizing these preliminary decisions allowed for areas that had not been addressed previously to be considered. For example, the idea of contingency planning and accounting for potential delays was incorporated into the final deliverable to present a more accurate solution. These decisions also identified areas that required further research for cost reduction opportunities. Through this, it was also realized more detailed costs still needed to be established to further the project.

Additionally, the decision-making process identified where the most opportune steps to prioritize were at that time. Other processes not considered were later explored as information was gathered from industry professionals and their experience on HDD projects.

5.0 Safety and Regulatory Requirements for Horizontal Directional Drilling

A substantial aspect of the project scope was to ensure that safety held the utmost importance throughout both the design and implementation phases. Safety requirements and regulatory documents were gathered through online research and speaking to industry professionals. These documents and the highlighted relevant sections can be found below in Appendix VII – Safety and Regulatory Documents for HDD Projects. Each regulatory document and the value it adds to the project are outlined in Table 17.

Table 17: Safety and Regulatory documents to consider when completing an HDD project.

Regulatory Document	Value to Project
Fisheries Act [35]	• Provided information regarding construction or work done in and around water bodies. • Outlined standards to protect the marine wildlife in the area.
Navigable Waters Protection Act (NWPA) [36]	• Set requirements for approval for any projects in or around water bodies.

Regulatory Document	Value to Project
Canadian Energy Regulator Onshore Pipeline Regulations Under the National Energy Board Act [37]	• Outlined regulations for safety and general construction for onshore pipeline projects. • Considered when developing a general construction plan.
Alberta Pipeline Act [38]	• Considered through all steps including planning and construction.
Alberta Code of Practice for Pipelines and Telecommunication Lines Crossing a Water Body [39]	• Outlined regulations for planning and completing construction when crossing a water body.
Planning Horizontal Directional Drilling for Pipeline Construction [16]	• Provided the best practices and procedures for the investigation, planning and execution of the HDD project.
Alberta Occupational Health and Safety Regulation [40]	• Outlined safety procedures for all labour projects in Alberta.
CSA Z662: 19 Oil & Gas pipeline systems [27]	• Pipeline was required to comply with these standards at a federal and provincial level.

6.0 Pseudo Project: Wapiti River Crossing

A crossing along the Wapiti River in Grand Prairie, Alberta was designed. This included modelling the pipe profile, calculating pipe stresses, providing a cost estimate, a general construction plan and risk mitigation. This crossing was used as a basis to validate the solution and the details are outlined below.

6.1 Modeling

Section 6.1 outlines the modelling completed for the Wapiti River crossing. Pipe stress calculations were completed to determine the relevant stresses on the pipe. Hoop, longitudinal compressional, combined as well as max allowable were the different stresses calculated for the pipe. Once it was determined that the combined stress was less than the maximum allowable stress, the grade of the pipe and the wall thickness values were inputted into AutoPIPE.

6.1.1 Pipe Stress Calculations

The calculations completed for determining the inputs for AutoPIPE were done using the formulas outlined in CSA Z662 [27]. Initial calculations were completed to establish the grade of the steel, the minimum required wall thickness, and to determine if the design was within the maximum allowable stress. Additionally, the material of the pipe needed to be specified. The options that were considered were carbon steel and stainless steel. Stainless steel is beneficial because it does not corrode but is much more expensive than carbon steel and not often used in the oil and gas industry [41]. Due to the cost, carbon steel was selected for the pipeline [41]. Carbon steel provided the required structural and thermal strength and although corrosion can occur, corrosion inhibitors can be used as a protection method [41].

A spreadsheet was created to vary inputs for these calculations to determine the best conditions for the pipe. The results are shown in Table 18. The detailed calculations are displayed in Appendix VIII – Pseudo Project Outputs.

Table 18: Results from pipe stress calculations.

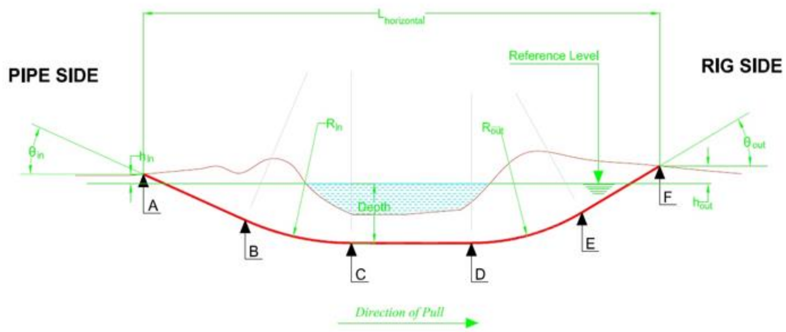
Design Parameter	Determined Value
Pressure (kPa)	9930
Minimum Yield Strength (MPa)	550
Outside Pipe Diameter (mm)	1219.2
Minimum Required Wall Thickness (mm)	13.76
Hoop Stress (MPa)	440.0
Longitudinal Compressional Stress (MPa)	-4.62
Combined Stress (MPa)	444.6
Maximum Allowable Stress (MPa)	495.0
Maximum Operating Temperature (°C)	45
Installation Temperature (°C)	-10

The pressure, maximum operating temperature, installation temperature, and outside pipe diameter were values provided by the client in the pseudo project [3]. The minimum yield strength, also known as the grade of the pipe, was selected from available grades of carbon steel used in industry and by observing the effect the grade had on the wall thickness. The minimum yield strength of 550 MPa was chosen because it allowed for a thinner wall thickness and was easily available for purchase [42]. When lower grades were analyzed, a much larger wall thickness was required. When the wall thickness was larger than 19 mm, more complications occurred when bending the pipe [30]. The combined hoop stress and longitudinal compressional stress were calculated to ensure it was lower than the maximum allowable stress.

6.1.2 Design of 2D Crossing Profile

The first step in designing the Wapiti River crossing was to complete the 2D crossing profile. This was completed using an online HDD design calculator provided by the client [43]. The inputs required for the calculator were design parameters that must be accounted for when planning HDD crossings. These parameters were researched and calculated and are shown in Appendix VIII—B Pipeline Crossing

Parameters. Once the inputs were entered into the website, a profile was generated with lengths of the pipe sections and angles identified. This is shown below in Figure 11.



Description	Type	Angle	Direction	Length
Section A to B	Straight	10 °	Downwards	L_{AB} = 5.382 m
Section B to C	Curved	10 ° to 0°	Downwards	L_{BC} = 118.736 m
Section C to D	Straight	0°	Horizontal	L_{CD} = 109.975 m
Section D to E	Curved	0° to 15 °	Upwards	L_{DE} = 79.158 m
Section E to F	Straight	15 °	Upwards	L_{EF} = 1.381 m
	Total drilling length of the HDD crossing			L_{drill} = **314.632 m**

Figure 11: The 2D profile of the Wapiti River crossing with lengths and angles of pipe section identified.

The online calculator also generated an analysis of the forces the pipe would experience during the pullback process, and stress analysis. The results are shown in Appendix VIII—C Additional Results from 2D Profile Analysis. For the stress analysis, challenges were faced when ensuring the calculated stress was less than the maximum allowable stress. To better analyze and guarantee that the stresses were within an acceptable range and follow code regulations, an AutoPIPE simulation was used. This is discussed in the following Section 6.1.3 AutoPIPE Simulation .

6.1.3 AutoPIPE Simulation of Wapiti River Crossing Pipe Profile

An AutoPIPE simulation of the 2D crossing was required to analyze the profile's feasibility and test the pipe stresses in different soils. Simulations were run to see how different soils would apply stresses that would ultimately affect the pipeline's vertical displacement underground.

An analysis of the pipe's stresses and displacement in different soils was conducted. It was required in order to prove why drilling into unknown regions underground can lead to issues during installation. All simulations were carried out at the highest operating temperature to imitate the worst-case scenario, as a pipe enables the most movement when heated. If the pipe withstood stresses at the highest heat, it was safe to operate at any temperature below it. The results from the AutoPIPE simulations can be found in 0Appendix VIII—D AutoPIPE Simulation. Table 19 summarizes these results. A column accounting for the change in vertical displacement at the bend on the exit side was included as it underwent the most stress.

Table 19: Results from AutoPIPE simulation [44].

Figure Number in Report	Exit Bend Radius (mm)	Soil Type in Simulation	Vertical Displacement of Exit Bend (mm)	Safe to Operate
Figure 27	28352	Soft Clay	117	No
Figure 28	36576	Soft Clay	85	Yes
Figure 29	36576	Stiff Clay	56	Yes
Figure 30	36576	Loose Sand	124	Yes
Figure 31	36576	Compact Sand	58	Yes

In the simulation profiles found in Appendix VIII—D AutoPIPE Simulation, the colour pink suggested the pipe met all standards and was safe to operate, while any red areas suggested the stress was too high and the pipe failed. After the first iteration of simulations, the client suggested lengthening the pipe on the exit side to alleviate the stress experienced by the exit bend. All simulations were deemed safe with the modified exit bend radius of 36576 mm as no red areas were visible on the profiles. Stiff clay proved to be the most compact as the pipe underwent the least vertical displacement and thus resisted the applied forces most effectively. A component of the pseudo project was to select a soil type for the crossing. For the reasons outlined above, stiff clay has been selected. AutoPIPE was a valuable tool as it helped to understand why ambiguity around the subsurface conditions and their effects on the pipe brought about risks and anticipated failure.

6.1.4 Application of Constraints to the Pseudo Project

As previously mentioned in Section 1.5 Constraints, constraints were outlined for the project. All action items to ensure that constraints were accounted for in the Wapiti River crossing were documented. Table 20 below shows the outlined constraints and how they were met.

Table 20: The constraint areas relevant to the project along with an outline for how the constraints have been met.

Constraints	How Constraints Have Been Met
Trenchless Technique	• An HDD technique was selected as the installation method for the design [3].
Climate	• AutoPIPE simulation software was utilized which accounted for various climate aspects and provided the pipe specification outputs required [45].
Cost	• Research was conducted on the average costs of various materials and processes [33]. • Finalized costs were validated by three industry professionals to ensure their accuracy and feasibility [46] [47] [33].
Time	• A detailed work breakdown structure can be found in Appendix XII—B Work Breakdown Structure. This management tool identified project deadlines and goals to ensure the design timeline constraint have been met. • A suggested window of implementation was proposed to optimize installation while also accounting for a margin of error on timeline requirements as mentioned below in Section 6.2 General Construction Plan for Wapiti River Crossing.
Depth	• Research was conducted on depth requirements for HDD installations below waterbodies which was found to be 20 ft below the riverbed [9]. • These requirements were incorporated into the design and inputted into AutoPIPE [45].
Land Space	• The space requirement for the right of way and drill rig set up have been identified through interviews with contractors. • A specific crossing point was selected using spacing requirements as a decision metric. • Google Earth was used to identify potential crossings with the spacing requirements [11].
Length	• Google Earth and AutoPIPE were used to determine 315 m as the crossing length. • As 2.95 km is the current record in Canada for the longest HDD crossing, length will not be an issue [17].
Field Bends	• The AutoPIPE simulation was leveraged to ensure that all bends were feasible field bends [45].

Constraints	How Constraints Have Been Met
Environmental Impact	• All codes regarding environmental requirements were followed which are listed in Table 17. • Environmental advisors have also been contacted to learn best practices and ways to reduce the environmental impact of HDD projects [18].

6.2 General Construction Plan for Wapiti River Crossing

A general construction plan outlining the installation process of the Wapiti River crossing was created. This plan can be found in Appendix VIII—E General Construction Plan. The plan was a component of the pseudo project used to forecast the timelines of an HDD project. The timeline was generated through researching past projects such as the TransCanada Energy 2018 Peace River crossing and meeting with industry professionals from Brothers HDD [48].

Assuming construction goes as planned, the entire construction process is expected to take 12.5 days which encompasses the drilling, reaming, and pullback. The construction will commence on January 3rd of 2022 and terminate on the 15th. January was selected as the ground will be cold and solidified providing ideal construction conditions [48].

6.3 Failure Modes and Effects Analysis for Wapiti River Crossing

A failure modes and effects analysis was completed to identify potential failures for the Wapiti River crossing and outlined measures to eliminate these failures or minimize their risk. This analysis can be seen in Appendix VIII—F Failure Modes and Effects Analysis Table for Wapiti River Crossing.

Potential failure modes were identified and listed in the table. After this, the additional columns were filled out through discussing the impacts and causes of these failures along with scoring their severity, occurrence, and detection. These failure modes were then ranked according to their calculated RPN (severity X occurrence X detection).

After meeting with more industry professionals following this analysis, knowledge on risks during HDD construction had been enhanced. Therefore, the FMEA underwent multiple iterations; The finalized version is included in this report. To fill out the right-most columns of the table, it was decided to focus on the top ten failure modes. These are the failure modes which had the most anticipated impact on the construction of the project and action was taken to mitigate the risk associated with them. The top failure modes are summarized in Table 23 below.

Table 21: Top ten failure modes from Wapiti River crossing FMEA.

Failure Mode	RPN	Risk Mitigation
Hole collapses during reaming	192	Make construction plan so that borehole is left open for the minimum amount of time. In the design plan, have multiple reaming passes while slowly increasing the reamer size and ensure an experienced professional is on-site.
Project overschedule	192	Complete more research on technology that maps subsurface conditions. Make construction plan so that it accounts for possible delays in the project.
Overschedule of reaming and delays project	96	Complete more research on technology that maps subsurface conditions.
Loss of tooling downhole during reaming	96	Complete more research on technology that maps subsurface conditions.
Drill head breaks	81	Complete more research on technology that maps subsurface conditions. Ensure contractor is familiar with drill head protection.
Small fluid loss to formation	70	Complete more research on technology that maps subsurface conditions and detect problematic formations that could lead to fluid loss.
Hole collapses and wiping pass gets stuck	64	Make construction plan so that reamed hole is left open for the minimum amount of time. Complete geotechnical study to understand properties of the soil being drilling through.
Not enough drilling mud to lubricate pullback	54	Calculate amount of drilling mud required months in advance of construction and order extra in case of complications.
Pipe damaged during installation	54	Complete geotechnical investigation on area to be aware of any structures underground that could damage the pipe during installation. Ensure crew completing process is trained and has experience.
Transportation delays of equipment and materials	48	Account for weather conditions in planning stages closer to the construction commencement.
Hole collapses during pullback	24	Determine the friction the pipe would encounter prior to pullback process and calculate the amount of drilling mud required.

The outcome of completing the FMEA was a list of all the potential failure modes for the project. Once these failure modes were studied, it was apparent that completing a proper geotechnical investigation prior to construction lowered the occurrence of risks leading to increased costs. Therefore, these results sparked the need to further research subsurface technology.

6.4 Original Economic Analysis for Wapiti River Crossing

An economic analysis was completed for a 315m long crossing over the Wapiti River. The analysis encapsulated the material, equipment, labour, and miscellaneous costs to install the HDD crossing. A preliminary list of the costs was created and then validated using HDD feasibility studies as well as industry professionals. Brothers HDD and Surerus Murphy, two contracting companies in Alberta, provided insight on costs related to the specific crossing [33] [10]. Additionally, two ball valves were included in the design of the pipeline so that the connecting sections could be installed at any point in the year. The overall cost of the proposed crossing can be found in Table 22 below and a more detailed view in Table 47. Once the list of costs was generated, Brothers HDD helped to determine the range of costs for a typical 315m NPS 48 crossing suited to the Wapiti River conditions. The costs are listed using a low-end and high-end range to account for the large variances between contractors. The variance was largely a result of different practices across contractors and equipment used in construction.

Table 22: Cost estimate for the Wapiti River crossing [33].

Costs		**Overall Cost (Low)**	**Overall Cost (High)**
Materials	Coating for Joints	Included in Welding	
	Coated Pipe	$ 373,912.50	$ 373,912.50
	Mud	$ 2,700.00	$ 2,808.00
	Water	$ 87,750.00	$ 91,260.00
	Fuel	$ 50,000.00	$ 62,500.00
	Ball Valve	$ 200,000.00	$ 200,000.00
	Casing	$ 160,000.00	$ 320,000.00
Equipment	Drill Rig	$ 600,000.00	$ 600,000.00
	Welding (+Coating and SideBooms)	$ 600,000.00	$ 600,000.00
	Crane	$ 192,000.00	$ 384,000.00
	Side Booms	Included in Welding	
	Drill Head	Included in Drill Rig	
	Reamer	Included in Drill Rig	
	Power Unit & Generators	$ 5,625.00	$ 6,875.00
	Water Pump	$ 36,000.00	$ 36,000.00
	Mud Mixing Tank	$ 9,375.00	$ 9,375.00
	Mud Pump	$ 50,000.00	$ 50,000.00
	Exit Mud containment Tanks	$ 625.00	$ 1,250.00
	Cuttings Tank	$ 625.00	$ 625.00
	Pipe Racks	$ 12,500.00	$ 37,500.00
	Testing Pigs	$ 10,000.00	$ 10,000.00
	Pipe Rollers	$ 100,000.00	$ 100,000.00
	Bending Machine	$ 20,000.00	$ 40,000.00
	Wire line Steering system	$ 19,500.00	$ 19,500.00
	Mud Motor	$ 48,000.00	$ 48,000.00
	Drill recorder	$ 87,500.00	$ 87,500.00
	Centrifuge	$ 40,687.50	$ 40,687.50
Labour/Construction	Labourers	$ 5,000.00	$ 7,500.00
	Hydro Testing	$ 8,000.00	$ 10,000.00
	Geotechnical Drilling	$ 6,000.00	$ 7,200.00
	Trucking of pipe	$ 80,000.00	$ 100,000.00
	Hydrovac	$ 31,250.00	$ 31,250.00
	Trucking	$ 11,000.00	$ 22,000.00
Geotechnical Investigation	Boreholes	$ 65,000.00	$ 65,000.00
	ERT Survey and Analysis		
	Seismic Refraction Survey and Analysis		
Miscellaneous	Land	$ 30,000.00	$ 30,000.00
	Drilling Mud Disposal	$ 9,140.63	$ 9,506.25
	Washroom	$ 1,250.00	$ 2,500.00
	Control Room	$ 1,250.00	$ 1,250.00
	Lights	$ 15,000.00	$ 22,500.00
Total		**$ 2,969,690.63**	**$ 3,430,499.25**

As seen in Table 22, the expected costs for this project ranges between $2.9 - $3.4 million. These costs were validated by other contractors such as Michels and Sureus Murphy [17] [46].

7.0 Second Iteration of Design Solution

As described in Section 4.2 Narrowing Down Ideas for Cost Reduction Solutions, the plan after completing the decision-making process was to focus on the drilling and reaming steps for cost reduction opportunities. Although these steps in the HDD construction process are time consuming and expensive, when discussing this path with industry professionals, there was not significant support [10]. The overall feedback was that these steps were already well defined and the ways to cut costs could lead to unsafe and more risk filled projects [10]. Numerous professionals advised to consider drilling mud and technologies to better understand subsurface conditions at the crossing location [10] [33] [49] [47].

In addition, support for focusing on drilling mud and subsurface mapping technologies increased while completing the Wapiti River crossing. While working through the process of designing the crossing, it became clear how important understanding the ground conditions under the water crossing is. Additionally, when determining the cost of drilling mud disposal for this crossing, it became evident how expensive this process is and if the volume of mud could be reduced slightly, it could have a significant impact on the project's overall construction cost.

After completing more research on the HDD construction process and talking with Paul Kelly from Sureus Murphy, subsurface mapping technologies were selected as the area to focus on for cost reduction opportunities [46]. This decision was made because although there is significant opportunity for cost reduction involving drilling mud, there is already plenty of research being completed on this subject [50]. To focus on a less researched subject allowed for more innovation and a larger probability of finding a unique solution. Additionally, the majority of the issues identified in the HDD construction process such bore hole integrity and equipment problems stemmed from limited subsurface knowledge. Therefore, selecting this path allowed for more issues to be addressed and had the largest opportunity to make a significant improvement for HDD construction costs.

8.0 Geophysics for Horizontal Directional Drilling Crossings

This section discusses the geophysical methods researched, how specific methods were selected for the solution, how the methods should be used for different projects, failure modes associated with the solution and its limitations.

8.1 Process for Geophysics Method Selection

Research was completed on what methods are currently used in the industry and what methods are used in other industries such as military, archeology, and construction. The research revealed that it is uncommon for projects to complete thorough geophysical studies on HDD water crossings [10]. In cases where studies were completed, land data was gathered, but rarely were waterborne techniques utilized to determine the ground conditions directly under the waterbody [10]. In most cases, the minimum ground investigation requirements are completed, which include drilling boreholes on either side of the water body [33]. After this, it is common practice to extrapolate soil conditions under the waterbody, which often leads to inaccurate results [10]. Once this issue was identified, specific geophysical techniques were investigated which included multichannel analysis of surface waves (MASW), seismic refraction, seismic reflection, and electrical resistivity tomography (ERT). The method's advantages and limitations were outlined which helped determine which methods were most suitable for HDD water crossings. From the research and discussions with industry professionals, it was concluded that ERT or seismic refraction were the most appropriate methods [6]. The research completed on these two methods are shown below in Section 8.2 Background Research and the research on MASW and seismic reflection is in Appendix IX – Additional Geophysics Background Research.

More research was completed on how these techniques could be utilized for water crossings. A research paper was found suggesting that ERT and seismic refraction could be applied in conjunction to improve HDD water crossing projects [51]. This paper written by Alastair McClymont et al. outlines how the ERT and seismic refraction methods could be applied in different scenarios [51]. The two methods compliment one another. ERT is used to determine the soil profiles and can also be used to determine the bedrock profile if there is a contrast in electrical resistivity between the bedrock and overburden [51]. When there is not significant contrast and the bedrock layer is difficult to locate, seismic refraction can be used to validate the bedrock profile [51].

8.2 Background Research on Geophysical Methods

To develop a better understanding of ERT and seismic refraction, more in-depth research was completed on these geophysical methods. The findings are summarized in the following sections.

8.2.1 Electrical Resistivity Tomography

The electrical resistivity tomography method maps the subsurface conditions by measuring the apparent electrical resistivity [52]. The resistivity of the subsurface can vary due to the water content and composition [52]. Materials that have low electrical resistivities are finer grained like clay or silt [51]. Sands and gravels are coarser and therefore will have higher resistivities [51]. This method works by using a pair of current electrodes to inject electrical current into the earth and using a pair of potential electrodes to measure the potential difference [52]. Many different configurations of the electrodes and tests need to be done to gather the data [52]. The data is processed and can produce images that show how the resistivity varies in the subsurface [52]. ERT is useful for determining areas that contain granular material which can lead to borehole instability or loss of fluid to formation [51]. The equipment required to complete these tests include a resistivity metre and electrodes [52]. A set up of the equipment is shown in Figure 12 below.

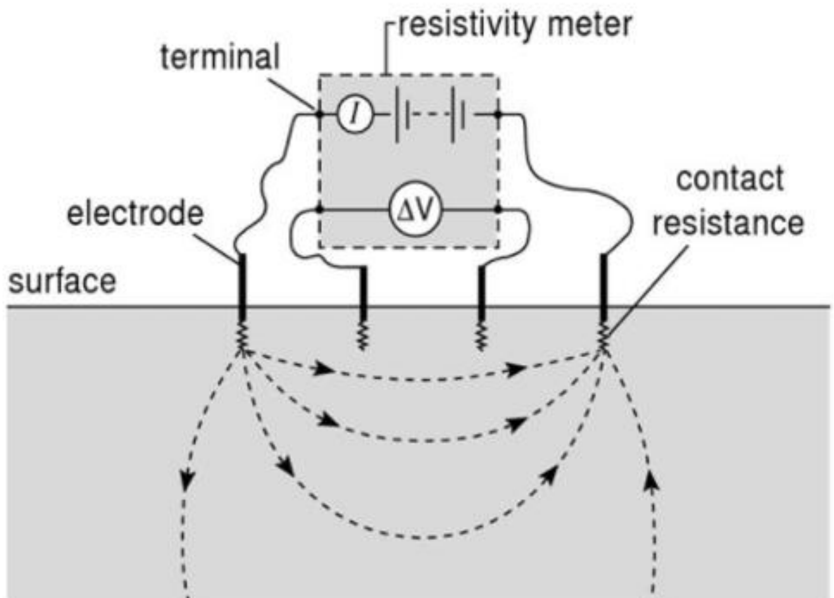


Figure 12: The equipment and set up for the electrical resistivity method [50]. The resistivity meter is a current meter and voltmeter all in one [50].

An advantage of using this method is that it is versatile compared to other methods used in the industry [52]. A disadvantage of using this method is that the resolution of the results is not as high as some other available methods and can make interpretations of the produced images difficult [52]. Another disadvantage is that the depth that can be reached using this method is dependent on the maximum separation of the current electrodes [52]. The separation of the electrodes depends on the space that is available when completing the ground investigation.

8.2.2 Seismic Refraction

Seismic refraction uses refraction of the seismic waves to determine the subsurface conditions [53]. A seismic source is used to generate energy [51]. Ones that are commonly used are striking of a sledgehammer against a plate on the ground or small explosives [51]. This method uses Snell's Law which outlines the relationship between wave angles and refraction when moving through different kinds of soil [53]. When waves move through different kinds of soils, their velocity changes [53]. Additionally, when the waves pass from one soil condition to another, the waves are refracted [53]. This method also measures the time it takes for the waves to return to the surface using geophones to determine the depth profile [53]. The typical set up for both land and water applications are shown in Figure 13 and Figure 14 below.

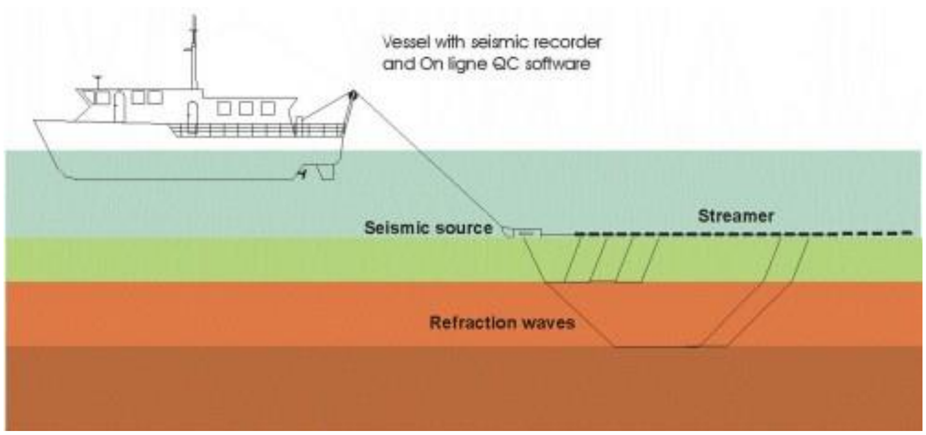


Figure 13: The equipment and set up for the seismic refraction method for water applications [53].

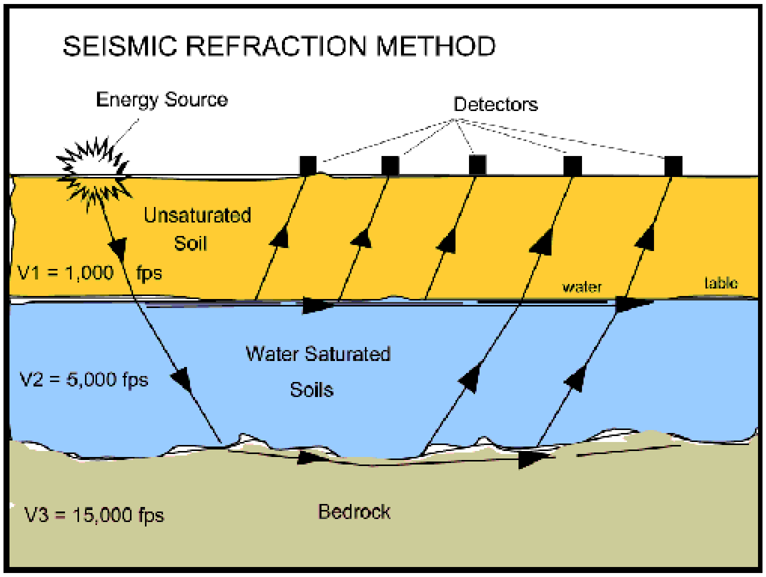


Figure 14: The equipment and set up of the seismic refraction method for land applications [53].

An advantage to using this method is that it is not as expensive as other available methods [54]. Another advantage is that this method is very useful for identifying the bedrock layer [51]. A disadvantage is that this method has a depth limitation of less than 100 metres [47]. Additionally, this method works best when the seismic velocity of layers increases with the depth [54]. For example, if clay, which is a high velocity layer, is above sand, which is a low velocity layer, then the deeper layers may not be able to be detected [54].

8.2.3 Waterborne Electrical Resistivity Tomography and Seismic Refraction

The waterborne methods of ERT and seismic refraction have the same principles as the land techniques but require different equipment [51]. For ERT, the electrode array can either be towed as a streamer behind a boat or attached to a tensioned rope across a narrow waterbody [51]. This can be seen in Figure 15 and Figure 16, respectively.

[51].

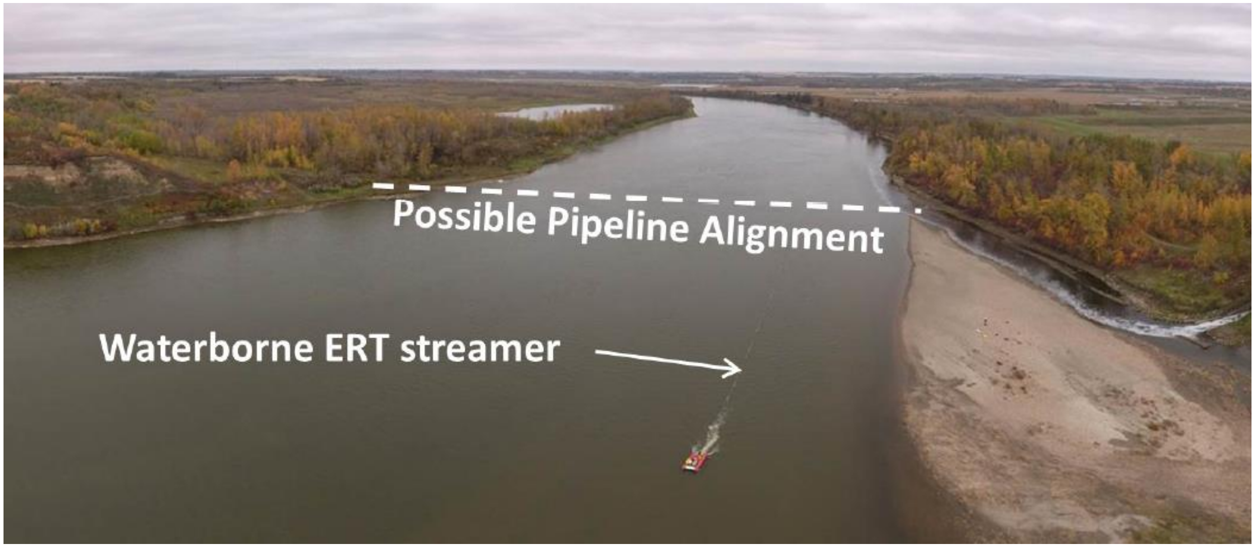


Figure 15: Photo of a streamer attached to the back of a boat to take ERT or seismic refraction surveys [51].

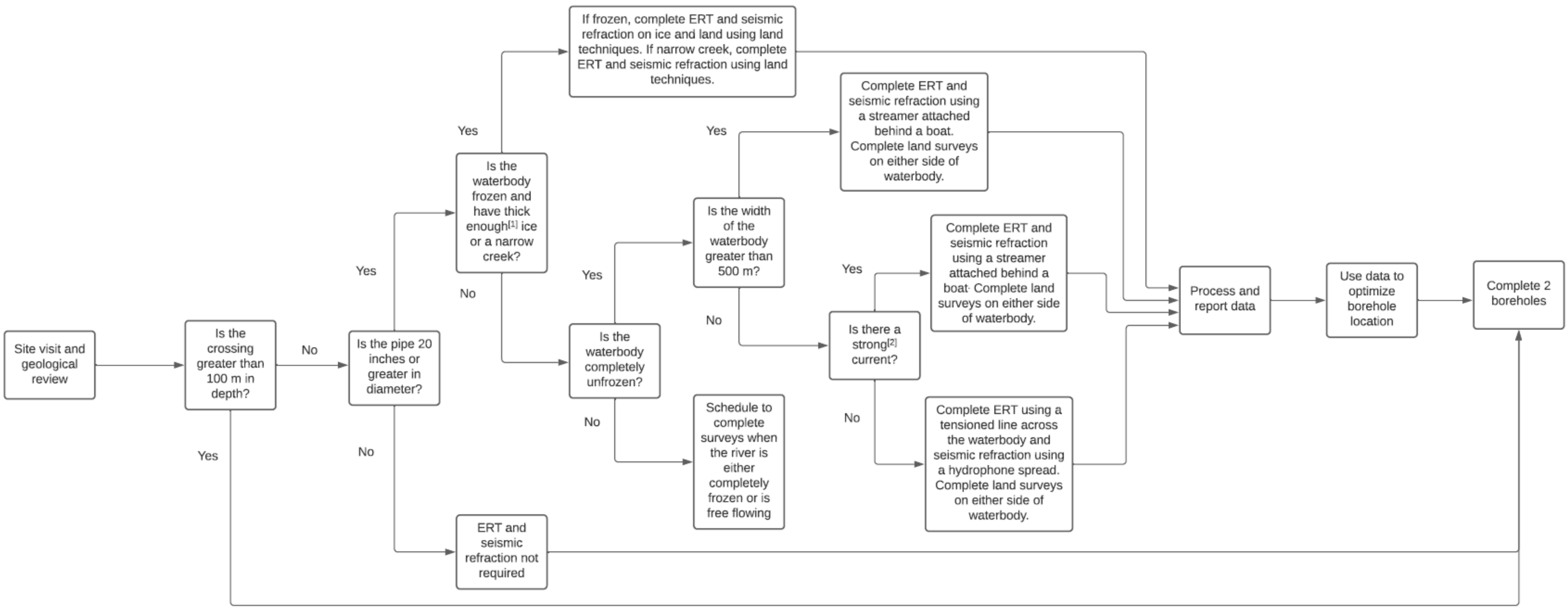
Figure 16: Photo of an ERT cable that is attached to a tensioned rope that is strung across a narrow river [51].

Similar methods are used for seismic refraction, where instead of geophones, hydrophones are used [51]. They can be attached as a streamer behind a boat in a similar manner to the ERT waterborne technique as seen in Figure 15, or they can be laid out as a spread in the water as shown in Figure 17 [51]. The seismic source also differs for water applications and is often a marine airgun or low energy acoustic type source [51].

Figure 17: Photo of a seismic survey with a hydrophone spread in water [55].

9.0 Geophysics Application Recommendation

As every water crossing is unique, ERT and seismic refraction surveys can be completed in a variety of ways. Figure 18 outlines how geotechnical surveys should be conducted depending on the conditions of the water crossing. This flowchart was created using information from the paper written by Alastair McClymont et al. and from meetings with industry professionals [10] [55] [33] [47] [56].



[1]: Thick enough ice is defined as ice that has a thickness of 10" or greater in order to safely support a medium sized truck.
[2]: A strong current is defined as water flow that would cause for the cables to become disloged or damaged if held in place by a tensioned line.

Figure 18: Flowchart that can be used to determine if and how ERT and seismic refraction should be used for different HDD water crossings.

The flowchart begins with the first step that should be taken when completing a geotechnical survey, which is reviewing available information on the land [57]. This includes completing a desk study to determine other utilities or if there are published papers on projects that were completed in the area [57]. It is also advised to go to the water crossing site to determine its conditions and logistics for access [16].

The next phase is to identify if the crossing is greater than 100 metres in depth. This is required due to the geophysical methods depth limitations. ERT and seismic refraction cannot produce clear, useful images deeper than this depth and therefore should not be used with crossings that drill this far into the ground [10]. Instead, it is suggested that two boreholes should be completed on either side of the crossing [10]. The goal of these boreholes is to determine the bedrock depth because it can be assumed that once bedrock is reached, it is consistently bedrock below that point [33]. Therefore, if drilling deeper than the bedrock depth, consistent ground conditions will be encountered, and the correct equipment can be prepared for those conditions.

For crossings that are not greater then 100 metres in depth, the next question that needs to be addressed is if the pipe is 20 inches or greater in diameter. Pipes with diameters smaller than this experience fewer complications and are easier to install [33]. It was recommended by Jamie McClennon, owner of Brothers HDD, that geophysical techniques do not need to be used for crossings that have small pipe diameters [33]. Instead, he recommended that two boreholes are completed on either side of the waterbody to get an understanding of the ground conditions in the area [33].

For pipes that are greater then 20 inches in diameter, geophysics should be used as these are the HDD projects that are more complicated and experience more issues [33]. To determine how to apply ERT and seismic refraction, the next aspect that needs to be addressed if is the waterbody is frozen and has thick enough ice, or if it is a narrow creek (width of waterbody is less than 19 meters) [58]. As seen in the flowchart, ice is required to have a thickness of 10 inches or more to support a medium sized truck [59]. This is important to identify because if the waterbody is frozen and can support the required equipment or if it is a narrow creek, then land techniques can be used for the ERT and seismic refraction surveys [51]. In the frozen scenario, the ERT electrodes can be placed in the ice and geophones could be used for the seismic refraction survey [51]. If it is a narrow creek, the waterbody's width is small enough that the land techniques can still detect the ground conditions under the waterbody [51].

If the waterbody does not have thick ice or is not a narrow creek, it needs to be determined if the water is fully thawed. These geophysics methods should not be used for a water crossing that is not completely frozen with thick ice or not completely free flowing [55]. These conditions make it difficult to use the waterborne ERT and seismic refraction techniques; completing surveys during these times should be avoided [55]. Alternatively, if the waterbody is free flowing and not partially frozen, then there are multiple paths that could be taken to complete the geophysical surveys.

If the width of the waterbody is greater than 500 metres, then the method discussed in Section 8.2.3 Waterborne Electrical Resistivity Tomography and Seismic Refraction, which uses the streamers attached behind a boat, should be used [55]. Both the ERT and seismic refraction surveys should be completed in this manner over the water body [55]. In addition, both sides of the water crossing should also be surveyed using land techniques [55].

Alternatively, if the width of the waterbody is less than 500 metres, then the current of the waterbody comes into consideration [55]. A waterbody with a strong current could have a water velocity in the range of 1.6 m/s to 3.1 m/s [60]. If the water velocity is below this range, then it could be concluded that the waterbody has a weak current [60]. The current is dependent on multiple factors such as the slope gradient, roughness of the waterbed, and the tides [60]. If the current is strong and would dislodge or damage the cables if a tensioned line were to be used, then the method should be used with the streamers attached to a boat for both the ERT and seismic refraction surveys [55]. Although, if the current is not strong, then a tensioned line with the ERT cables and the hydrophone spreads should be used [55]. In both these scenarios, the surveys should also be conducted on both sides of the waterbody using land techniques [51].

Following the scenarios where ERT and seismic refraction methods were used, the next step in the flowchart is for the data to be processed and reported [51]. This allows for the data gathered to be converted to an image outlining areas with different soil conditions as well as the location of the bedrock surface [51]. An example of what these images may look like is shown below in Figure 19. The image depicts the results from attaching the streamers to the boat for both the ERT and seismic refraction surveys.

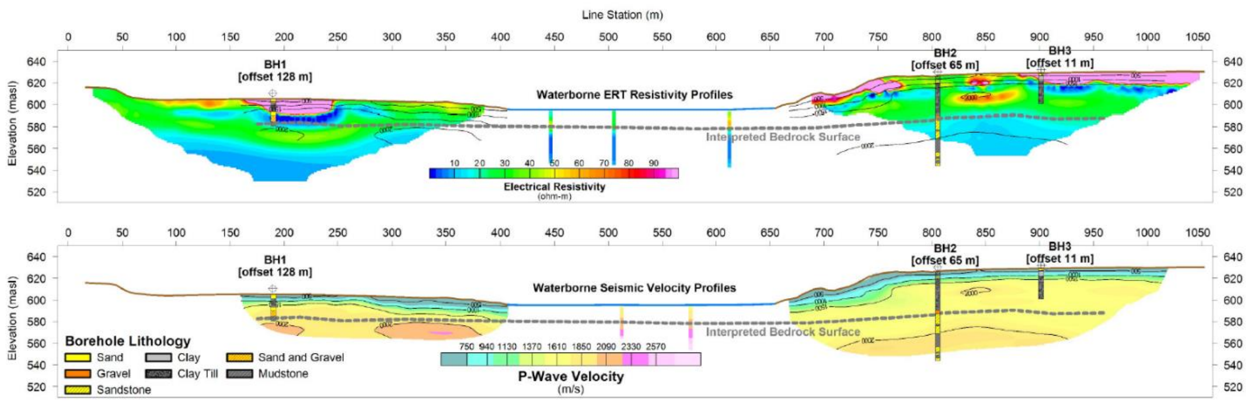


Figure 19: Example of images produced using geophysics. The top image is the image produced using ERT and the bottom image is produced using seismic refraction [51].

After receiving and analyzing the processed data, the next step entails using this image to optimize the location of the boreholes on either side of the waterbody [47]. The goal of the boreholes is to obtain soil data and extract important parameters for the water crossing design [47]. The soil parameters are used to tailor the design of the crossing to the specific environmental conditions. For example, they can be used to model the stresses on the pipe, these calculations can be seen in Appendix VIII—B Pipeline Crossing Parameters. An optimal location for boreholes would be one that provides an accurate representation of the area and is as close to the drill path as possible, within regulations [33].

9.1 Failure Modes and Effects Analysis for Geophysical Solution

A FMEA was completed on conducting a geotechnical survey using geophysics and boreholes and can be found in Appendix XI – Geophysics Failure Modes and Effects Analysis. The top five failure modes related to either the data collected being inconclusive, or equipment being destroyed, and are listed below in Table 23. Highlighting the top five failure modes allowed for mitigation strategies to be outlined for eliminating or minimizing the effects the failures could have on the project.

Table 23: Top five failure modes from geophysical methods FMEA.

Type of Geotechnical Method	Failure Mode	RPN	Risk Mitigation
Seismic Refraction	Geophones do not detect the waves.	280	Review the data on-site to ensure collection was successful and all required inputs were retrieved. Review areas of concern or uncertainty from the survey so that mitigation strategies can be implemented to reduce the risk of failure occurring.
Seismic Refraction	Cables get caught along water crossing.	168	Study the area prior to conducting the survey and have people prepared with rods on the river sides to untangle the hydrophones if it occurs.
Data Processing and Analysis	After completing all surveys, anomalies occur and cause complications.	128	If the data concludes there may be an anomaly, consider doing additional investigation to prevent further complications in the construction process. A borehole can be utilized to verify results.
Seismic Refraction	Geophone that is used on ice gets water damage and breaks.	84	Ensure contracting crew is equipped to handle conditions on site and brings all equipment in case of accidents.
Boreholes	Boreholes do not go as deep as required for the crossing.	81	Review construction plan and worst-case scenario for depth to ensure boreholes collect all required data. Ensure a contractor is present while the boreholes are being completed [57].

9.2 Solution Limitations

Although this solution has been validated and supported by many industry professionals –as will be discussed in Section 11.0 Value and Validation– there are some limitations. A limitation of these geophysics methods is that boulders can go undetected [10]. Non-anticipated boulders can affect the drilling process of an HDD project resulting in delays [10]. For example, an HDD project completed by Surerus Murphy encountered this issue, costing them $300,000 in delays [10]. Although this event was unavoidable, the inability of ERT and seismic refraction to detect boulders poses a limitation.

Another consideration is that airguns used for seismic refraction surveys in marine environments can be expensive and harmful to aquatic species [51]. Progress is being made to find low energy acoustic type sources that overcome these challenges [51]. Additionally, these alternatives are better suited for shallow rivers and streams [51]. The seasonality of these geophysical methods is also a limitation as they are best equipped for either completely frozen or thawed waterbodies [55]. These surveys should not be completed if these conditions are not met.

Finally, there is a limitation with the continuity of the surveys for wide or high-current waterbodies. As seen in Figure 19 above, the data gathered using a boat provided information for small sections under the waterbody. This is a result of the surveys being completed perpendicular to the pipeline path, see Figure 15 [51]. The results from these surveys are comparable to that of water boreholes at a fraction of the cost. This data can be supplemented by taking additional surveys along the path to minimize risks and uncertainty.

10.0 Safety and Regulatory Requirements for Geophysics

After finalizing the solution, safety and regulatory requirements were researched using online databases. These archives pertained to boreholes, ERT, seismic refraction and the general steps to conduct a geophysical survey. Table 24 below lists the land and marine regulatory guidelines to carry out a geophysical investigation. The relevant information from these documents was summarized, however the documents in their entirety should be reviewed and put into practice before completing a project. The relevant sections from each topic of interest and the value it added to the project can be found in Appendix X – Safety and Regulations for Geophysical Surveys.

Table 24: Safety and regulatory guidelines for geophysical surveys.

Topic of Interest	Relevant Information
Land Regulations	• Training Required [61] • Incident Reporting and Investigation [61] • Lightening Protection [61] • Ice Safety [61] • Boreholes [62] • Electrical Resistivity Tomography [63] [64] • Seismic Refraction [65]
Marine Regulations	• Small Boat Operations [61] • Safety Training [66] • Incident Reporting [66] • Personal Protective Equipment [66] • Deployment and Recovery of In-Sea Equipment [66] • Environmental Mitigations [67]
General Safety and Regulations	• Alberta Occupational Health and Safety Regulation [40] • Planning Horizontal Directional Drilling for Pipeline Construction [16]

11.0 Value and Validation

The rationale for completing research and delivering an optimized HDD crossing design is to minimize time and cost while maximizing safety. The forms of value that can be realized in this project are the monetary, environmental, and social impacts. Additionally, to substantiate this value, the design required validation. This was achieved by meeting with industry professionals and a cost assessment on the Wapiti River crossing.

11.1 Value of Solution

After validating the design with industry professionals, essential details to prove the solution's value were gathered. The results can be found below in Table 25. Each value item expands on the monetary, environmental, and social value it provides. The continuous themes are that the value items reduce environmental damage to the area, improve the company's reputation within the industry, and save money by mitigating risk. The listed items were deemed legitimate as they were reviewed and agreed upon by more than three different industry professionals with experience in HDD projects and conducting geotechnical surveys. The information gathered proves the solution achieves level 3 external metrics which can be found in Section 1.8 Project Metrics. Each value, their impact on the project, and their effect on the individuals involved are discussed in the sections below.

The predominant theme of the project's derived value can be tied to its ability to reduce risk. Completing HDD projects is a highly varying process that goes hand in hand with delays and unexpected costs. The main factor for this variance can be tied to the unknown subsurface conditions as outlined in Section 6.3 Failure Modes and Effects Analysis for Wapiti River Crossing. Therefore, by eliminating the risks associated with these subsurface conditions, project costs can be reduced alongside its environmental impact.

Table 25: Outline of monetary, environmental, and social value of design solution.

<table>
<tr><th>Value Item</th><th>Description</th><th>Monetary Impact</th><th>Environmental Impact</th><th>Social Impact</th></tr>
<tr><td>Improve bid offers</td><td>It is quite common for contractors to mark-up their bids for projects with limited ground investigation.
Solution Impact
By utilizing ERT and seismic refraction to complete a more thorough ground investigation in advance it is likely to result in lower contractor bids and more transparent bid assessments.</td><td>One contractor interviewed said he will increase a bid by up to 50% to offset the risk and avoid these types of jobs [46].

The table below outlines the potential cost increases with a 20% and 50% cost increase.

<table><tr><td>Markup</td><td>Cost (Low)</td><td>Cost (High)</td></tr><tr><td>–</td><td>$3.0 mm</td><td>$3.5 mm</td></tr><tr><td>20%</td><td>$3.6 mm</td><td>$4.2 mm</td></tr><tr><td>50%</td><td>$4.5 mm</td><td>$5.25 mm</td></tr></table>
*Million (mm)</td><td>N/A</td><td>Providing contractors with a confident understanding of the subsurface conditions would attract lower bids and create a positive and professional reputation in the industry. More contractors would be willing to work with a client that minimizes risk and supplies them with the data required to complete the project successfully.</td></tr>
<tr><td>Less standby time</td><td>During HDD construction ground knowledge limitations results in standby time. This is when the construction crew cannot proceed due to unforeseen soil types and ground conditions as these will impact the tool choices.
Solution Impact
A complete investigation into the location of different soils and ground anomalies will allow for a more robust</td><td>According to two contractors almost every HDD project will have at least two days of standby time due to unexpected conditions [68] [69]. **The cost implication of this is 75-80% of a shift cost – typically between $20,000-$40,000. Additionally, on projects with limited ground in**vestigations this standby time is likely to increase from a few days to a week [68] [69].

The table below outlines the potential cost impact of standby time.</td><td>Workers, trucks, machines, and loud noises would drive away species living in the area. Less standby time ultimately shortens the length of the project. This in turn allows the area to return to its natural condition and animals to come back to their habitat near the crossing.</td><td>Less standby time would benefit the clients/contractors as it proves their project planning was successful. This in turn will encourage other companies and crews to work with them because they are organized and efficient. The less time spent on a project, the more time available to complete other projects.</td></tr>
</table>

<table>
<tr><th>Value Item</th><th>Description</th><th>Monetary Impact</th><th>Environmental Impact</th><th>Social Impact</th></tr>
<tr><td></td><td>construction plan
and eliminate standby time.</td><td><table>
<tr><td>Standby Time</td><td>Cost (Low)</td><td>Cost (High)</td></tr>
<tr><td>1 days</td><td>$20,000</td><td>$40,000</td></tr>
<tr><td>2 days</td><td>$40,000</td><td>$80,000</td></tr>
<tr><td>1 week</td><td>$280,000</td><td>$560,000</td></tr>
</table></td><td></td><td></td></tr>
<tr><td>More accurate equipment buying</td><td>When developing a construction plan, contractors will typically over-buy on equipment to hedge their risks. For example, extra drill heads will be purchased in case unforeseen conditions wear out the head prematurely.
Solution Impact
Understanding the conditions surrounding the drill path will help to better accurately model the
equipment required and specific quantities. This
will eliminate the need to over purchase and reduce construction costs.</td><td>As seen in Figure 20 the costs associated with HDD project and in particular the equipment can be significant. Therefore, by increasing your certainty in ground conditions and project requirements the buying of excess equipment can be eliminated.</td><td>If less equipment is required, it will reduce the area used to store the machinery. This allows more of the surrounding habitat to remain natural and less work in the end during site remediation.</td><td>N/A</td></tr>
</table>

Value Item	Description	Monetary Impact	Environmental Impact	Social Impact
More accurate equipment use	The HDD construction process requires a significant amount of detail to plan and time the equipment use. Solution Impact A detailed understanding of the drill path conditions can allow for optimization on equipment use.	The process of changing a tool while drilling can be a very expensive process therefore ensuring that the correct tools are being used at all times is pivotal for cost efficiency. For example, to change drill heads on a rig has an expected cost of $300,000 dollars by improving the mapping of ground conditions, a plan can be developed on what equipment should be used and when, with a decreased risk in unexpected conditions [34].	Understanding the soil conditions allows for the drill head to be changed a minimal number of times which in turn disrupts the environment and species living around it less.	N/A
More accurate amount of drilling mud	Drilling mud is used throughout the drilling, reaming and pullback process to stabilize the drill path and lubricate the equipment. It is expensive to purchase and manage during the construction process. Solution Impact Known soil conditions and formations will allow for more accurate calculations on the required drilling mud. Therefore, it will allow for a reduction in excess drilling fluid.	Soil conditions can be harnessed to optimize drilling fluid consistency and quantities during HDD projects. This will ultimately result in more accurate estimations on fluid requirements, meaning fewer units can be purchased [68] [70].	No excess drilling mud ultimately means there will be less to dispose of and release into the environment. Also, less drilling mud reduces the risk of having frac-outs while drilling due to less fluid pressure on the surrounding soil.	N/A

Value Item	Description	Monetary Impact	Environmental Impact	Social Impact
Decreased drilling mud disposal costs	The process of disposing of drilling mud can be one of the largest cost components of an HDD project. This is due to the transport costs of the mud and sizeable land disposal costs. Solution Impact By reducing the amount of drilling mud required and eliminating over purchasing, disposal costs can be decreased resulting in significant financial savings.	Similar to above reducing the amount of drilling fluid used can result in significant cost savings as the disposal of drilling mud can be one of the largest expenses of a project [50]. For example, a 1km crossing under the Peace River cost $3.25 mm to dispose all of the drilling mud [46].	Fewer trucks and general ways to transport drilling mud would be required which releases less pollution into the air. Also, less drilling mud to dispose of would alleviate its impact on the environment and groundwater.	Surrounding communities will be more willing to work with or support pipeline projects if there is a minimal impact to the surrounding environment. This will increase encouragement for the industry and lessen the carbon footprint of these projects.
Optimize composition of drilling fluid	For typical HDD projects, the drilling mud composition is estimated based on limited information. This could result in a composition that is not optimal for the conditions and lower the efficiency. Additionally, if additives are required to better the composition after the project commenced, this can lead to delays and standby time. Solution Impact Having more information on the soil conditions can allow for an optimal composition to be prepared at the beginning of the project and result in better efficiency.	N/A	Understanding the soil conditions allows for the drilling mud composition to be altered ahead of time to suit the environment which in turn could require less drilling mud.	N/A

Value Item	Description	Monetary Impact	Environmental Impact	Social Impact
Borehole optimization	Boreholes are often completed on HDD water crossings at either side of the water body, but in arbitrary locations. This can still be helpful to get an idea of the soil conditions in the area, but they could be more strategically placed to get the most out of the data. Solution Impact Doing ERT and seismic refraction prior to the borehole completion can allow for borehole location optimization and be able to gather data that is more useful when designing the HDD crossing.	Boreholes associated with ground investigation can quickly become a large project expense as they are typically implemented every 250-300m and each cost $35,000-$40,000 [46]. However, borehole locations are chosen somewhat arbitrarily along the drill path and due to the constantly changing terrain can often be misleading on what soil types are more widely present. Therefore, to ensure the boreholes are optimized for accurate soil representation a need for additional boreholes can be eliminated.	If borehole location were optimized, less boreholes would be required to be drilled. This means less land disturbed and therefore less of an environmental impact.	N/A
Optimize amount of casing required	When selecting the amount of casing to install on HDD crossings, the contractors often select casing that is longer than required to minimize the risk of fluid loss to the formation and the probability that the borehole will collapse. Solution Impact By having more knowledge on the subsurface conditions, the amount of casing required can be selected to still mitigate the	Pipeline casing is an extremely challenging aspect of HDD installations due to the significant expense and persnickety nature of installation. In an interview with a contractor, it was mentioned that by utilizing increased geotechnical surveys on a recent project they were able to shorten the casing by 30 meters and ultimately save $400,000.	If less casing is required, then less land will be disturbed. This will lower the environmental impact of the project and will not harm the earth or potential habitats as significantly.	N/A

Value Item	Description	Monetary Impact	Environmental Impact	Social Impact
	risks, but it can be minimized to reduce costs.			
Optimizes drilling path location	Typical HDD projects only complete two boreholes on either side of the water crossing and then extrapolate what the soil layers may look like under the water body. This leads to risk when designed the drill path location as the soil conditions are estimated and not completely known. **Solution Impact** By knowing the soil layers under the water crossing, the drill path can be optimized to go through the soil layers that are most compatible for drilling and to minimize the probability of the borehole collapsing.	Optimizing the drilling path location has the potential to decrease cost savings by selecting the optimal soil types for drilling. Some examples of areas for saving include • Faster drilling time • Reduced wear on drill head due to soil type • Eliminating need for casing • Faster and fewer reaming passes due to soil type • Less drilling mud required for crossing	If the optimal drilling path is determined, then there is a lower chance that the borehole collapses. This impacts the environment because if a borehole does collapse, a new hole is drilled in a nearby area. This disturbs even more of the land than originally planned for.	If the drilling process goes smoothly and less borehole collapses occur because of using the geophysical methods, this could create a reputation within the industry of high success and skill. This could lead to more opportunities or have the chance to change industry standards.
Fewer boreholes required	Usually, two boreholes are drilled within 250-300m of the entry and exit points. More than two boreholes may be required to understand the subsurface conditions if other geotechnical surveys are not used. **Solution Impact** Using ERT and seismic refraction will ensure	As previously mentioned, **boreholes have a** significant associated cost therefore eliminating the requirements for additional boreholes can save on cost.	With fewer drilled holes into the earth, the smaller the environmental impact. Less land or habitats gets disturbed.	N/A

Value Item	Description	Monetary Impact	Environmental Impact	Social Impact
	at most two boreholes have to be drilled as they will provide more data for interpretation of the area. This will in turn save money as it is cheaper to use ERT and seismic refraction than drilling additional boreholes.			
Less invasive for the environment	Unlike boreholes ERT and seismic refraction are both non-invasive survey techniques with respect to the environment. Drilling into the ground causes vibrational disruption to the surrounding land, and in turn animals living nearby. Solution Impact Using ERT and seismic refraction will ensure the least amount of altering is done to the environment and the area can remain the same.	N/A	Using geophysical methods does not require the ground to be disturbed to gather subsurface data. The alternative for gathering more data would be to drill more boreholes which affects and harms the environment.	Selecting methods of ground investigation that are less invasive could lead to a good reputation within the industry for taking careful consideration of the environment.
Avoids the use of water boreholes	Water boreholes are very invasive to the marine environment and are very expensive. Most of the time, contractors will choose not to do this because of the time and money involved, leaving the soil layers under the riverbed to be extrapolated	At this point in time a cost estimate for water boreholes has not been found, however Ben McClement, a geophysics expert said they can run for double the price of a regular borehole [71].	Water boreholes require the waterbody and its ground underneath to be disturbed to drill the borehole. This has the potential to affect the water, the surrounding wildlife, and the earth	By selecting alternative methods for subsurface mapping under waterbodies that impact the environment less, it could change industry practice. More companies may adopt this method to

Value Item	Description	Monetary Impact	Environmental Impact	Social Impact
	from boreholes drilled on either river side. **Solution Impact** Using ERT and seismic refraction will allow only the surface of the water to be used leaving the marine species untouched. Any vibrational disturbances will be minimal and not harmful.		underneath. This process is very invasive, therefore using geophysical methods to determine the conditions under the waterbody is better for the environment.	lower their environmental impact.
More accurate studies and screening for projects can decrease reputational risk	Clients who do not provide contractors with the subsurface information they need cause issues and many unknowns while completing an HDD project. This leads to bad business and a poor reputation within the industry. **Solution Impact** Completing further geotechnical surveys rather than just boreholes will allow sufficient information of the area to be provided to the construction crew. This ensures a smooth process with minimal risk and an inclination for companies to work together again.	A better reputation in the industry is likely to yield an increased number of contractor bids on projects, and in turn lower project bids.	N/A	Providing thorough information to the construction crew about the ground conditions and eliminating some risk involved with the project allows for more proper planning and organization of the project. Providing this information to the contractors makes their jobs, and ultimately the whole project, go smoother. The result of groups having a positive experience working together has a large impact on future projects and opportunities of them working together again. It also builds a reputation and can provide more

Value Item	Description	Monetary Impact	Environmental Impact	Social Impact
				opportunities on other projects in the future.

11.2 Validation of Proposed Solution

Section 11.2 outlines the various methods used to validate the proposed design solution and their respective results.

11.2.1 Validation of Proposed Solution by Industry Professionals

The outlined validation plan for this project was to speak with industry professionals and get their input, feedback, and advice on the final solution and recommendations. This has been instilled throughout the duration of the project to validate the solution. As the design solution encompassed pipeline design, budgeting, and geophysics, various experts in each respective field were contacted to validate different portions of the final solution. Table 26 below summarizes the industry professionals consulted to validate the design and the project component that was validated.

Table 26: Outline of project validation.

Industry Professional	Validated Item	Description of Meeting
Katia Greco [30]	Wapiti River crossing design	Katia verified that the design met all codes and would be appropriate for installation utilizing AutoPIPE. The pipe stresses, pipe angles, and depth were all confirmed fit for construction.
Ben McClement [71]	Proposed design solution	Ben verified that the proposed design solution was appropriate for its intended use and would effectively map subsurface conditions. Additionally, Ben validated the cost of the solution used in the cost estimate in Figure 20.Ben provided valuable insight from the perspective of a geophysicist and professional engineer.
Sam Wilson & Craig Lenderbeck [68] [69]	Proposed design solution	Sam and Craig from CCI Solutions validated the proposed design solution and provided feedback on its application. Sam is a trenchless engineer manager and Craig is a construction manager.
	Wapiti River cost estimate	Sam and Craig validated the cost estimate for the proposed crossing.
	Construction plan	Sam and Craig reviewed the proposed construction plan from Table 45 to ensure all timelines were feasible and accurate to real-life projects.
Paul Kelly [46]	Proposed design solution	Paul reviewed and validated the proposed solution of using ERT and seismic refraction to map subsurface conditions on HDD projects.

Industry Professional	Validated Item	Description of Meeting
	Construction plan	Paul reviewed the proposed construction plan to ensure all timelines were feasible and accurate to real-life projects.
	Wapiti River cost estimate	Paul validated the cost estimate for the proposed crossing.
Jamie McLennon & Des Ross [33]	Proposed design solution	Jamie and Des from Brothers HDD validated the proposed ERT and seismic refraction solution.
	Wapiti River cost estimate	Jamie and Des helped develop and validate the cost estimate created for the Wapiti River crossing.
	Construction plan	Jamie and Des provided their extensive experience working on HDD projects to help develop and validate an accurate construction timeline for the Wapiti River Crossing.
Kshama Roy [70]	Proposed design solution	Kshama validated the proposed ERT and seismic refraction solution.

11.2.2 Validation by Cost Analysis on Wapiti River Crossing

As previously detailed in Section 6.4 Original Economic Analysis for Wapiti River Crossing, a cost estimate for the Wapiti River was created. This estimate included all basic costs for a typical HDD crossing. However, once the design solution was finalized the cost estimate was updated to reflect the expenses of conducting a geotechnical investigation.

Figure 20 below is a detailed breakdown of the expected costs of completing an HDD crossing over the Wapiti River with the solution implemented. The table presents the total expenses of the crossing from four perspectives. The two right-hand columns represent the project cost range for a crossing completed with ERT and seismic refraction surveys. Of these two columns the left-hand side is a low-end cost range for the project and conversely high-end on the right. These ranges were included to account for the variable costs of an HDD project, as they are dependent on contractors and equipment rental prices. To the left of these columns are the cost estimates for a project without a thorough ground investigation. Ben McClement, a geophysics expert at Geophysics GPR was contacted to discuss the costs of these surveys. Ben believed the costs to range from $80,000-$100,000 for a 315m crossing [71]. These costs can be seen on the estimate with green arrows adjacent to them. These arrows represent the cost increase required for the solution. During an interview with Sam Wilson and Craig Lenderbeck from CCI Solutions, it was revealed that projects which do not complete a thorough ground investigation prior to construction can expect to payout anywhere from 15-200% in additional costs [68] [69]. Therefore, a line item representing this additional cost has been included at the bottom of the cost estimate. These costs are due to construction delays, unexpected soil formations, equipment failures, and drilling complications stemming from unknown conditions. To outline how the solution reduces the additional cost, red arrows have been incorporated into the estimate anywhere a decrease is expected.

							Without Solution Implemented		With Solution Implemented	
Costs		**Quantity (Low)**	**Quantity (High)**	**Hours to Complete**	**Cost (Low)**	**Cost (High)**	**Overall Cost (Low)**	**Overall Cost (High)**	**Overall Cost (Low)**	**Overall Cost (High)**
Materials	Coating for Joints	N/A			$5,000/weld	$10,000/weld	Included in Welding		Included in Welding	
	Coated Pipe	200m			$1,177.50/meter		$ 373,912.50	$ 373,912.50	$ 373,912.50	$ 373,912.50
	Mud	292.5m^3	304.2m^3		$12/bag(~1.3m^3)		$ 2,700.00	$ 2,808.00	$ 2,700.00	$ 2,808.00
	Water	585m^3	608.4m^3		$150/m^3		$ 87,750.00	$ 91,260.00	$ 87,750.00	$ 91,260.00
	Fuel	2,000 L/day		18 shifts (9 days)	$4,000/day	$5,000/day	$ 50,000.00	$ 62,500.00	$ 50,000.00	$ 62,500.00
	Ball Valve	2			$100,000/valve		$ 200,000.00	$ 200,000.00	$ 200,000.00	$ 200,000.00
	Casing	20m	40m		$8,000/meter		$ 160,000.00	$ 320,000.00	$ 160,000.00	$ 320,000.00
Equipment	Drill Rig	1		6 shifts (3 days)	$3,000/meter	$5,500/shift	$ 600,000.00	$ 600,000.00	$ 600,000.00	$ 600,000.00
	Welding (+Coating and SideBooms)	1	2				$ 600,000.00	$ 600,000.00	$ 600,000.00	$ 600,000.00
	Crane	2	4	4 shifts (2 days)	$2,000/hr		$ 192,000.00	$ 384,000.00	$ 192,000.00	$ 384,000.00
	Side Booms	1	2	Price included in Welding			Included in Welding		Included in Welding	
	Drill Head	1	3	Price included in Drill Rig			Included in Drill Rig		Included in Drill Rig	
	Reamer	1	3	Price included in Drill Rig			Included in Drill Rig		Included in Drill Rig	
	Mud Cleaning Machine	4	5	18 shifts (9 days)						
	Power Unit & Generators	1		25 shifts (12.5 days)	$450/day	$550/day	$ 5,625.00	$ 6,875.00	$ 5,625.00	$ 6,875.00
	Water Pump	1		25 shifts (12.5 days)	$2,000/shift		$ 36,000.00	$ 36,000.00	$ 36,000.00	$ 36,000.00
	Mud Mixing Tank	1		25 shifts (12.5 days)	$750/day		$ 9,375.00	$ 9,375.00	$ 9,375.00	$ 9,375.00
	Mud Pump	1		25 shifts (12.5 days)	$2,000/shift		$ 50,000.00	$ 50,000.00	$ 50,000.00	$ 50,000.00
	Exit Mud containment Tanks	1	2	25 shifts (12.5 days)	$50/day		$ 625.00	$ 1,250.00	$ 625.00	$ 1,250.00
	Cuttings Tank	1		25 shifts (12.5 days)	$50/day		$ 625.00	$ 625.00	$ 625.00	$ 625.00
	Pipe Racks	1		25 shifts (12.5 days)	$1,000/day	$3,000/day	$ 12,500.00	$ 37,500.00	$ 12,500.00	$ 37,500.00
	Testing Pigs	3			$10,000/project		$ 10,000.00	$ 10,000.00	$ 10,000.00	$ 10,000.00
	Pipe Rollers	20		25 shifts (12.5 days)	$400/day		$ 100,000.00	$ 100,000.00	$ 100,000.00	$ 100,000.00
	Bending Machine	1		8 shifts (4 days)	$5,000/day	$10,000/day	$ 20,000.00	$ 40,000.00	$ 20,000.00	$ 40,000.00
	Wire line Steering system	1		6 shifts (3 days)	$6,500/day		$ 19,500.00	$ 19,500.00	$ 19,500.00	$ 19,500.00
	Mud Motor	1		6 shifts (3 days)	$16,000/day		$ 48,000.00	$ 48,000.00	$ 48,000.00	$ 48,000.00
	Drill recorder	1		25 shifts (12.5 days)	$7,000/day		$ 87,500.00	$ 87,500.00	$ 87,500.00	$ 87,500.00
	Centrifuge	1		25 shifts (12.5 days)	$3,255/day		$ 40,687.50	$ 40,687.50	$ 40,687.50	$ 40,687.50
Labour/Construction	Labourers	10	15	25 shifts (12.5 days)	$400/day	$600/day	$ 5,000.00	$ 7,500.00	$ 5,000.00	$ 7,500.00
	Hydro Testing	N/A		2 days	$4,000/day	$5,000/day	$ 8,000.00	$ 10,000.00	$ 8,000.00	$ 10,000.00
	Geotechnical Drilling			1 day	$250/hr	$300/hr	$ 6,000.00	$ 7,200.00	$ 6,000.00	$ 7,200.00
	Trucking of pipe				Project Estimate		$ 80,000.00	$ 100,000.00	$ 80,000.00	$ 100,000.00
	Hydrovac			25 shifts (12.5 days)	$2,500/day		$ 31,250.00	$ 31,250.00	$ 31,250.00	$ 31,250.00
	Trucking				Project Estimate		$ 11,000.00	$ 22,000.00	$ 11,000.00	$ 22,000.00
Geotechnical Investigation	Boreholes	2	2				$ 65,000.00	$ 65,000.00	$ 65,000.00	$ 65,000.00
	ERT Survey and Analysis								$ 40,000.00	$ 50,000.00
	Seismic Refraction Survey and Analysis								$ 40,000.00	$ 50,000.00
Miscellaneous	Land				Project Estimate		$ 30,000.00	$ 30,000.00	$ 30,000.00	$ 30,000.00
	Drilling Mud Disposal	585m^3	608.4m^3	56 loads	$125/load (~8m^3)		$ 9,140.63	$ 9,506.25	$ 9,140.63	$ 9,506.25
	Washroom	1	2	25 shifts (12.5 days)	$100/day		$ 1,250.00	$ 2,500.00	$ 1,250.00	$ 2,500.00
	Control Room	1		25 shifts (12.5 days)	$100/day		$ 1,250.00	$ 1,250.00	$ 1,250.00	$ 1,250.00
	Lights	4	6	25 shifts (12.5 days)	$300/day		$ 15,000.00	$ 22,500.00	$ 15,000.00	$ 22,500.00
Typical Cost Increase							$ 445,453.59	$ 3,430,499.25	$ -	$ -
Final Cost							**$ 3,415,144.22**	**$ 6,860,998.50**	**$ 3,049,690.63**	**$ 3,530,499.25**

Figure 20: Cost breakdown for the Wapiti River crossing including implementation of design.

Table 27 below summarizes the cost breakdown and evaluates it against the pre-defined design criteria. When reviewing the high-end costs, implementing the solution results in a 49% decrease of overall costs, therefore achieving a level 3 rating. On the low-end of the spectrum a cost reduction of 11% can be realized by implementing a thorough ground survey. These cost analysis results validate the success of the project with respect to its ability to reduce overall costs. Additionally, it validates the investment required to complete the ERT and seismic refraction surveys prior to construction.

Table 27: Cost of crossing without design solution implemented, along with 8%, 5%, and 3% reductions on overall costs. Followed by a comparison against cost with solution implemented.

Project Metrics	**Without Solution Implemented**	**Level 3 (8%)**	**Level 2 (5%)**	**Level 1 (3%)**
High-End				
Crossing cost without solution	$ 6,860,998.50	$6,312,118.62	$6,517,948.58	$6,655,168.55
Crossing cost with solution	$ 3,530,499.25 (~49% decrease)			
Difference between cost without and with solution	$3,330,499.25			
Low-End				
Crossing cost without solution	$ 3,415,144.22	$3,141,932.68	$3,244,387.01	$3,312,689.89
Crossing cost with solution	$ 3,049,690.63 (~11% decrease)			
Difference between cost without and with solution	$365,453.59			

11.2.3 Assessment Against Metrics

As outlined in Section 1.8 Project Metrics, metrics were created early in the project to determine how the final deliverable would be assessed. These metrics shaped the project decisions and guided the design to be as effective as possible. Table 28 below displays the assessment of the solution against the evaluation metrics. As seen in the table, the solution achieves mostly level 3 ratings indicating a successful project.

Table 28: Results from validating design solution against defined project metrics.

Feature	Level 3	Level 2	Level 1
External Design Metrics			
Construction Cost Reduction	>8% reduction	8-3% reduction	<3% reduction
	A level 3 was assigned to the cost reduction feature. As outlined in Table 27, the cost reduction of the solution is ~49% on the high end and ~11% on the low end.		
Safety	All codes and standards will be met throughout the design and implementation of this project.		
	A level 3 was assigned to the safety feature as all codes and standards pertaining to safety have been considered and incorporated into the design.		
Solution Versatility	Adaptable to any HDD or pipeline construction project.	Design is only successful with Wapiti River crossing	Not feasible
	A level 3 was assigned to the versatility feature as the design solution can be applied to any HDD project, regardless of location and terrain features.		
Robustness of Design	Designs considers possible delays and provides prevention strategies	Design considers possible delays and provides solution strategies	Design does not consider delays
	A level 3 was assigned to the robustness of design feature as the design considers delays in the construction plan as well as provides a range in the cost estimate. Additionally, the design of pipe crossing in AutoPIPE has been designed with a buffer for increased stresses.		
Validation from Professionals	Validated by more than three industry professionals	Validated by three or less industry professionals	Validated by no industry professionals
	A level 3 was assigned to the validation feature as the final solution was validated by eight industry professionals as outlined in Table 26.		
Risk Mitigation	>8% reduction	8-3% reduction	<3% reduction
	A level 3 was assigned to the risk mitigation feature as the proposed solution reduced the project's risk by seven out of the top ten failure modes of HDD project. This can be seen in Table 21.		
Internal Project Metrics			
Project Timelines	Deliverables completed on time or early	Deliverable two days late	Deliverable > two days late
	A level 3 was assigned to the timeliness feature as the deliverables were submitted in a timely manner.		
Provide proof of concept by project end	Detailed design of crossing	High-level overview of design and crossing	No deliverable accompanying project

Feature	Level 3	Level 2	Level 1
External Design Metrics			
	A level 3 was assigned to the proof of concept as the design deliverable provides complete documentation on the proposed solution and how the result was attained.		
Stakeholder Requirements	Design meets all design criteria and constraints	Design meets some design criteria and constraints	Design meets no design criteria and constraints
	A level 3 was assigned to the stakeholder requirements feature as the design considers and achieves the design criteria outlined in Section 2.0 Stakeholder Analysis, Table 6. No stakeholders will be negatively affected by the proposed solution.		
Client Satisfaction	Design exceeds expectations	Design meets expectations	Design does not meet expectations
	No level was assigned to the client satisfaction feature as the client team is required to evaluate their expectations. A level 2 or 3 is estimated for this feature.		
Clarity of Design	Delivery of project is clear, easy to interpret and is straight-forward to apply from an external perspective with no prior knowledge on HDD	Delivery of project is partially clear, can be interpreted but is difficult to apply from an external perspective with no prior knowledge on HDD	Delivery of project is not clear, difficult to interpret and is difficult to apply from an external perspective with no prior knowledge on HDD
	A level 3 was assigned to the clarity feature as the delivery of the design was rated easy to comprehend from individuals with no prior knowledge on the topic of HDD design and geophysics.		

12.0 Conclusion

Over the course of September 2020 to April 2021, research was conducted on ways to reduce the high costs of installing pipelines across rivers. Exploration was completed on different trenchless methods before selecting HDD as the primary target. This was chosen as it is the prominent installation method with varying construction processes from project to project [3]. Through interviews with HDD experts and reading case studies, knowledge was accumulated and documented on the processes, complications, and costs of all HDD facets. This information was then used to complete an extensive idea generation process on ways to reduce costs. After an analytical approach to decision making, it was decided that efforts would be focused on optimizing the drilling and reaming processes as they had the most room for improvement. The design solution pivoted after a memorable meeting with Paul Kelly who reinforced that most project limitations were either a direct or indirect result of unclear subsurface conditions. This was further reinforced when an FMEA of HDD crossings was completed, as most failure modes could be linked to unknown ground conditions. This prompted the research into ground surveying techniques and ultimately the final design solution.

To decrease HDD project costs, it is recommended to complete a comprehensive subsurface investigation. This investigation uses electrical resistivity tomography and seismic refraction in conjunction with boreholes to create a map of the soil layers and acquire their unique specifications. This universal solution reduces the overall cost and environmental impact of HDD projects. HDD projects can expect to see significant cost savings by implementing ground investigation surveys. For the Wapiti River crossing the savings are expected to range anywhere from 11% on the low end to 49% on the high end. These savings are a result of reduced construction time, decreased project risk, and eliminated standby time.

13.0 Recommendations

This section discusses the recommendations for how the solution should be implemented and includes future considerations that could be studied further to improve HDD projects.

13.1 Implementation Recommendations

The steps for how the solution should be implemented in the future were outlined and are shown in Table 29 below. Since the final solution has not been tested on-site, testing is the first step that should be taken. The next steps require alterations to be made to the solution based on the testing results. This will be an iterative process and should be repeated until no further improvements can be identified. Once an optimal result is achieved, then it can be implemented on a real project. Even once fully implemented, the solution will still require monitoring to ensure it is operating correctly and efficiently.

Table 29: Recommended solution implementation plan.

Step	Timeline	Action Required	Validation
Gather required ERT and seismic refraction equipment for testing	May 2021	Contact necessary companies to receive required equipment for testing	N/A
Test solution on pilot projects in areas with significant ground investigation data	June 2021-August 2021	Use solution on pilot project and collect data	Compare results with previously gathered data
Test solution on pilot projects in areas with less ground investigation data	August 2021-September 2021	Use solution on pilot project and gather data	Compare results to data obtained from wellbores or cores

Step	Timeline	Action Required	Validation
Make improvements from test results	June 2021-October 2021	Review results, identify errors, and make any necessary changes	Observe if changes made have improved results
Repeat testing and revising process until no further improvements can be made	October 2021-December 2021	Repeat actions above	Results are increasing in quality until no further improvements can be made
Market idea to oil and gas companies	May 2021-Future	Attend conferences to present solution to industry professionals Market solution to companies	N/A
Implement solution for first project	December 2021	Ensure final solution is optimized and planning is done properly to implement the solution smoothly	Solution implementation is smooth and provides results as expected

13.2 Future Considerations

Throughout this project, there were many ideas and potential paths that were considered and researched. Although most of them were not selected to move forward with, they are still potential ideas for cost reduction, and it is recommended that they be researched further. As mentioned previously, focusing on drilling mud for cost reduction opportunities is a potential path. Although plenty of research is currently being done on this subject, it is still an area that could allow for significant cost reductions. There are multiple companies completing research on this topic; Their ideas are promising to either reduce the volume of mud required or find ways to treat the mud on-site [50].

Another area that is recommended to be researched further are geophysics methods that can provide continuous data beneath the water crossing. As mentioned in solution limitations, the surveying method that uses a boat only provides information of a small area where the boat intersects the pipeline path. A method that has the potential to solve this issue is underwater MASW. Currently there are two companies in North America that are researching underwater MASW [72]. This method places the receivers on the waterbed parallel to the pipeline path and collects continuous data [72]. Since this is a new technology and not commonly used, this method is expensive and is not recommended to be used in the near future [72]. Over time this method could gain traction in the industry and become more commonly used, and therefore become less expensive. In this case, this geophysics method would be recommended to use when completing the geotechnical investigation for water crossings.

After validating the solution with Kshama Roy, he proposed to create a database that contains information on boreholes completed in a either Alberta or Canada [56]. Currently, when completing a study on an area where an HDD crossing might take place, the only information available from municipalities is the location of where boreholes have been completed [56]. No information is available on the soil data from these boreholes unless the company that completed the investigation is willing to share the information. Due to the competitive nature of the industry, most companies are not willing to share the geotechnical information because they purchased the resources to gather this data. This results in companies having to complete their own boreholes, even though multiple may have been previously completed in the area, which increases project costs. If companies agreed to share the information gathered, then less boreholes would need to be completed and money would be saved. Additionally, this would result in diminished environmental impact as boreholes are invasive. In conjunction with this recommendation, it would be beneficial to include all subsurface data collected on a project rather than solely boreholes.

Finally, the last recommendation is to research further into machine learning and artificial intelligence to design a model that could be used for HDD projects [56]. By gathering enough data to train the model, the model could be used to predict the soil conditions along the HDD path for a certain region [56]. To gather the data, numerous geotechnical investigations could be completed. This compliments the previous recommendation as the database could be imported to train the model [56]. If the model was able to accurately predict the soil conditions for the calibrated region, this would ultimately reduce overall project costs [56].

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Appendix I – Background Information

Initial research was conducted on microtunneling, HDD and HAB. The following sections outlines the information collected.

Appendix I—A Horizontal Auger Boring

Horizontal auger boring (HAB) is a trenchless method used to excavate soil and install pipelines below railways, bodies of water, and roads. HAB involves a revolving cutting head that leads the technology through the ground. The soil is transported to the shaft area by the rotation of the helical auger flights within the steel pipe casing [73]. First, a launch pit must be excavated to allow safe operation of the machine and to accommodate the pipe [74]. Factors to be considered at this stage are slope stability, flooding potential, and presence of other underground utilities [74]. The operator sets the auger boring machine to a specific height and allows it to follow a track through the soil. Once the machine reaches the end of the tracks, the casing pipe is released, and the machine returns to its initial position [74].

This design is best to use for pipelines that will begin and end on grade or have a gravity run off design [75]. Typical applications to use this method are for oil, gas, water and sewer pipelines with a casing between 24-70 inches [75]. Figure 21 below shows a diagram of auger boring and how it is driven through the soil.

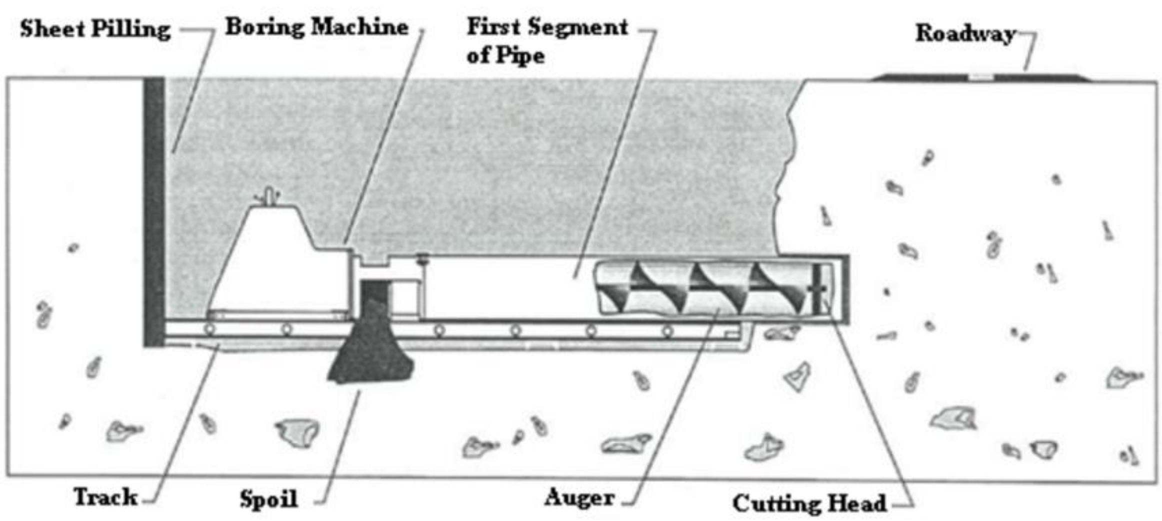

Figure 21: Diagram displaying horizontal auger boring under a roadway.

Disadvantages to auger boring are that it cannot be steered and any slight change in course can cause the excavation to taker a completely different path as they are unable to visually see the course of the machine [73]. Although it has accuracy constraints, it is still proven to be more cost effective than HDD. It is also safe and has little to no disruption to the ground surface, buildings, railways, or roads [76]. Bores of less than six inches are more suitable for HDD, while larger bores can be satisfied by HAB [73].

Appendix I—B Microtunneling

Microtunneling is a trenchless technology that is made to drill smaller tunnels and is mainly used for pipelines of 0.6m to 1.5m in diameter [77]. This process uses microtunnel boring machines (MTBM) that are operated remotely from a control panel which is located at the surface. The operator can control the boring process remotely through receiving continuous data of the location and orientation of the boring tool [77].

The MTBM is launched into the ground by an entry hole by hydraulic jacks and pipes get pushed behind the machine until it reaches a reception shaft [77]. During this process, friction is often present and can cause issues. To minimize friction, one method is to have the MTBM make a path with a slightly larger diameter than the pipe to have a small space between the outside of the pipe and the earth [77]. Another method is to inject some type of lubricant so that the friction between the pipe and the earth is minimized [77]. A diagram that outlines the main components of this process is shown in below Figure 22.

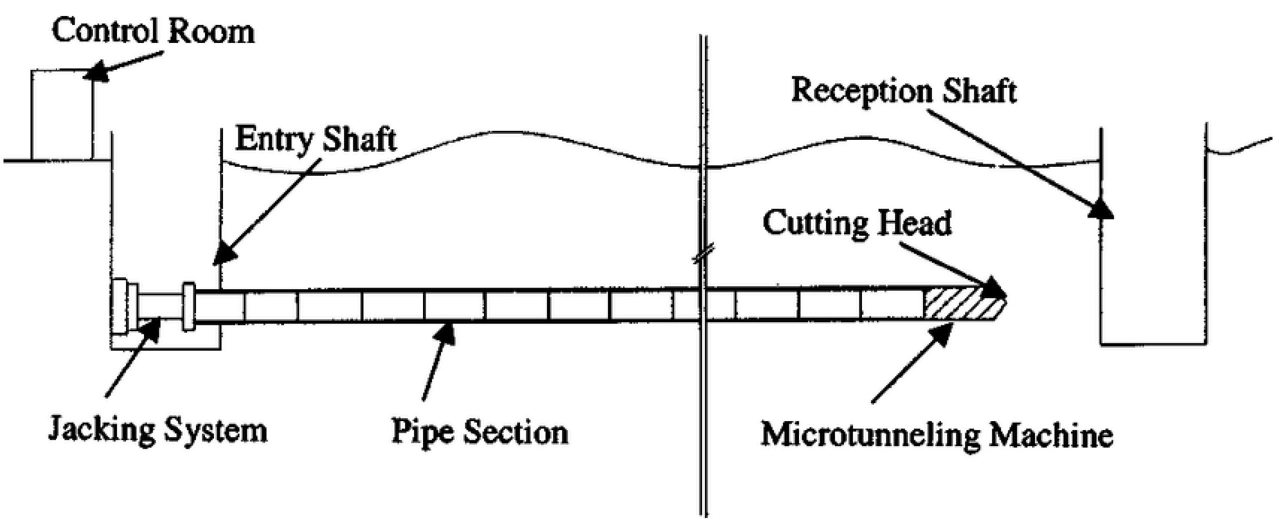

Figure 22: Diagram showing the microtunnelling process [9].

Appendix I—C Comparison of Trenchless Techniques

A table was used to compare microtunneling, HDD and HAB based on the initial significant areas of interest.

Table 30: Comparison of microtunneling and HAB to HDD in key areas of interest.

Area of Interest	Microtunnelling	Horizontal Directional Drilling	Horizontal Auger Boring
Accuracy	• Machines can achieve an accuracy of +/-10mm [78]	• Machines can achieve an accuracy of +/-100mm [78]	• Machines can achieve an accuracy of +/-30mm [29]
Upfront Cost	• Requires shafts to be dug at either end of the pipeline [78] • These holes need to be filled upon completion [78]	• Surface-launched and do not require a pit to be made [78]	• Requires use of steel casing when a jacking pipe is being used [29] • Cost of installation can be high [29] • Still cheaper than microtunneling or HDD [75]
Time	• More time required to dig and fill shafts [78]	• No shafts required, so less time required [78]	• More time required to dig launch pit
Long-term risk	• Greater pipeline integrity [78] • Could save money on maintenance costs in the future [78] • Lower risk of failure [78]	• Faster installation may lead to more time invested in the future [78] • Bends in pipeline can become weak points that lead to increases in maintenance cost and a higher risk of failure [78]	• Not suitable for wet running ground or ground where high frequency of boulders exists [75] • Since direction of bore is not seen, it may hit a boulder and contractors have to begin again [79]
Popular areas of installation	• Highways [80] • Railway lines [80] • Major rivers [80]	• Palustrine wetlands [80] • Streams [80] • Creeks [80]	• Displaceable soils [28] • Under-ground water [28] • Sandy and gravel soils [28]
Length of installation	• Exceed 225 m with varying depths [80]	• Greater than 1,800 m and depths up to 15 m [80]	• Can be 180 m but usually about 120 m [75]
Types of pipelines	• Gravity pipelines [80] • Gas pipelines [80] • Water pipelines [80] • Cable lines [80]	• Pressure lines [80] • Water lines [80] • Cables [80] • Gas pipelines [80]	• Oil pipelines [75] • Gas pipelines [75] • Water pipelines [75] • Sewer pipes [75]

Appendix I—D Economic Comparison Between Trenchless Techniques

All the trenchless pipeline techniques researched had different upfront and overall costs. Microtunneling is the most expensive technique to carry out as it has very high initial costs. Although microtunneling can be used to install pipelines that are over 1800 mm in diameter, they are far too costly to be seriously considered. HAB is less expensive to use for medium diameters compared to HDD, however HDD is most commonly used and was suggested for the deliverable of the project. Figure 23 below shows the comparison of average prices for all three techniques [13].

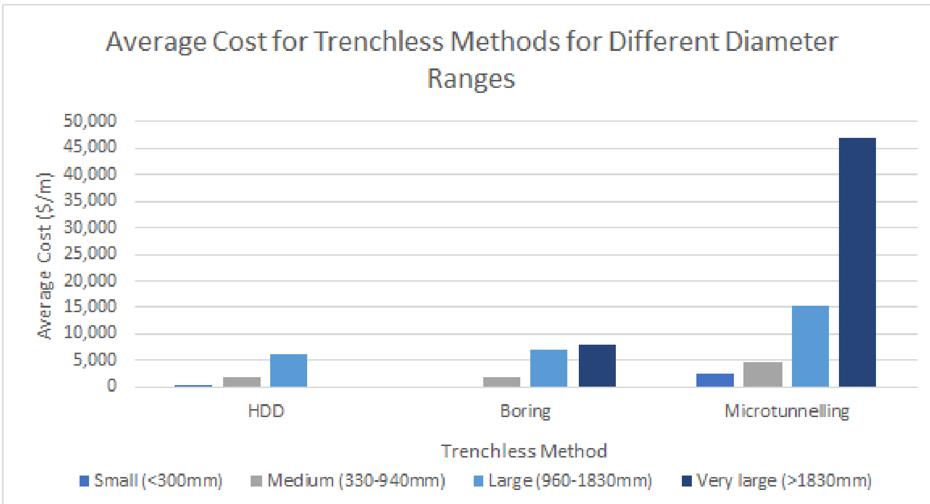

Figure 23. This graph displays the average costs for the trenchless pipe installation techniques presented in this report [13].

Appendix II – Definition and Descriptions of Construction Process Steps

To ensure anyone can understand the terminology related to HDD, descriptions of each process are outlined in Table 31.

Table 31: Table of construction steps and their respective descriptions.

Step	Description
Access & Clearing	Prepping the worksite to be in proper conditions to proceed with the project. This includes [15]: o Clearing trees o Bunching o Mulching o Grubbing
Stripping and Grade	Stripping the topsoil and flattening the soil to make it easier for the rubber-tired vehicles to move [15].
Trenching and Excavations	Exposing buried facilities via non-mechanical excavation. These are aspects like pipelines, cables, and power lines. This is often done using a hydrovac [15].
Possible Features in crossing	Determining what is in area of crossing [15].
Buoyancy control	Method used to keep pipe from floating once placed in the ground. This can be achieved through using: o Screw piles and a strap around the top of the pipe o Bag weights o Concrete coating Note: This is only used in very wet areas [15].
Stringing	Laying out the pipe beside the HDD process [15].
Bending and Engineering	Bending the pipe into the desired shape to fit into the drilled hole [30].
Welding	"Mainline crew" comes and welds straight and easy sections of the pipe. After, the "Poor boy" crew comes in and welds the more difficult tie-ins sections. Welds made with cellulosic electrodes are subject to a 24-hour hold before NDE due to concerns with hydrogen-induced cold cracking. Some welding processes are: o Shielded Metal Arc Welding (SMAW) o Flux Cored Arc Welding (FCAW) o Submerged Arc Welding (SAW) Note: All welds use a first pass on one shack then two welders will come and do a second pass. Mainline: Above ground welds made with the mainline crew. For large diameter long pipelines and typically Mechanized GMAW.

Step	Description
	Poor boy: Non-mainline welds made above ground typically SMAW, FCAW or MCAW [15].
Non- Destructive Examination (NDE)	Scans the welds and determines if there are any defects. Defects may include: o Lack of fusion o Lack of cross penetration o Cracks o Internal undercut o Slag entrapment These criteria are from CSA Z662 workmanship criteria [15].
Coating	Exposed area at the end of joints needs to be coated. This includes: o Pre-jeeping and repair They check for discontinuity and breaks in coating. This protects the steel from corrosion [15].
Hydrostatic testing and pigging	Pigging: o Pigs (construction or cleaning) and gauge plate are pushed through the line with compressed air to clean debris out of the line. o Gauge plate are used to determine if there are dents or deformities in the pipe. o Pigging heads are welded on both ends. Fill: o Section is filled with water from hydrotest water source. Note: Have to have certain pressure criteria dependent on length and altitude to complete these tests. If there are significant elevation changes, then more tests need to be done in smaller sections. Hydrostatic test: o Primary tests test areas of the pipe that cannot be visually inspected. This is a four-hour strength test. o After, there is a four-hour leak test with a maximum of 15 kPa fluctuation over four hours. o Secondary test contains 1-hour concurrent strength and leak test for all fully exposed pipe. o Some of these activities are: ▪ Dewatering ▪ Caliper pigging ▪ Drying ▪ Air drying Methanol wash [15]
Pilot hole drilling	Drilling the initial hole from the entry to the exit site [15].
Back reaming	Using a reamer that moves from the exit site to the entry site to increase the diameter of the hole so that the pipe can fit [15]. The larger hole being drilled depends on soil type, stability, depth, drilling mud etc [9].

Step	Description
Swab pass (not common in use)	Additional passes are made with the same size reamer if the operator feels the hole is not properly reamed or there is a collapse of the hole [9].
Drilling mud - used in pilot hole drilling, back reaming, and pull in	Drilling mud is injected into the borehole during cutting and reaming to stabilize the hole and remove soil cuttings. Examples of mud come from clay or polymers, usually bentonite. Drilling mud is designed to be like the surrounding soil. Exposing of the drilling mud is an expensive process [9].
Pullback process	The act of pulling the pipe into the hole back through drilling mud along the hole pathway. This requires expensive equipment such as: o Cranes o Sidebooms Axial tension force readings, constant insertion velocity, mudflow circulation/exit rates, and footage length should be recorded. Common pullback speeds can be between 1-2 feet per minute [15].
Site restoration	The attempt to return the site back to conditions prior to the project. Some of these actions could include [15]: o Planting trees and shrubs o Enhancing the topsoil o Mulching o Seeding

Appendix III – Project Assumptions

Assumptions have been defined based off research on the environmental conditions, regulatory guidelines and details surrounding the pseudo project [3]. These assumptions have been reviewed by industry professionals to analyze their validity and eliminated where possible.

Table 32: Project assumptions.

Area of Project	Assumptions

Regulations	• The regulator is the Canadian Energy Regulator [26].
	• All permits are acquired properly and there are no delays associated in obtaining them.
	• All CSA Z662 code (Oil and Gas Pipeline Systems) is being followed in all aspects on the design and construction [27].
	    • Clause 4.22 states the requirements for pipelines installed using HDD including a feasibility assessment to assess subsurface conditions, drill path designed considering the location and subsurface influences, determine risk and mitigation for release of drilling fluid and for steel pipe, longitudinal stress during installation does not exceed minimum yield strength of pipe [27].
	    • Clause 6.2.11.2 HDD Construction requires a written drilling execution plan prior to construction including drill bit technology, workspace requirements at entry/exit points, layout of pipe drag section, drilling fluid requirements, environmental protection and monitoring plan, pressure and volume measurement plan, contingency plans, equipment specifications, and mitigation of effects of geological formations [27].
	    • 7.2 Arc and gas welding, 9.2 Selection of external coatings for buried or submerged piping [27].
	• Pipes are installed to a depth of at least 20 ft below expected future river bottom. Borings are usually made 40 ft below riverbed [16].

Safety	• Clause 10.2.1 states all construction crew members will have completed formal training through their licensed contractor [27]. • A minimum of 51% of construction crew will have previous experience on similar projects. • The construction will be completed by a reputable contractor. The contractor will have completed a project of this size and scale before. • Clause 13.3.7.8 assumes construction shifts are a standard length of 12h [27].
Design Scope	• Scope includes only installation with consideration of site clearance and remediation [3]. That is drilling, reaming, and pullback. • The focus will be on the river crossing, not the pipeline routing [3].
Surrounding Environment	• Drilling is permitted in location provided by client [3]. • No above-ground structures, such as power lines, are present at construction site. • Would be able to get transport resources using Highway 40 that is close by. • Soil/sand is compatible with HDD drill and reamers that are available [3]. • Pipe will not be exposed due to erosion over time. • The climate is typical Grande Prairie conditions [3]. This includes factors such as:

Area of Project	Assumptions
	• Temperatures ranging from -15.5°C to 15.5°C, • Rainfall of up to 472 cm per year, • Snowfall of up to 1544 mm per year, • In a transitional biome between boreal forest and prairie.
Cost	• Follows typical HDD project costs of this size and scale as outlined in the economic analysis. • Determined costs are comparable to what other contractors would charge. • Cost range provided by Jamie McLennon are reliable and accurate [48].
Drilling	• Drilling of the pilot hole follows bore path accurately. • The hole does not collapse during construction phase. • Equipment required will be available. • No interaction with preexisting pipes or utilities in the ground. • Equipment selected to be used like the specific reamer and drill bit are well suited for the ground conditions. • Amount of drilling mud selected will be sufficient (234 m^3). • Have enough materials so that the equipment will run properly such as fuel. • Drill string will not break during construction.

Pipe	• No major destruction or damage to the pipe during the pullback process.
	• Pipe will satisfy all the hydraulic requirements. These requirements include:
	  • Flow capacity,
	  • Working pressure rating,
	  • Vacuum capacity.
	• Pipe will be able to withstand the forces/loads acting on it. Some of these forces would include:
	  • External hydrostatic pressure,
	  • Hydrodynamic,
	  • Earth load,
	  • Friction,
	  • Groundwater load,
	  • Surcharge loads,
	  • Tensile pull forces,
	  • Tensile bending stresses.
	• Designed pipe bends are accurate for the drilled hole.
	• Pipe stays in correct position and no shifting occurs.
	• Selected grade and thickness would be available to be purchased.

Drilling Mud Disposal	• The most appropriate method for drilling mud disposal will be selected and includes:
	  • Average land disposal costs,
	  • Average trucking costs for disposal.

Subsurface Conditions Technology	• The Wapiti River does not have a strong current (<5 km/h). • Conducting both an ERT and Seismic Reflection survey will follow average costs.

Appendix IV – Stakeholder Interviews

Table 33: Outline of all contacted stakeholders, point of contact and topics discussed.

Company	Stakeholder Type	Contact	Topic/Specialization
TC Energy	Pipeline Companies	Mustafa Yulek	Trenchless methods and current concerns [21].
TC Energy	Pipeline Companies	Jason Gunderson	Drilling mud concerns with respect to high costs and regulatory considerations [50].
Canada Energy Regulator	Regulatory Body	Wayne Marshall	Concerns with (pipeline) water crossings, environmental considerations, approval process, quality control process [88].
YPAC	Client/Pipeline Company	Lindsay Drozdiak (TC Energy) Katia Greco (TC Energy) Mohamed Rashid (Inter Pipeline) Kshama Roy (Northern Crescent)	Trenchless methods and current concerns, environmental concerns [3].
TC Energy	Pipeline Companies	Craig Schell	Concerns surrounding the environmental impact of trenchless pipeline installations as well as project considerations [18].
Interpipeline	Pipeline Companies/Indigenous Nations	Michelle Goodkey	Concerns of Indigenous Nations with pipeline installations as well as required engagement in projects [23].
Canadian Energy Regulator	Regulatory Body	Lianne Germaine	Regulations regarding HDD crossings [89].
TC Energy	Pipeline Companies	Rob Purcell	HDD project overview and complications with installations [15].
TC Energy	Pipeline Companies	Dale Madsen	HDD project overview and complications with installations [34].
InterPipeline	Pipeline Companies	Pat Scharf	Contractor [90].
CCI Consulting	Contractor	Sam Wilson & Craig Lenderbeck	Areas of improvement and costs surrounding HDD installations [47].

Company	Stakeholder Type	Contact	Topic/Specialization
Surerus Murphy	Contractor	Derek McLean	Areas of improvement and costs surrounding HDD installations [49].
Surerus Murphy	Contractor	Paul Kelly	Areas of improvement and costs surrounding HDD installations [10].
Brothers HDD	Contractor	Jamie McClennon Des Ross	Specific costs of HDD projects and the feasibility of cost reduction opportunities [33].
MASW | Park Seismic	Contractor (geophysicist)	Choon Park	Underwater MASW feasibility for subsurface conditions mapping [72].
Geophysics GPR	Contractor (geophysicist)	Ben McClement	Geophysics techniques for ground investigation focusing on MASW, seismic refraction/reflection and ERT [55].

Appendix V – Additional Idea Generation Information

This section includes the results from some of the idea generation methods used.

Appendix V—A Construction Step Ideation Results

Table 34 shown below outlines the results from completing the Post-it Note idea generation method on ways to reduce costs of various construction steps.

Table 34: Post-it Note technique for generating ideas on ways to reduce the time/cost of various construction techniques. The various steps were generated from interviews with a project manager at TC Energy, Rob Purcell [12].

Step	Description	Ideas to Lower Costs
Access & Clearing	Prepping the worksite to be in proper conditions to proceed with the project. This includes: • Clearing trees, • Bunching, • Mulching, • Grubbing, [28]	• Hire multiple groups to complete this so this step done in less time. • Hire cheaper contractors to complete this work. • Find different machines that can clear quicker. • Use less expensive machinery. • Try to find land that requires minimal clearing.
Stripping and Grade	Stripping the topsoil and flattening the soil to make it easier for the rubber-tired vehicles to move [29].	• Use more machines to strip the topsoil so it can be completed in a shorter time. • Make the area smaller. • Change the tires so that a larger variety of machines can get in without work being done.
Trenching and Excavations	Exposing buried facilities via non-mechanical excavation. These are aspects like pipelines, cables, and power lines. This is often done using a hydrovac [29].	• Determine locations of preexisting buried facilities before excavating, not finding them could set back project timeline. • Select site that does not have any facilities nearby to eliminate this step if possible. • Select the most efficient hydrovac or other equipment that can complete the excavations faster.
Possible Features in crossing	Determining what is in area of crossing [29].	• Complete analysis before construction so there are no surprises that will

Step	Description	Ideas to Lower Costs
		elongate the project and cost more money. • Have contingency plans prepared for the site based on what is most likely/possible.
Buoyancy control	Method used to keep pipe from floating once placed in the ground. This can be achieved through using: • Screw piles and a strap around the top of the pipe, • Bag weights, • Concrete coating, Note: This is only used in very wet areas [29].	• Choose a cheaper option to limit buoyancy of pipe. • Design a new way to limit buoyancy specific to the location and use of HDD. • Determine if this step is even required for the site of interest. • Possibility for flotation.
Stringing	Laying out the pipe beside the HDD process [29].	• Use less cranes. • Find different way to transport pipe that is quicker and cheaper. • String the whole pipe at one time so the cranes can be used at one time and then leave the site. • Use cheaper materials to complete this task like skids or equipment to raise the pipe off the ground. • Do not use equipment to raise the pipe off the ground.
Bending and Engineering	Bending the pipe into the desired shape to fit into the drilled hole [30].	• Use cold bends if possible. • This equipment and energy required can be completed on site [30]. • Avoid having to use induction bends because they take more time, use more equipment, and have to be completed off-site [31].
Welding	Mainline crew comes and welds straight and easy sections of the pipe. After, the poor boy (additional pipe crew) crew comes in and welds the more difficult tie-ins sections. Welds made with cellulosic electrodes are subject to a 24-hour hold before non-destructive examination due	• Way to use mechanized gas metal arc weld (GMAW) all the time. • Having two separate crews is not efficient, so hire crew that can do both tasks. • Use alternative to cellulosic electrodes to avoid the 24-hour wait period.

Step	Description	Ideas to Lower Costs
	to concerns with hydrogen-induced cold cracking. Some welding processes are: • Shielded Metal Arc Welding (SMAW) • Flux Cored Arc Welding (FCAW) • Submerged Arc Welding (SAW) Note: All welds use a first pass on one shack then two welders will come and do a second pass. Mainline: Above ground welds made with the mainline crew. For large diameter long pipelines and typically Mechanized GMAW Poorboy: Non-mainline welds made above ground typically SMAW, FCAW or MCAW [29].	• Use a more automated process to complete this step faster • Spend more time to ensure the welding is accurate before pressure testing to ensure there are no failures or issues later on • Ensure best practices are used because it can affect lifetime of the pipe
Non- Destructive Examination (NDE)	Scans the welds and determines if there are any defects. Defects may include: • Lack of fusion • Lack of cross penetration • Cracks • Internal undercut • Slag entrapment These criteria are from CSA Z662 workmanship criteria [29].	• May be cheaper or quicker way to use this technology • Other brands of technology that are being created to do the same process could cost less
Coating	Exposed area at the end of joints needs to be coated. This includes: • Pre-jeeping and repair They check for discontinuity and breaks in coating. This protects the steel from corrosion [29].	• Use cheaper coating that serves same purpose • Use cheaper technology for jeeping the pipe
Hydrostatic testing and pigging	Pigging: • Pigs (construction or cleaning) and gauge plate are pushed through the line with compressed air to clean debris out of the line.	• Use cost-effective pigs • Use a cheaper material for the gauge plates • Instead of using multiple pigs, find a way to only use one

Step	Description	Ideas to Lower Costs
	• Gauge plate are used to determine if there are dents or deformities in the pipe. • Pigging heads are welded on both ends Fill: • Section is filled with water from hydrotest water source Note: Have to have certain pressure criteria dependent on length and altitude to complete these tests. If there are significant elevation changes, then more tests need to be done in smaller sections. Hydrostatic test: • Primary tests test areas of the pipe that cannot be visually inspected. This is a four-hour strength test. • After, there is a four-hour leak test with a maximum of 15 kPa fluctuation over four hours. • Secondary test contains one-hour concurrent strength and leak test for all fully exposed pipe. • Some of these activities are: • Dewatering • Caliper pigging • Drying • Air drying • Methanol wash [29]	• Use a less expensive gas to purge the pipeline • Try to eliminate significant elevation changes to avoid having to do multiple tests on sections • This can be done by the selection of the trench or by excavation to level the land • Shorten the length of the strength test • Shorten the length of the leak test • Have a quicker method to complete these tests • Ensure pigging procedure is well planned to minimize errors and therefore, costs
Pilot Hole drilling	Drilling the initial hole from the entry to the exit site [29].	• Design technology to not lose drilling head • Design technology to locate and retrieve drilling head if it falls off • Use the most time-efficient drill bit • Use the shortest distance possible • Minimize depth of the line • Ensure soil is easy to drill in (no solid rock bed)

Step	Description	Ideas to Lower Costs
		• Avoid areas with slopes • Minimize curvature of hole to avoid a radius break • Do not drill for elbow bends • Extensively preplan the bore path
Back reaming	Using a reamer that moves from the exit site to the entry site to increase the diameter of the hole so that the pipe can fit [29]. The larger hole being drilled depends on soil type, stability, depth, drilling mud etc [9].	• Use most cost-effective reamer • Use reamer that can complete the job the fastest • Use the reamer that can make the diameter the minimum size • Use reamer that minimizes the potential of the hole collapsing
Swab pass (not common in use)	Additional passes are made with the same size reamer if the operator feels the hole is not properly reamed or there is a collapse of the hole [9].	• Eliminate this step if the back reaming is sufficient
Drilling Mud - used in pilot hole drilling, back ream ing, and pull in	Drilling mud is injected into the borehole during cutting and reaming to stabilize the hole and remove soil cuttings. Examples of mud come from clay or polymers, usually bentonite. Drilling mud is designed to be like the surrounding soil. Exposing of the drilling mud is an expensive process [9].	• Reuse drilling mud for site restoration so less money to dispose of it elsewhere • Reuse drilling mud for all processes to produce less to dispose of • Minimize the amount of drilling mud used • Avoid using land spray as farmland may not be nearby • This could result in high transportation costs if farm is far away • Use a different form of lubricant • Use polymer mud to cut down on waste • Less heavy than current drilling mud and the waste does not build up as fast • Reduce amount of testing that is required to be completed on the drilling mud to save time • Avoid surface heaving by studying the subsurface thoroughly
Pullback Process	The act of pulling the pipe into the hole back through drilling mud along the	• Use less cranes or different technology

Step	Description	Ideas to Lower Costs
	hole pathway. This requires expensive equipment such as: • Cranes • Sidebooms Axial tension force readings, constant insertion velocity, mudflow circulation/exit rates, and footage length should be recorded. Common pullback speeds can be between 1-2 feet per minute [29].	• Minimize the amount of sidebooms needed by planning the maximum load each one can carry and space them out as far as possible • When feeding the pipe into the whole, be more time-efficient to minimize the hours the cranes and sidebooms are used • Before this stage, ensure the hole has not collapsed • Ensure the pipe will not get stuck • This can happen if curvature is too large • Would require pipe thruster and major delays
Site Restoration	The attempt to return the site back to conditions prior to the project. Some of these actions could include: • Planting trees and shrubs, • Enhancing the topsoil, • Mulching, • Seeding, [29]	• Hire local companies • Use plants retrieved from access & clearing. • This could be by saving the soil from this step and putting it back once the project was completed.

Appendix V—B Horizontal Directional Drilling Ideation Results

Figure 24 shows the results of completing a mind map to ideate on all facets related to an HDD project.

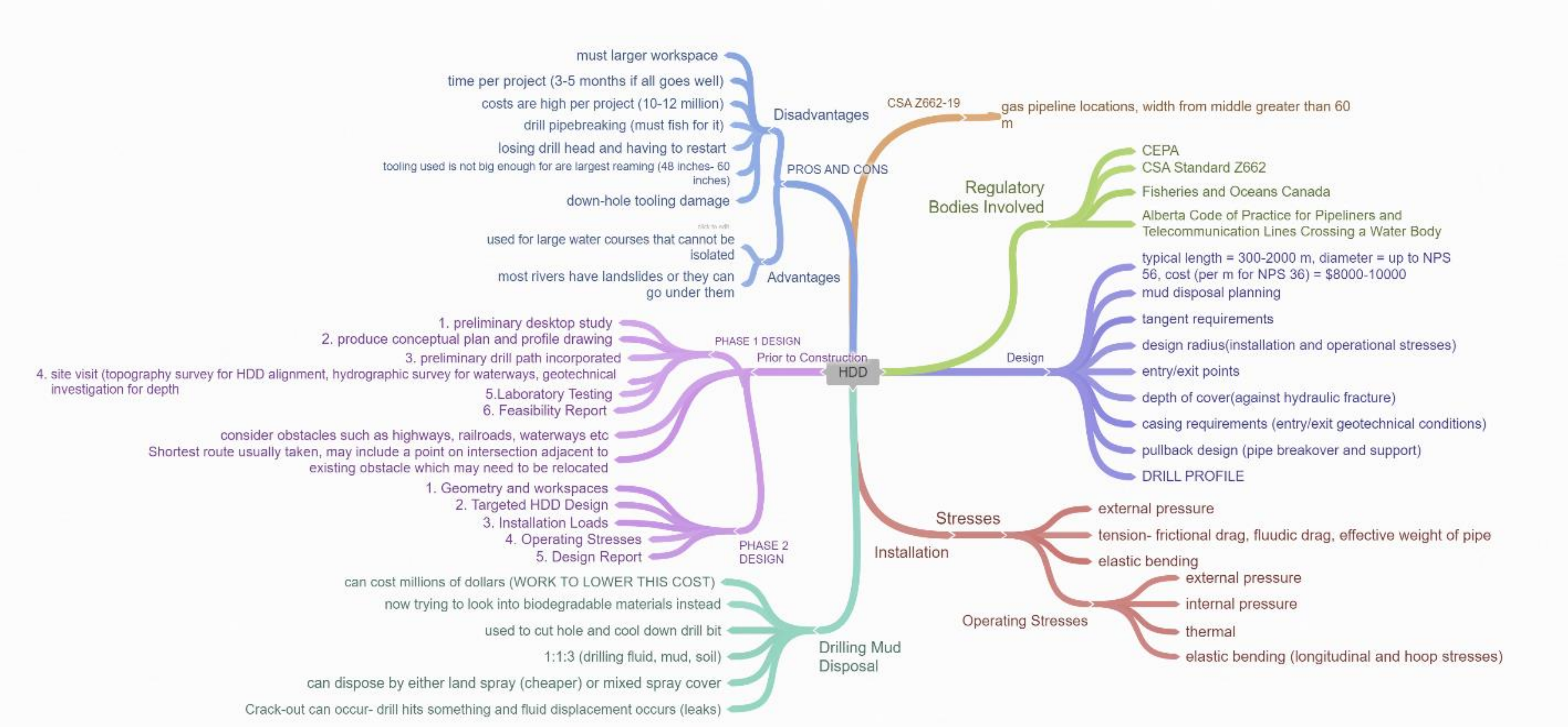

Figure 24: Mind map generated on HDD components and processes using coggle.

Appendix V—C Extreme Conditions Ideation Results

Table 35 shown below outlines the results from completing the Reverse Solution idea generation method.

Table 35: Results from the reverse solution breakdown method including the worst-case scenarios for different steps in the HDD process, along with ideas to prevent them from happening or to resolve the issue if they occurred.

Design Aspect	Worst-Case Scenario	Prevention/Remediation Strategies
Pilot Hole Drilling	• Drilling head gets lost	• Find a way to track drill head • Attach a magnet • Find a way to ensure drill head does not fall off ○ Secondary strap or connection point
	• Drilling deviates significantly from designed path	• Use a device that attracts drill head surfaces at correct location • Use a sensor that can detect the drill head deviating before it occurs • Being knowledgeable of subsurface so that no new soil is encountered • Use a sensor that can predetermine if collision/undesirable terrain is being approached • Decrease feedback time from drill head to operators
	• A frac-out occurs when drilling mud either surfaces or contaminates a nearby water body	• Decrease volume of drilling mud used • Decrease pressure of injection of drilling mud • Drill further away from surface or water body • Drill in more dense soil
	• Drilling slow and the project gets delayed	• Choose a location with less dense soil • Choose a drill head better suited for the soil • Use higher power machines • Increase people/shifts to have continuous drilling • Choose to drill in dry/cold conditions
	• Drill head gets stuck and cannot proceed	• Pull the drill head out the way it came • Lubricate the drill head to aid in removal • Increase the power of the drilling machine
Reaming	• Drilled hole collapses	• Have a more gradual increase in reamer size • Increase drilling mud volume • Put the pipe in as quickly as possible after reaming to avoid collapse • Increase rotational speed of reamer • Ream in denser soil • Be knowledgeable of forces from above the hole

Design Aspect	Worst-Case Scenario	Prevention/Remediation Strategies
	• Reaming slow and the project gets delayed	• Increase speed of the reamer • Increase the number of people working • Decrease the number of passes of the reamers • Increase drill diameter to decrease the number of reaming passes
	• Reamer detaches or head falls off	• Increase strength of weld • Find a way to track reamer • Attach a magnet • Find a way to make sure reamer head does not fall off ○ Secondary strap or connection point
Pipe Pullback	• Curvature of path is incompatible with curvature of pipe	• Measure curvature before installing pipe • Increase hole diameter in certain areas if necessary • Take note of any areas where drilling path deviated from initial path ○ Communicate to bending crew to adjust for this
	• Pipe gets stuck in hole	• Use pipe thrusters to push pipe through • Use more drilling mud to lubricate it • Pull pipe back out and increase diameter through an additional reaming pass
	• Pipe breaks	• Use stronger material • Excavate and weld pipe • Improve strength testing before installment • Identify any weak points before installment

	• Pull head detaches from pipe	• Strengthen the attachment of the pull head to the pipe
		• Use alternative way to pull the pipe into the hole
		• Increase area of contact between pull head and pipe
		    ○ Use collar-like attachment on pipe to aid in pulling
		    ○ Potentially use multiple of these collar-like attachments every few metres

	• Pipe suffers severe deformation	• Excavate deformed areas and decrease the pressure on the pipe so it can return to original shape • Use pig to push dents and return pipe to original state • Inject air into pipe to push the dent out • Use high-pressure gas in the pipe when installing to decrease deformities

Design Aspect	Worst-Case Scenario	Prevention/Remediation Strategies
	• Friction forces are too large to pull pipe in	• Use high-pressure gas to increase buoyancy and therefore reducing friction in some areas • Decrease viscosity of drilling mud

Pipe Preparation	• Have an insufficient coating and can cause corrosion to occur	• Ensure coating does not have discontinuities
		• Pick an alternative coating that goes on easier and more consistent
		• Use an additional corrosion protector such as a cathodic protection
		• Extra coating passes
		• Use corrosion-resistant pipes
		• Combine coating and welding to minimize time and ensure fewer/no discontinuities
		• Automate pipe coating to reduce human error
		• Use material of pipe that is defined as "self-cleaning"
		  ○ Could use a superhydrophobic surface
		  ○ An anti-microbial agent chemically bound to the surface to destroy microbes

	• Incorrect stringing of the pipe (in the wrong order)	• Check plans for piping when laying out the pipe to ensure the correct order • Number pipes before layout
	• Welding is poorly completed, and pipe sections are not attached	• Automate the welding process so that all welds are consistent and less prone human error • Look at alternative welding materials to improve welds • Increase amount of time spent on each weld • Alter amount of material used per weld
	• Pipe cannot withstand pressure testing	• Ensuring welding is improved/up to code • Identify commonly known "weak-spots" and prepare for above-code standards
	• Pigs get stuck in pipe	• Ensure no deformities in the pipe before sending in pig • Increase amount of lubricant used when sending in pig • Ensure diameter of pig is compatible with pipe diameter • Use flexible pigs in case of issues to aid in removal • Deploy "smart-pig" with locator to identify where pig may be stuck • Deploy multiple pigs in case any get stuck others can help remove it

Design Aspect	Worst-Case Scenario	Prevention/Remediation Strategies
		• Ensure there is sufficient water/gas to propel the pigs through the pipe
Drilling mud	• Maximize amount of drilling mud used	• Use polymer mud instead as required volume is significantly lower due to fewer fluid "turnovers" • Deploy mud filter to clean mud enough to be reused in the drilling/reaming/pulling processes • Use pressurized air in drilling process as opposed to drilling mud • Employ a vacuum type of addition to the drill/reamer to decrease amount of debris that mixed into the mud
	• Maximize cost of disposing mud	• Choose the closest location possible to dispose of mud • Reduce the transportation costs of mud to disposal site • Minimize amount of soil that needs to be transported off-site (Use some mud in the restoration of the site)
	• Increase environmental effect of drilling mud	• Ensure proper testing on drilling pit is completed daily • Ensure dumping site is compatible soil type • Minimize transportation distance to reduce emissions
Site Restoration	• Site is left as-is after construction	• Ensure no traces of vehicles/equipment are left behind • Re-soil land with added nutrients to improve growth • Replant all cleared trees and more • Ensure wildlife is re-introduced to area • Ensure no frac-outs occur • Ensure all environmental regulations are met or exceeded during site remediation
	• Wildlife is not restored to region	• Prepare a restoration plan early before project completion • Use methods to attract wildlife to the site • Find ways to increase mating at site to improve population count
	• Harmful chemicals are released into environment from construction processes	• Reduce amount of harmful chemicals used • Use efficient or up-to-date technology with less emissions • All equipment must be on special pads to reduce possibility of gas-leaks

Design Aspect	Worst-Case Scenario	Prevention/Remediation Strategies
		• Ensure coating does not release harmful chemicals into the surrounding area • Prepare a contingency plan in case any spills/releases occur
	• Site does not pass inspection for meeting environmental standards and surrounding community satisfaction	• Ensure all regulations are known beforehand and ensure site restoration plans meet all relevant criteria

Appendix VI – Additional Decision Making Information

This section includes the additional information and tools used for decision making.

Appendix VI—A Possible Crossing Location Profiles

Figure 25 below includes screenshots from Google Earth outlining the elevation profiles for the three possible crossings over the Wapiti River between Grand Prairie and Grovedale, Alberta. Information pertaining to crossing length, maximum slope and elevation change can be found in the image.

Figure 25: Three options for crossing locations on the Wapiti River between Grovedale and Grand Prairie.

Appendix VI—B House of Quality

Figure 26 below shows the House of Quality developed from the client's point of view.

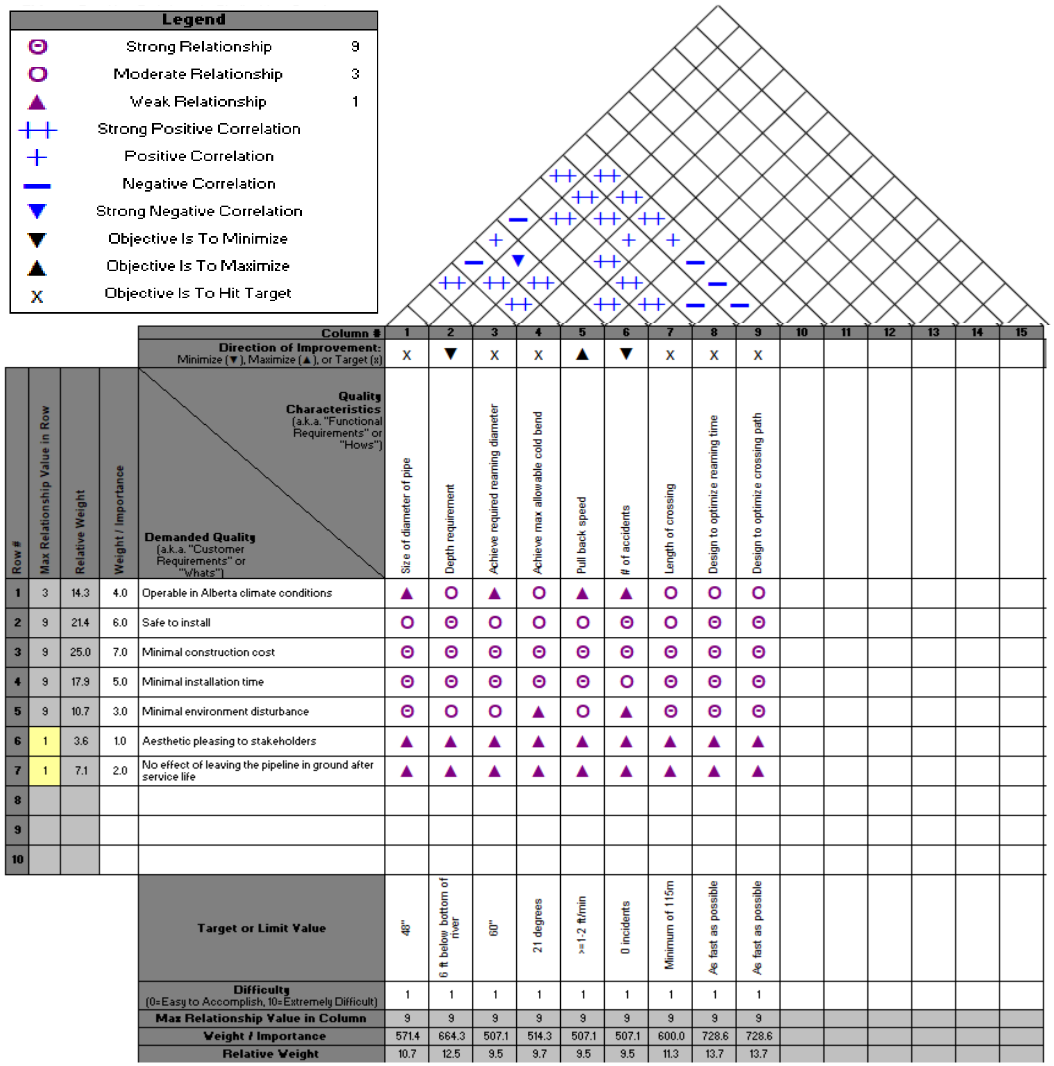

Figure 26: House of Quality, representing YPAC's and CEPA's needs.

Appendix VII – Safety and Regulatory Documents for HDD Projects

Relevant sections from each regulatory document have been outlined that pertains to an HDD project.

Table 36: Relevant information from each regulatory HDD document.

Regulatory Document	Relevant Information
Fisheries Act [35]	• Section 20: Provides for safe passage of fish. • Section 22: Provides for flow of water and passage of fish. • Section 30: Provides for water diversions or intakes to have a fish guard or screen. • Section 32: Prohibits the destruction of fish by any means other than fishing except as authorized by the Minister of Fisheries and Oceans (MFO) or regulation. • Subsection 35(1): Prohibits works or undertakings that result in harmful alteration, disruption or destruction of fish habit (HADD). • Subsection 35(2): Allows for the authorization of HADD by the MFO. • Subsection 36(6): Prohibits the deposition of deleterious substances in waters frequented by fish.
Navigable Waters Protection Act (NWPA) [36]	• Section 5(1)(a): No work shall be built or placed in, on, over, under, through or across any navigable water unless approved by the Minister. • Subsection 5(2) Except in the case of a bridge, boom, dam or causeway, paragraph 5(1) (a) does not apply to any work that in the opinion of the Minister does not interfere substantially with navigation.
Canadian Energy Regulator Onshore Pipeline Regulations Under the National Energy Board Act [37]	• Section 18: Construction Safety. • Section 29: Maintenance Safety. • Section 46: Training Program. • Section 47: Safety Management Program. • Section 48: Environmental Protection Program. • All Other Sections.
Alberta Pipeline Act [38]	• All Sections.
Alberta Code of Practice for Pipelines and Telecommunication Lines Crossing a Water Body [39]	• Section 5: Emergency. • Section 6: Plans. • Section 8: Construction methods and conditions. • Section 9: Restricted activity periods. • Section 10: Certification. • Section 11: Reporting. • Section 12: Record Keeping and Information Availability. • Section 13: Monitoring of works.
Planning Horizontal Directional Drilling for Pipeline Construction [16]	• All Sections.

Regulatory Document	Relevant Information
Alberta Occupational Health and Safety Regulation [40]	• Part 1: General. • Part 4: Records and Fees. • 34.1 Employer records of certificates and permits. • Part 5: Programs, Approvals and Designated Organizations.
CSA Z662: 19 Oil & Gas pipeline systems [27]	• All Sections.

Appendix VIII – Pseudo Project Outputs

This section outlines the calculations, parameters, and outputs generated when designing the Wapiti River crossing.

Appendix VIII—A Pipe Stress Calculations

Variables used in the following equations were determined from clauses and tables in CSA Z662, which are outlined in Table 37 [27].

Table 37: The clauses and tables including the value of the variables were determined from in standard CSA Z662 [27].

Variable	Associated Clause or Table
Design factor (*F*)	Clause 4.3.6
Location factor (*L*)	Clause 4.3.7.1 in Table 4.2
Joint factor (*J*)	Clause 4.3.8 in Table 4.3
Temperature factor (*T*)	Clause 4.3.9 in Table 4.4

To calculate the minimum required wall thickness, Equation 1 was used [27].

$$P = \frac{2 * S * t}{D} * F * L * J * T \tag{1}$$

where *P* is design pressure (MPa), *S* is specified minimum yield strength (MPa), *t* is wall thickness (mm), *D* is outside diameter of pipe (mm), *F* is design factor, *L* is location factor, *J* is joint factor, and *T* is temperature factor [27]. The calculations are shown below.

$$t = \frac{P * D}{2 * S * F * L * J * T}$$

$$t = \frac{(9930\ kPa) * (1219.2\ mm)}{2 * (\frac{550}{1000} MPa) * (0.8) * (1) * (1) * (1)}$$

$$t = 13.76\ mm$$

To calculate the hoop stress, Equation 2 was used [27].

$$S_h = \frac{P * D}{2 * t_n} \tag{2}$$

where S_h is hoop stress (MPa) and t_n is pipe nominal wall thickness (mm) [27]. The pipe nominal wall thickness is the wall thickness of the pipe that can actually be purchased. It is highly unlikely that a wall thickness of exactly 13.76 mm will be able to be purchased, so the closest thickness available was 15.4 mm [42]. The calculations are shown below.

$$S_h = \frac{(9930\ kPa) * (1219.2\ mm)}{2 * (14\ mm)} * \frac{1}{1000}$$

$$S_h = 440.0\ MPa$$

To calculate the longitudinal compressional stress, Equation 3 was used [27].

$$S_L = v * S_h - (E_c * \alpha * (T_2 - T_1)) \tag{3}$$

where S_l is longitudinal compressional stress (MPa), v is Poisson's ratio, E_c is the modulus of elasticity of steel (MPa), α is the linear coefficient of thermal expansion (°C^{-1}), T_2 is maximum operating temperature (°C), and T_1 is the ambient temperature (°C). The values of v, E_c, and α are provided in Clause 4.6.6 in CSA Z662 [27]. The calculations are shown below.

$$S_L = (0.3) * (440.0\ MPa) - ((207000\ MPa) * (12 * 10^{-6}°C^{-1}) * \left((45°\mathrm{C}) - (-10°\mathrm{C})\right))$$

$$S_L = -4.62\ MPa$$

To calculate the combined stress, Equation 4 was used [27].

$$S_C = S_h + S_L \tag{4}$$

where S_C is the calculated combined stress (MPa). The calculations are shown below.

$$S_C = (440.0\ MPa) - (-4.62\ MPa)$$

$$S_C = 444.6\ MPa$$

The maximum allowable stress was required to be calculated to ensure the calculated combined stress was lower. This determine this, Equation 5 was used [27].

$$S_{Max} = 0.9 * S_C * T \tag{5}$$

where S_{Max} is the maximum allowable stress (MPa). The calculations are shown below.

$$S_{Max} = 0.9 * (444.6\ MPa) * (1)$$

$$S_{Max} = 495.0\ MPa$$

Since the calculated combined stress is lower than the maximum allowable stress, the selected design parameters are acceptable.

Appendix VIII—B Pipeline Crossing Parameters

This section outlines the design parameters used to model the pseudo project pipeline.

Appendix VIII—B1 Pipe Parameters

Table 38: Pipe Parameters [43].

Description	Symbol		Value
Pipe steel outside diameter	D_s	=	1219.2 mm [3]
Pipe steel wall thickness	t_s	=	15.4 mm
Corrosion allowance	CA	=	1.64 mm
Specified minimum yield strength of steel	$SMYS$	=	550 MPa [91]
Density of steel of pipe	ρ_s	=	7850 kg/m^3 [91]
Young's modulus of elasticity of steel	E_s	=	207000 MPa [91]
Poisson's Ratio	v	=	0.3 [91]
External coating thickness [1st coat]	t_{coat1}	=	0.35 mm [92]
External coating density [1st coat]	ρ_{coat1}	=	1440 kg/m^3 [92]
External coating thickness [2nd coat]	t_{coat2}	=	0.6 mm [92]
External coating density [2nd coat]	ρ_{coat2}	=	1440 kg/m^3 [92]

Appendix VIII—B2 Design Parameters

Table 39: Design Parameters [43].

Description	Symbol		Value
Design pressure of pipeline	P_d	=	9.93 MPa [3]
Minimum hydrostatic test pressure of pipeline	P_h	=	11.3 MPa [93]
Design temperature of pipeline (buried)	T_d	=	30 ^oC [3]
Ambient temperature of pipeline (installation)	T_{amb}	=	-10 ^oC [3]
Avg. co-efficient of friction b/w pipe & soil	μ_{soil}	=	0.3 [94]
Avg. co-efficient of friction on roller support	μ_{roller}	=	0.2 [94]
Distance between roller supports	L_{roller}	=	10 m [33]
Radius of Overbend [pipe on conveyors]	R_o	=	500 m
Drag co-efficient between pipe and bentonite	μ_{mud}		350 N/m^2 [95]
Density of bentonite in the drilled hole	ρ_{bent}	=	1078.44 kg/m^3 [95]

Appendix VIII—B3 Maximum Allowable Stress Percentages

Table 40: Maximum Allowable Stress Percentages that were selected for the crossing [43].

Description	Symbol		Value
Maximum allowable longitudinal stress	F_L	=	40 % SMYS
Combined equivalent stress [hydrotesting]	F_H	=	90 % SMYS
Combined equivalent stress [operation]	F_O	=	81 % SMYS
Safety factor for computed elastic bend radius	F_{EBR}	=	1.1 times

Appendix VIII—B4 Drilling Profile

Table 41: The drilling profile parameters that were selected for the crossing [43].

Description	Symbol		Value
Horizontal length of crossing	L_h	=	313 m
Depth of crossing w.r.t RL	*Depth*	=	10.36 m
Angle of entry of pipe string	ϑ_{in}	=	10 deg
Angle of exit of pipe string	ϑ_{out}	=	15 deg
Radius of curvature (pipe side)	R_{in}	=	680.31 m
Radius of curvature (rig side)	R_{out}		302.36 m
Entry height w.r.t RL	h_{in}	=	0.91 m
Exit height w.r.t. RL	h_{out}	=	0.3 m

Appendix VIII—B5 Parameters for Maximum Permissible Overburden on Pipe

Table 42: The parameters for the maximum permissible overburden on the pipe [43].

Description	Symbol		Value
Height of soil column above pipe	H_{soil}	=	6.096 m
Height of water column above pipe	H_{wtr}	=	4.267 m
Density of soil column above pipe	ρ_{soil}	=	2130 kg/m^3
Density of water column above pipe	ρ_{wtr}	=	1000 kg/m^3

Appendix VIII—C Additional Results from 2D Profile Analysis

The section includes the force and stress analysis outputs at different sections of the pipe of the Wapiti River crossing.

Appendix VIII—C1 Force Analysis

Table 43: Results from the force analysis.

FRICTIONAL FORCE BETWEEN ROLLERS AND PIPE							
Location of Pipe End	**Pipe on rollers (m)**	**Frictional force on rollers**		**Location of Pipe End**	**Pipe on rollers (m)**	**Frictional force due to rollers**	
Point A	314.632	29.099	MT	Point D	80.538	7.449	MT
Point B	309.250	28.601	MT	Point E	1.381	0.128	MT
Point C	190.513	17.620	MT	Point F	0.0	0.0	MT
FRICTIONAL FORCE BETWEEN SOIL AND PIPE							
Description	**Section length down hole (m)**	**Frictional force down hole**		**Description**	**Section length down hole (m)**	**Frictional force down hole**	
At Point A	0.0	0.0	MT	Section CD	109.975	10.184	MT
Section AB	5.382	0.491	MT	Section DE	79.158	30.369	MT
Section BC	118.736	2.099	MT	Section EF	1.381	0.123	MT
DRAG FORCE DUE TO BENTONITE MUD							
Description	**Section length down hole (m)**	**Drag force down hole**		**Description**	**Section length down hole (m)**	**Drag force down hole**	
At Point A	0.0	0.000	MT	Section CD	109.975	15.058	MT
Section AB	5.382	0.737	MT	Section DE	79.158	10.839	MT
Section BC	118.736	16.258	MT	Section EF	1.381	0.123	MT
FORCE DUE TO CHANGE IN ELEVATION							

Location of Pipe End	Change in elevation (m)	Force due to change in Elevation		Location of Pipe End	Change in elevation (m)	Force due to change in Elevation	
El. at Point A	0.9	0.000	MT	Section CD	0.0	0.0	MT
Section AB	0.9	0.288	MT	Section DE	10.3	3.189	MT
Section BC	10.3	3.194	MT	Section EF	0.4	0.110	MT

PIPE PULLING LOAD OUTPUT

Location of Pipe End	Pipe length down hole (m)	Angle	Direction	Pipe Section Pull Force (MT)		Total Pull Force (MT)	
At point A	0.0	10°	Downwards	(Pipe on rollers)		F_A =	29.099
At point B	5.4	10° to 0°	Downwards	F_{AB} =	0.939	F_B =	29.541
At point C	124.1	0°	Horizontal	F_{BC} =	15.162	F_C =	33.721
At point D	234.1	0° to 15°	Upwards	F_{CD}=	25.243	F_D =	48.793
At point E	313.3	15°	Upwards	F_{DE} =	44.396	F_E =	85.868
At point F	314.6	15°	Upwards	F_{EF} =	0.423	F_F =	86.163

Required pulling capacity for HDD Rig (1.25 times of F_F) **F_{Rig} =** **107.7** **MT**

Appendix VIII—C2 Stress Analysis

As shown below in Table 44, the output of the stress analysis was that all stress values on the pipe were greater than the allowable stress. To analyze the stresses further and to remediate the problem, AutoPIPE was used. The results from this analysis are shown in Appendix VIII—D AutoPIPE Simulation. As discussed in Section 6.1.3 AutoPIPE Simulation of Wapiti River Crossing Pipe Profile, the solution to alleviating these stresses was to lengthen pipe on the exit side.

Table 44: Results from the stress analysis [43].

TABLE 1.6.1 STRESS SUMMARY						
Description		**Value**		**Percentage of SMYS**		**Stress Value < Allowable Stress**
Max. Longitudinal Stress :						
• Installation condition	[$S_{L,in}$]	431.80	MPa	**78.51**	%	False
• Hydrotest condition	[$S_{L,hy}$]	552.82	MPa	**100.51**	%	False
• Operation condition	[$S_{L,op}$]	452.44	MPa	**82.26**	%	False
Max. Combined Stress :						
• Hydrotest condition	[$S_{A,hy}$]	640.83	MPa	**116.51**	%	False
• Operation condition	[$S_{A,op}$]	712.60	MPa	**129.56**	%	False

Appendix VIII—D AutoPIPE Simulation

The figures below show the results from the AutoPIPE simulation of the stresses inflicted on the pipe in different soil conditions.

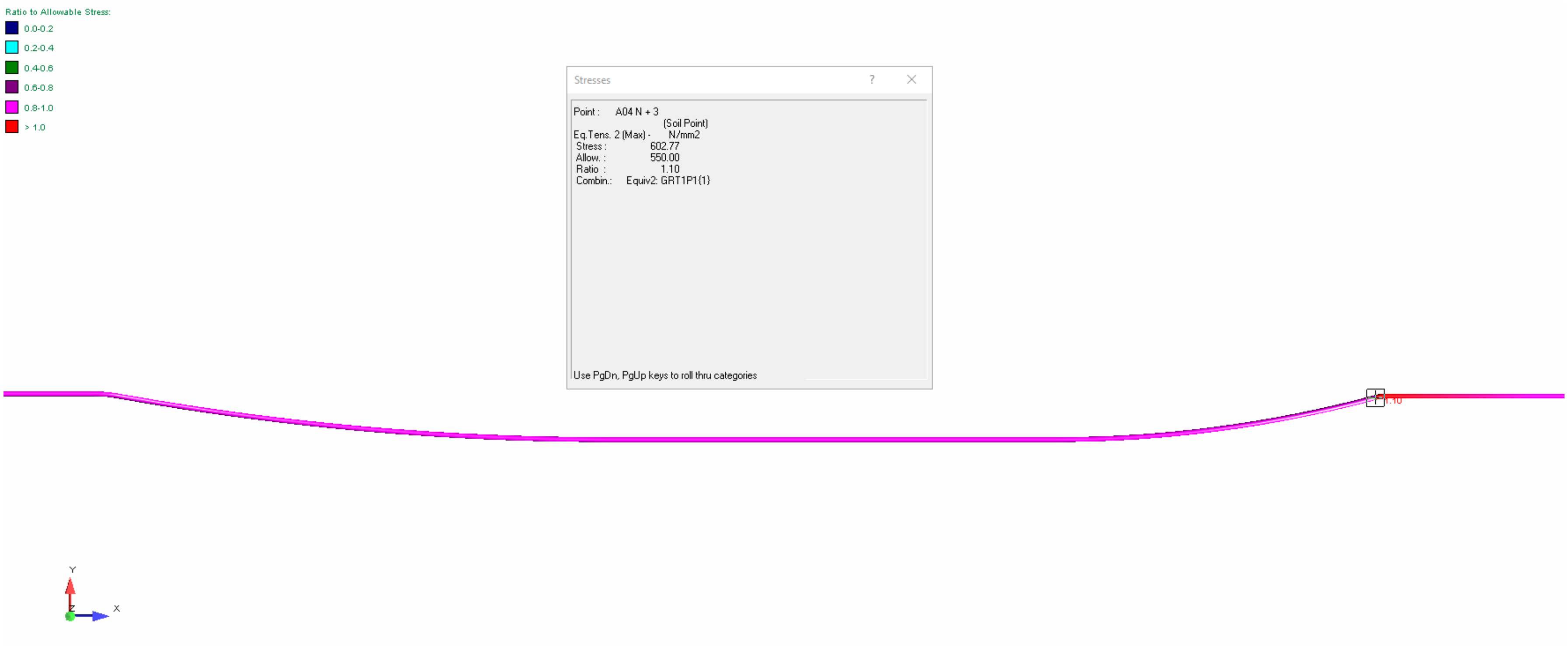

Figure 27: 28352 mm exit bend radius and soft clay [44].

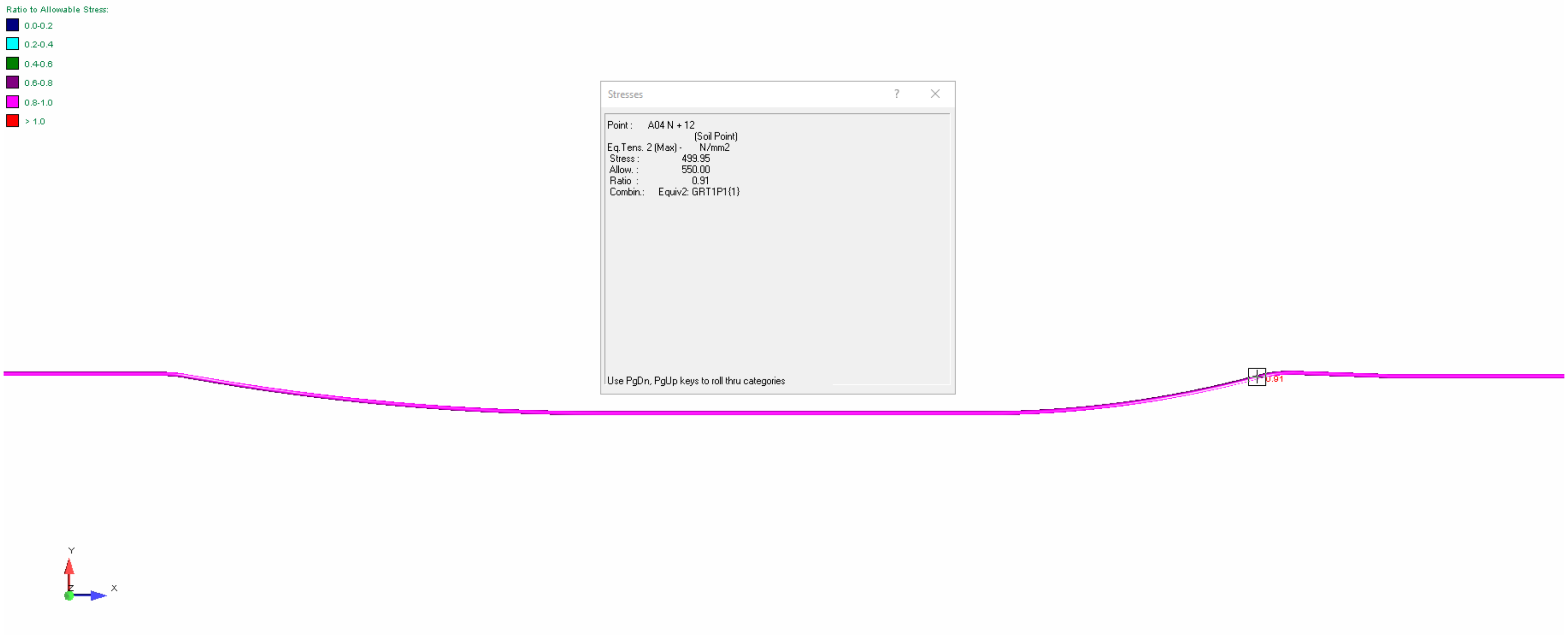

Figure 28: 36576 mm exit bend radius and soft clay [44].

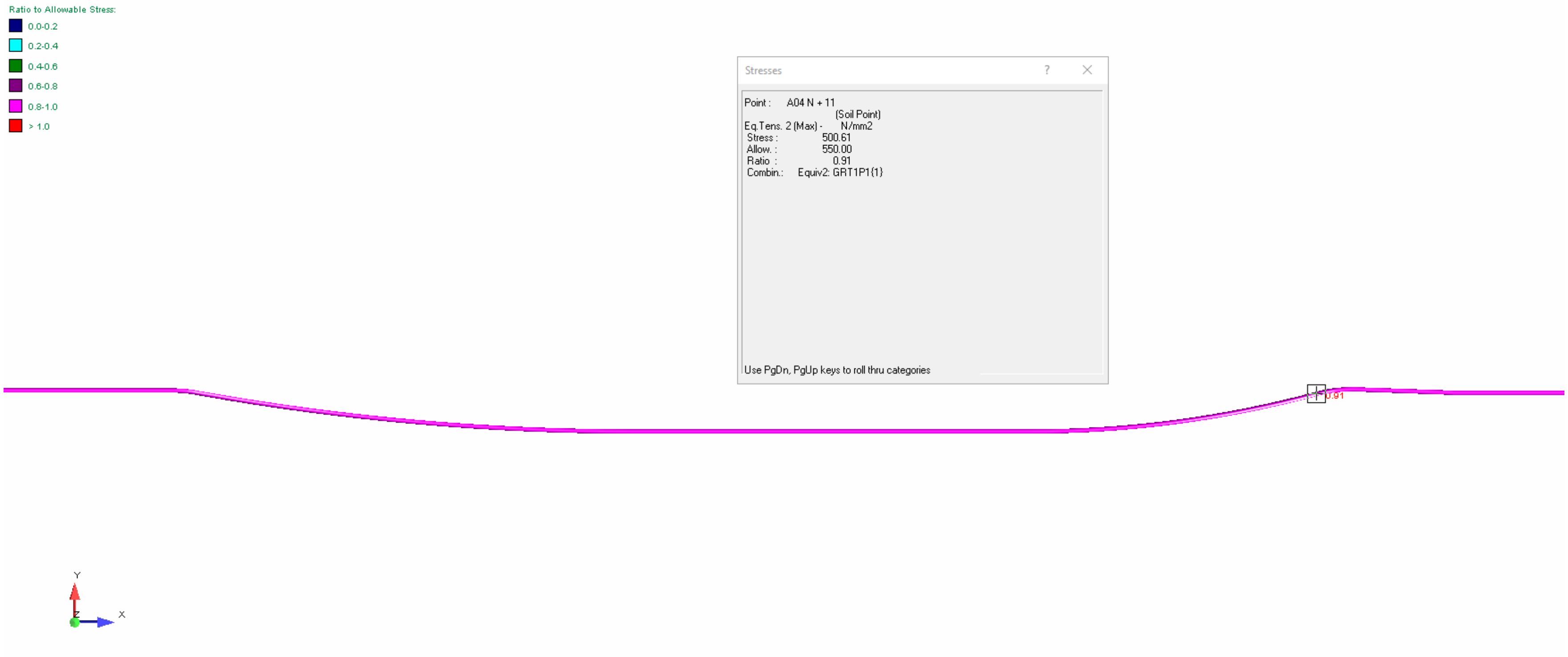

Figure 29: 36576 mm exit bend radius and stiff clay [44].

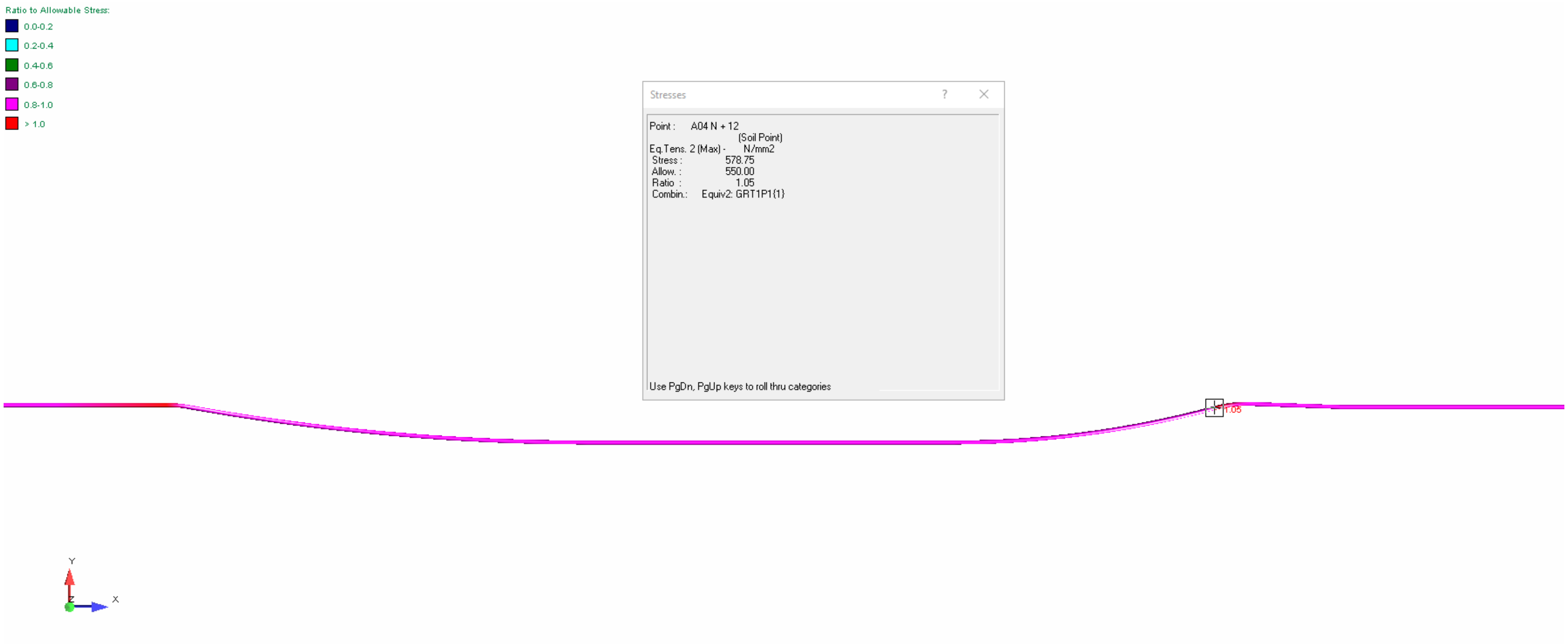

Figure 30: 36576 mm exit bend radius and loose sand [44].

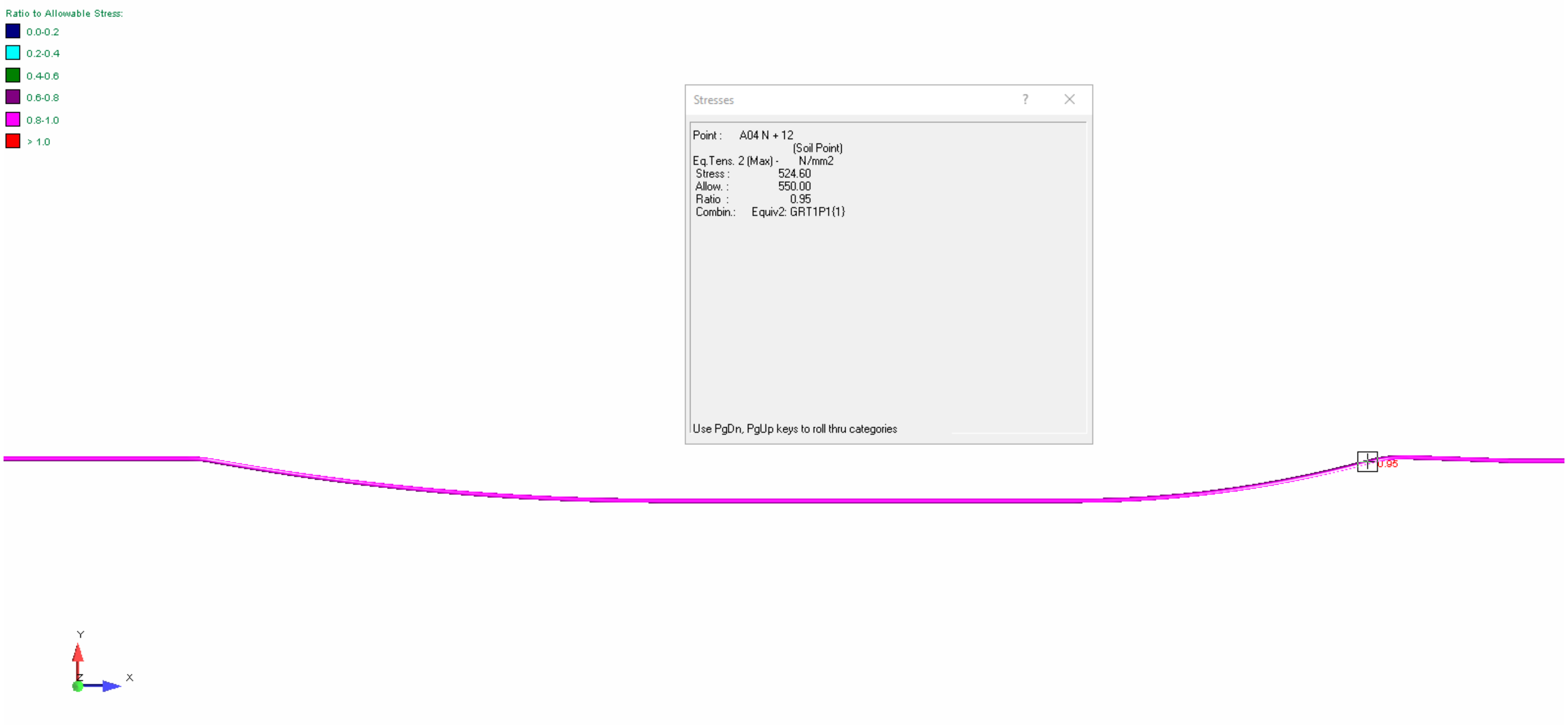

Figure 31: 36576 mm exit bend radius and compact sand *[44]*.

Appendix VIII—E General Construction Plan

Table 45: General construction plan of Wapiti River crossing that commences on January 3rd, 2022 and finishes on January 15th, 2022. The numbers in the table indicate the number of hours the task will take. For example, to mobilize the rigs to the project, it will take 12 hours/0.5 days.

Task Description	**Days (24 hr)**	**January**												
		3	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Mobilize Rigs to Project	0.5	12												
Set Up Entry/Exit Side Rigs	1.5	12	24											
Drill Pilot 18.00" Pilot Hole	3			24	24	24								
Ream 30 inch	1						24							
Ream 40 inch	1							24						
Ream 48 inch	1								24					
Ream 60 inch	1									24				
Wiper Cleaning Trip	0.5										12			
Demob Exit Rig	1										12	12		
Pull Product Line	1											12	12	
Rig Out Demobilize Entry Side	1												12	12
Total Number of Days	**12.5**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**0.5**

Appendix VIII—F Failure Modes and Effects Analysis Table for Wapiti River Crossing

Table 46 below outlines identified failure modes related to HDD crossings. The failure modes have been scored on their severity, occurrence, and detection capabilities to output an RPN. Rankings have been created according to each mode's RPN score to identify the most critical modes with rank 1 being high. Recommended actions have been developed for the highest scoring modes. These actions will help to mitigate risks during field implementation.

Table 46: FMEA completed for Wapiti River Crossing HDD steps.

Part Name, Number, & Function (Brief)		Potential Failure Mode	Potential Effect(s) of Failure	Severity	Potential Cause(s) of Failure	Occurrence	Design Verification	Detection	RPN	Rank	Recommended Actions
Reaming	The process of increasing the drill hole diameter.	Hole collapses	Reaming process is stopped, new drill path needs to be identified. Drilling process starts again.	10	Increasing the reamer size too quickly, leaving the drill hole open for too long, not firm enough soil. Drilling in soil that is not firm, drilling and reaming the hole too quickly.	6	Plan for gradual increase in reamer size. Continuously ream and then immediately go into the pullback process to avoid leaving the hole unoccupied for long periods of time. Select drilling location/depth of drill to go through soil that is firm like clay.	5	300	1	Make construction plan so that borehole is left open for the minimum amount of time. In the design plan, have multiple reaming passes while slowly increasing the reamer size and confirm with professional. Do more research on technology that maps subsurface conditions.
Drilling Process	The process of drilling the pilot hole from the entry side to the exit.	Overschedule	Delay's the project.	6	Drilling through unexpected soil conditions, not using the correct bit for the soil conditions.	8	Do a thorough geotechnical analysis of drilling location prior to project commencement. Use advanced technology to map the subsurface conditions.	6	288	2	Do more research on technology that maps subsurface conditions. Make construction plan so that it accounts for possible delays in the project.

Part Name, Number, & Function (Brief)		Potential Failure Mode	Potential Effect(s) of Failure	Severity	Potential Cause(s) of Failure	Occurrence	Design Verification	Detection	RPN	Rank	Recommended Actions
Drilling Process	The process of drilling the pilot hole from the entry side to the exit.	Drill Head breaks	Delays the project. Either a new pilot hole is required to be drilled or a tool retrieval process must be initiated.	9	Too much pressure on drill head. Overuse. Unsuitable ground conditions.	5	Design should verify subsurface conditions to a certain extent to ensure formations support drilling and mud. Experienced contractors should be used for drilling as they will understand appropriate speeds and pressures.	6	270	3	Do more research on technology that maps subsurface conditions. Ensure contractor is familiar with drill head protection.
Reaming	The process of increasing the drill hole diameter.	Overschedule	Delays the project.	6	Drilling through unexpected soil conditions, not using the correct bit for the soil conditions, many other reasons for delays.	6	Do a thorough geotechnical analysis of drilling location prior to project commencement. Use advanced technology to map the subsurface conditions.	6	216	4	Do more research on technology that maps subsurface conditions.
Drilling Process	The process of drilling the pilot hole from the entry side to the exit.	Small fluid loss to formation	Contamination of surrounding terrain with drilling mud. Additionally, more mud will be required to complete the project due to the loss.	7	Due to a natural fracture, a void, or in a high porosity/high permeability formation.	7	Design should verify subsurface conditions to a certain extent to ensure formations support drilling and mud.	3	147	5	Do more research on technology that maps subsurface conditions and inform of problematic formations that could lead to fluid loss.
Pull Product Line	The process of pulling the pipe through the reamed hole using a pull head from the exit to entry side.	Hole collapses during pullback	Pullback is stopped. Hole must be drilled and reamed again.	10	Hole is too small so there is too much friction between the pipe and soil.	3	Ensure the dimensions of the hole are accurate and reaming size is large enough for pipe to not cause too much force on hole walls.	4	120	6	Calculate the amount of drilling mud required and to determine the friction the pipe would encounter prior to pullback process.

Part Name, Number, & Function (Brief)		Potential Failure Mode	Potential Effect(s) of Failure	Severity	Potential Cause(s) of Failure	Occurrence	Design Verification	Detection	RPN	Rank	Recommended Actions
Pull Product Line	The process of pulling the pipe through the reamed hole using a pull head from the exit to entry side.	Not enough drilling mud to lubricate pullback	Friction causes pull head to disconnect from pipeline.	8	Inaccurate estimation of drilling mud required or path for drilling mud to travel through is backed up.	7	Plan ahead of the pullback process to ensure there is enough drilling mud and the technology to transport it is working.	2	112	7	Calculate amount of drilling mud required months in advance of construction and order extra in case of issue or construction needs to restart. Run tests on technology transporting drilling mud in the hole prior to completing the pullback process.
Reaming	The process of increasing the drill hole diameter.	Loss of tooling downhole	Delays the project.	6	Drilling through unexpected soil conditions, not using the correct bit for the soil conditions, not attaching the equipment correctly.	3	Do a thorough geotechnical analysis of drilling location prior to project commencement. Use advanced technology to map the subsurface conditions. Ensure contractor checks equipment before each step in the construction process.	6	108	8	Do research on GPR, ERT, and seismic technologies.
Wiper Cleaning Trip	The final pass of a reamer the size of the pipe diameter to make sure the hole is clear for the pipe to be installed.	Hole collapses and wiping pass gets stuck	Delays the project and a new drill path will need to be completed.	10	The hole was left open for too long, the soil conditions were not stable enough.	2	Plan to have the hole open for as short as possible and do thorough geotechnical analysis to complete crossing in stable, stiff soil.	5	100	9	Make construction plan so that reamed hole is left open for the minimum amount of time. Complete geotechnical study to understand properties of the soil being drilling through.
Mobilize rigs to project	The deployment of equipment and necessary machinery to the construction site in order to	Transportation delays of equipment and materials	Construction cannot commence until all required machinery and materials are on site.	8	Weather that may prohibit transportation. Unclear transportation scheduling.	4	Completed list of required construction materials well in advance. Checks to ensure all equipment has been received before	3	96	10	Account for weather conditions in planning stages closer to the construction commencement.

Part Name, Number, & Function (Brief)		Potential Failure Mode	Potential Effect(s) of Failure	Severity	Potential Cause(s) of Failure	Occurrence	Design Verification	Detection	RPN	Rank	Recommended Actions
	complete an HDD crossing.						construction commencement.				
Pull Product Line	The process of pulling the pipe through the reamed hole using a pull head from the exit to entry side.	Pipe damaged during installation	Pipe must be pulled out to fix or technology is sent through the pipe to detect and fix the damage.	8	Scratching from equipment or rigged formations underground.	3	Ensure reaming is completed to a large enough diameter prior to the pullback process. Also, complete a geotechnical study prior to construction to anticipate any rigged formations or existing pipelines underground.	4	96	10	Complete geotechnical report on area for construction to be aware of any structures underground that could damage the pipe during installation. Ensure crew completing process is trained and has experience.
Boreholes	A narrow shaft bored in the ground used to analyze the soil conditions along the drill path.	Boreholes do not go as deep as required for the crossing.	Not able to gather the required data regarding soil types/concentrations and bedrock information.	9	Unclear instructions send to geotechnical investigation team. Inaccurate drill path calculations.	3	Ensure drill path is accurate and required boreholes are mapped on the path. Have an engineer on site when boreholes are being drilled, verifying the depth requirements.	3	81	12	
Drilling Process	The process of drilling the pilot hole from the entry side to the exit.	Unstable pilot hole resulting in the hole's collapse	The pilot hole must be cleared, or a new pilot hole must be drilled extending the project timelines and costs.	10	Unstable ground conditions. Operation of drill. Drilling too fast/too slow. Too much pressure on surrounding terrain.	2	Design should verify subsurface conditions to a certain extent to ensure formations support drilling and mud. Experienced contractors should be used for drilling as they will understand appropriate speeds and pressures.	4	80	13	

Part Name, Number, & Function (Brief)		Potential Failure Mode	Potential Effect(s) of Failure	Severity	Potential Cause(s) of Failure	Occurrence	Design Verification	Detection	RPN	Rank	Recommended Actions
Wiper Cleaning Trip	The final pass of a reamer the size of the pipe diameter to make sure the hole is clear for the pipe to be installed.	Buildup of cuttings	Delays the project and may require more wiper passes to be completed.	5	Drilling fluid did not efficiently remove cuttings either because of its make-up or the rate it was injected into the hole when drilling.	4	Design for the correct use of the drilling fluid and optimize it to make sure the cuttings are removed properly considering flow rate and make-up.	4	80	13	
Set up entry/exit side rigs	The area surrounding the designated crossing where the equipment, machinery and trailers are set up.	Improper set up of drill pad	Construction process becomes significantly more difficult with an improper drill pad resulting in longer construction times.	9	Inexperienced contractors are in charge of set up. Available land does not allow for typical set up due to space or environmental conditions.	2	Ensure spacing and layout is planned beforehand once equipment has been secured and verified.	4	72	15	
Drilling Process	The process of drilling the pilot hole from the entry side to the exit.	A frac-out of drilling mud occurs, surfacing to land	Potential damage and contamination to the land resulting in extensive analysis that must be completed.	9	Uncertain ground and soil conditions. Downhole mud pressure exceeds the overburden pressure.	4	The first step is to assess the risk of frac-out prior to drilling. This can be done using specially designed software (e.g. DGeo Pipeline by Deltares) or pressure calculations. These methods compare the maximum allowable fluid pressure against the expected drilling fluid pressure. To ensure they are reliable, they require detailed information on the soils, drilling fluids and bore profile, and should be conducted by experienced personnel.	2	72	15	

Part Name, Number, & Function (Brief)		Potential Failure Mode	Potential Effect(s) of Failure	Severity	Potential Cause(s) of Failure	Occurrence	Design Verification	Detection	RPN	Rank	Recommended Actions
Reaming	The process of increasing the drill hole diameter.	Poor removal of cuttings	Makes proceeding reaming passes more difficult. Drill hole may not reach desire size. Pipe could get stuck during pullback.	6	Incorrect drilling fluid injection pressure, incorrect drilling fluid flow rate, drilling fluid not the correct consistency.	4	Test the soil properties of site prior to drilling to ensure the correct drilling fluid components are selected.	3	72	15	
Drilling Process	The process of drilling the pilot hole from the entry side to the exit.	A frac-out of drilling mud occurs, surfacing to water	Potential damage and contamination to the waterways resulting in extensive analysis that must be completed.	10	Uncertain ground and soil conditions. Downhole mud pressure exceeds the overburden pressure.	3	The first step is to assess the risk of fracout prior to drilling. This can be done using specially designed software (e.g. DGeo Pipeline by Deltares) or pressure calculations. These methods compare the maximum allowable fluid pressure against the expected drilling fluid pressure. To ensure they are reliable, they require detailed information on the soils, drilling fluids and bore profile, and should be conducted by experienced personnel.	2	60	18	
Pull Product Line	The process of pulling the pipe through the reamed hole using a pull head from the exit to entry side.	Line gets damaged or dented during pullback	Delay the project by having to excavate where pipe damage is and fix it. If damage goes unnoticed, then corrosion or leaks could occur.	5	Borehole does not follow design path and pipe does not fit the hole correctly. Angles are too sharp for the pipe to be pulled back smoothly. Casing is not used in areas where it should be to protect pipe.	4	Ensure that the borehole follows the designed path and if changes occur, the pipe is adjusted for these changes. Additionally, if casing is required in certain areas it will	3	60	18	

Part Name, Number, & Function (Brief)		Potential Failure Mode	Potential Effect(s) of Failure	Severity	Potential Cause(s) of Failure	Occurrence	Design Verification	Detection	RPN	Rank	Recommended Actions
							be used to protect the pipe.				
Boreholes	A narrow shaft bored in the ground used to analyze the soil conditions along the drill path.	Borehole contacts ground water flow and water would flood out of hole.	Damage to the surrounding land, and potential fines from the government and landowners.	7	Unknown locations of water flow beneath the land. Improper desk studies.	2	Proper desk studies should be conducted before borehole process. Only experienced and reputable geotechnical companies should be contracted.	4	56	20	
Mobilize rigs to project	The deployment of equipment and necessary machinery to the construction site in order to complete an HDD crossing.	Missing construction components such as equipment and materials	Construction cannot commence until all required machinery and materials are on site.	8	Miscommunication of required equipment or poor project planning.	2	Complete list of required construction materials well in advance. Check to ensure all equipment has been received before construction commencement.	3	48	21	
Mobilize rigs to project	The deployment of equipment and necessary machinery to the construction site in order to complete an HDD crossing.	Unavailable equipment and materials	Construction cannot commence until all required machinery and materials are on site.	8	Many HDD projects scheduled simultaneously as there are limited rigs in Canada. Fewer contractors able to work on project.	2	Plan with contractors well in advance of the project start date to ensure equipment can be secured.	3	48	21	
Drilling Process	The process of drilling the pilot hole from the entry side to the exit.	Large fluid loss to formation	Contamination of surrounding terrain with drilling mud. Additionally, more mud will be required to complete the project due to the loss.	8	Due to a natural fracture, a void, or in a high porosity/high permeability formation.	3	Design should verify subsurface conditions to a certain extent to ensure formations support drilling and mud.	2	48	21	

Part Name, Number, & Function (Brief)		Potential Failure Mode	Potential Effect(s) of Failure	Severity	Potential Cause(s) of Failure	Occurrence	Design Verification	Detection	RPN	Rank	Recommended Actions
Boreholes	A narrow shaft bored in the ground used to analyze the soil conditions along the drill path.	Boreholes completed too close to drill path and frac-out could occur.	Drilling fluid contamination to the surrounding land.	8	Not following the regulations set out regarding borehole proximity.	2	ERT and seismic refraction results should be used in conjunction with regulatory guidelines to optimize borehole placement.	3	48	21	
Reaming	The process of increasing the drill hole diameter.	Drilling fluid control is lost	Could weaken the surrounding soil or lead to frac-outs.	5	Pressure sensor is not working accurately or unplanned for soil conditions are present.	3	Do a thorough geotechnical analysis of drilling location prior to project commencement. Use advanced technology to map the subsurface conditions. Ensure the pressure sensor on bit is working properly before reaming.	3	45	25	
Drilling Process	The process of drilling the pilot hole from the entry side to the exit.	Drill is unable to follow intended path	Delays the project. The borehole could collapse.	9	Drill head veers off course due to unknown subsurface conditions or poor planning of path prior to drilling.	2	Complete a geotechnical study to be aware of the layers of soil underground and plan an optimal drilling path to reach the accurate exit point with the soil and changes in elevation in mind.	2	36	26	
Reaming	The process of increasing the drill hole diameter.	Reamer snaps off	Delay the project.	6	Forcing the reamer to move faster than it should and the forces acting on the reaming head is too strong.	2	Ensure the sensors on the bit are working accurately and take their readings into consideration when drilling. Make sure to not force the	3	36	26	

Part Name, Number, & Function (Brief)		Potential Failure Mode	Potential Effect(s) of Failure	Severity	Potential Cause(s) of Failure	Occurrence	Design Verification	Detection	RPN	Rank	Recommended Actions
							reaming passes to go too fast.				
Demobilize exit rig	The deployment of equipment and necessary machinery from the exit side of the construction site once it is not needed anymore.	Transportation method is delayed	The rig stays on site for longer than planned for and increases the cost of the project.	4	Improper planning and communication to transportation company to come and take the rig off site.	3	Create a thorough and detailed construction plan and communicate with the transportation company to ensure they are aware of the plan and when they should arrive to site.	3	36	26	
Boreholes	A narrow shaft bored in the ground used to analyze the soil conditions along the drill path.	Boreholes may not capture an accurate representation of the drill path.	Inaccurate data about soil types and locations can lead to many construction problems such as fluid loss, improper tooling usage and collapse of borehole.	9	The boreholes may be located too far away from the drill path and no longer are an accurate representation of the crossing. Anomalies in the earth interfere with the borehole results.	2	ERT and seismic refraction can help verify the results of a borehole investigation and flag any variances for further examination.	2	36	26	
Boreholes	A narrow shaft bored in the ground used to analyze the soil conditions along the drill path.	Inconclusive borehole data.	Inconclusive data about soil types and locations can lead to many construction problems such as fluid loss, improper tooling usage, and collapse of borehole.	9	Inexperienced contractors may lead to unclear results and in turn inconclusive data. Anomalies in the land may also present inconclusive data.	2	The ERT and seismic reflection results should be used to optimize borehole locations to avoid anomalies and only highly experienced contractors should be hired.	2	36	26	
Pull Product Line	The process of pulling the pipe through the reamed hole using a pull head from the exit to entry side.	Coating damaged during installation	Pullback is stopped. Pipe is pulled out and coating is reapplied.	7	Scratching from equipment or rigged formations underground.	5	Ensure coating meets CSA Z662 regulations with extra coating in places that are foreseen to undergo possible damage during installation.	1	35	31	

Part Name, Number, & Function (Brief)		Potential Failure Mode	Potential Effect(s) of Failure	Severity	Potential Cause(s) of Failure	Occurrence	Design Verification	Detection	RPN	Rank	Recommended Actions
Rig out demobilize entry side	The deployment of equipment and necessary machinery from the entry side of the construction site at the end of the project.	Transportation method to remove equipment is delayed	Construction equipment cannot be removed from the site.	8	Weather that may prohibit transportation. Unclear transportation scheduling.	4	Prepare equipment prior to the scheduled date for pick-up. If delayed, account for this early on in the planning and include extra costs in the case that weather is not safe to travel in.	1	32	32	
Pull Product Line	The process of pulling the pipe through the reamed hole using a pull head from the exit to entry side.	Reamed hole is not fully cleared, and pipe cannot pass through	Delay the project by having to complete more reaming passes before the pipe is pulled into the hole.	5	The drilling fluid was not utilized correctly, the first wiper pass did not effectively clear the path.	2	Optimize the drilling fluid usage prior to drilling, select a reamer for the wiper pass that is as large or larger than the pipe to make sure the pipe can fit in the hole.	3	30	33	
Pull Product Line	The process of pulling the pipe through the reamed hole using a pull head from the exit to entry side.	Pull head snaps off	Delays the project by having to remove the pipe back out the hole and reattach the pull head.	6	Improper welding of the pull head onto the pipe, pulling force is too strong for weld, friction between pipe and soil is too large.	2	Ensure welding is done properly and is secure, ensure the drilled hole is large enough for pipe.	2	24	34	
Boreholes	A narrow shaft bored in the ground used to analyze the soil conditions along the drill path.	Cannot get the equipment to do the boreholes on site.	Unable to get borehole data and in turn soil types, formations, and ground conditions.	9	Location of HDD crossing is remote, and the location is unable to be graded to bring in equipment.	1	Only locations capable of supporting required equipment should be considered as it will also be pivotal for the construction.	1	9	35	
Pull Product Line	The process of pulling the pipe through the reamed hole using a pull head from the	Hole is not large enough to pull pipe through	Pipe must be pulled out from the exit side and hole must be reamed even larger.	8	Inaccurate drilling of hole diameter or poor estimation of diameter required.	1	Ensure the dimensions of the hole are accurate and reamer size is large enough for pipe to not cause	1	8	36	

Part Name, Number, & Function (Brief)		Potential Failure Mode	Potential Effect(s) of Failure	Severity	Potential Cause(s) of Failure	Occurrence	Design Verification	Detection	RPN	Rank	Recommended Actions
	exit to entry side.						hole destruction during installation.				

Appendix VIII—G Detailed Economic Analysis of Wapiti River Crossing Without Solution Implemented

Table 47: Detailed cost analysis of Wapiti River crossing without solution implemented.

Costs		Quantity (Low)	Quanitity (High)	Hours to Complete	Cost (Low)	Cost (High)	Overall Cost (Low)	Overall Cost (High)
Materials	Coating for Joints	N/A			$5,000/weld	$10,000/weld	Included in Welding	
	Coated Pipe	200m			$1,177.50/meter		$ 373,912.50	$ 373,912.50
	Mud	292.5m^3	304.2m^3		$12/bag(~1.3m^3)		$ 2,700.00	$ 2,808.00
	Water	585m^3	608.4m^3		$150/m^3		$ 87,750.00	$ 91,260.00
	Fuel	2,000 L/day		18 shifts (9 days)	$4,000/day	$5,000/day	$ 50,000.00	$ 62,500.00
	Ball Valve	2			$100,000/valve		$ 200,000.00	$ 200,000.00
	Casing	20m	40m		$8,000/meter		$ 160,000.00	$ 320,000.00
Equipment	Drill Rig	1		6 shifts (3 days)	$3,000/meter	$5,500/shift	$ 600,000.00	$ 600,000.00
	Welding (+Coating and SideBooms)	1	2				$ 600,000.00	$ 600,000.00
	Crane	2	4	4 shifts (2 days)	$2,000/hr		$ 192,000.00	$ 384,000.00
	Side Booms	1	2	Price included in Welding			Included in Welding	
	Drill Head	1	3	Price included in Drill Rig			Included in Drill Rig	
	Reamer	1	3	Price included in Drill Rig			Included in Drill Rig	
	Power Unit & Generators	1		25 shifts (12.5 days)	$450/day	$550/day	$ 5,625.00	$ 6,875.00
	Water Pump	1		25 shifts (12.5 days)	$2,000/shift		$ 36,000.00	$ 36,000.00
	Mud Mixing Tank	1		25 shifts (12.5 days)	$750/day		$ 9,375.00	$ 9,375.00
	Mud Pump	1		25 shifts (12.5 days)	$2,000/shift		$ 50,000.00	$ 50,000.00
	Exit Mud containment Tanks	1	2	25 shifts (12.5 days)	$50/day		$ 625.00	$ 1,250.00
	Cuttings Tank	1		25 shifts (12.5 days)	$50/day		$ 625.00	$ 625.00
	Pipe Racks	1		25 shifts (12.5 days)	$1,000/day	$3,000/day	$ 12,500.00	$ 37,500.00
	Testing Pigs	3			$10,000/project		$ 10,000.00	$ 10,000.00
	Pipe Rollers	20		25 shifts (12.5 days)	$400/day		$ 100,000.00	$ 100,000.00
	Bending Machine	1		8 shifts (4 days)	$5,000/day	$10,000/day	$ 20,000.00	$ 40,000.00
	Wire line Steering system	1		6 shifts (3 days)	$6,500/day		$ 19,500.00	$ 19,500.00
	Mud Motor	1		6 shifts (3 days)	$16,000/day		$ 48,000.00	$ 48,000.00
	Drill recorder	1		25 shifts (12.5 days)	$7,000/day		$ 87,500.00	$ 87,500.00
	Centrifuge	1		25 shifts (12.5 days)	$3,255/day		$ 40,687.50	$ 40,687.50
Labour/Construction	Labourers	10	15	25 shifts (12.5 days)	$400/day	$600/day	$ 5,000.00	$ 7,500.00
	Hydro Testing	N/A		2 days	$4,000/day	$5,000/day	$ 8,000.00	$ 10,000.00
	Geotechnical Drilling			1 day	$250/hr	$300/hr	$ 6,000.00	$ 7,200.00
	Trucking of pipe				Project Estimate		$ 80,000.00	$ 100,000.00
	Hydrovac			25 shifts (12.5 days)	$2,500/day		$ 31,250.00	$ 31,250.00
	Trucking				Project Estimate		$ 11,000.00	$ 22,000.00
Geotechnical Investigation	Boreholes	2	2				$ 65,000.00	$ 65,000.00
	ERT Survey and Analysis						N/A	N/A
	Seismic Refraction Survey and Analysis						N/A	N/A
Miscellaneous	Land				Project Estimate		$ 30,000.00	$ 30,000.00
	Drilling Mud Disposal	585m^3	608.4m^3	56 loads	$125/load (~8m^3)		$ 9,140.63	$ 9,506.25
	Washroom	1	2	25 shifts (12.5 days)	$100/day		$ 1,250.00	$ 2,500.00
	Control Room	1		25 shifts (12.5 days)	$100/day		$ 1,250.00	$ 1,250.00
	Lights	4	6	25 shifts (12.5 days)	$300/day		$ 15,000.00	$ 22,500.00
Total							**$ 2,969,690.63**	**$ 3,430,499.25**

Appendix IX – Additional Geophysics Background Research

This section discusses the research that was completed on MASW and seismic reflection.

Appendix IX—A Multichannel Analysis of Surface Waves

Multichannel analysis of surface waves, also known as MASW, is a non-intrusive method of analyzing subsurface conditions [96]. The profiling method operates by utilizing surface wave (ground roll) propagation, more specifically their shear-wave velocities, to determine ground stiffness [97]. Research has shown that shear-wave velocity is the best indicator of a material's stiffness [98]. This method can be used in either 1D, 2D or 3D and up to a maximal depth of 60m, however, in practice it is more commonly used up to 30m [96] [97].

MASW differs from seismic refraction and reflection as it uses lower frequency surface waves, typically between 1-30Hz [98]. It is also used for shallower investigations and preferred over other methods as the cost is typically lower for field operation, data collection, and data analysis [98].

Data is collected via a multichannel recorder system and receiver. It is common to use 24 or more geophones equally spaced in the field to collect the data. These geophones can be spread out over a distance of up to 200m [98]. The length of the receiver array of geophones positively corresponds to the depth of the investigation, while the distance between geophones negatively corresponds to the data resolution [97].

There are two types of MASW: active and passive. The active method achieves its analysis by deploying waves through an impact source [98]. A sledgehammer is a common example [98]. Passive analysis works by utilizing "naturally" and "culturally" produced waves. Natural waves are described as waves produced by events such as thunder, or tides, and cultural waves from events such as traffic [98]. The passive method is implemented when a deeper analysis is required as the produced waves are larger [98]. A comparison of the wavelengths from both methods can be seen below in Figure 32.

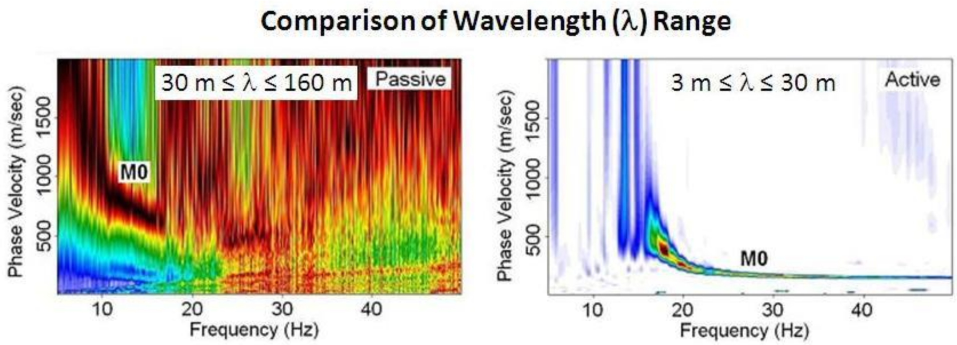

Figure 32: Comparison of wavelength ranges from passive and active MASW [97].

Appendix IX—B Seismic Reflection

Seismic reflection uses sound waves to determine the subsurface conditions. The method measures the time it takes for the reflection to travel through the ground and reflect back to the surface [99]. This information can be used to determine the depth of the features being investigated. This method works well for both land and water applications [99]. For land applications, truck-mounted vibrators or dynamite is used to create the sound waves and geophones are used to detect the reflected wave [99]. For water applications, air guns are attached to ships to make the sound waves and then hydrophones detect the reflected ray [99]. The data can be gathered and processed to produce 2D or 3D images. The typical set up for both land and water applications are shown in Figure 33 and Figure 34.

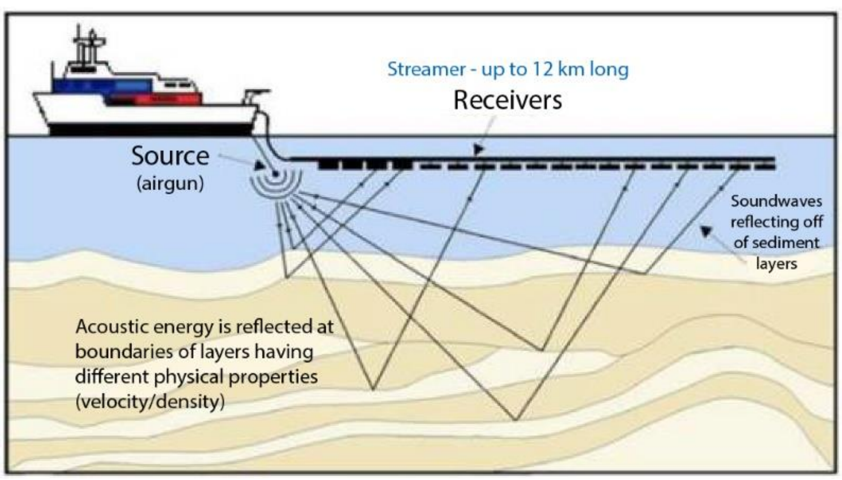

Figure 33: The equipment and set up for the seismic reflection method for water applications [99].

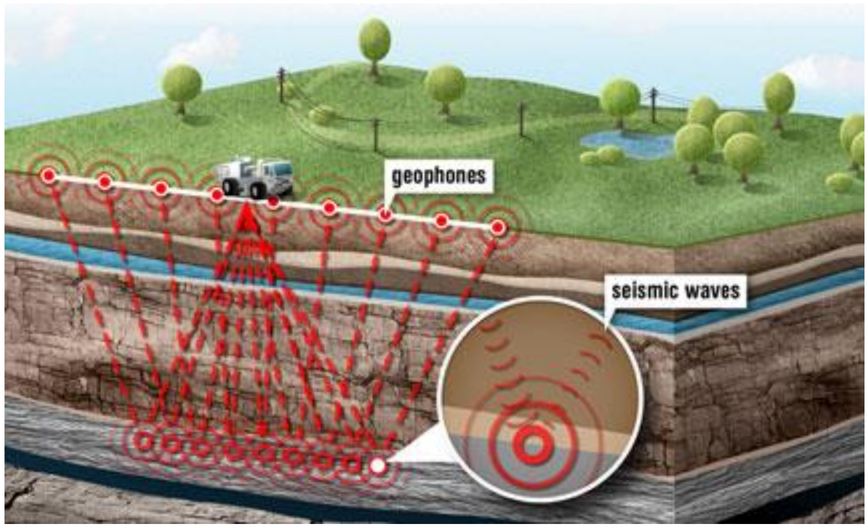

Figure 34: The equipment and set up of the seismic reflection method for land applications [99].

An advantage to utilizing this method is that it can be used for depths greater than 25-30 metres [54]. Another advantage for this project is that this technique is very well suited for water applications [99]. This is because water cannot transmit shear waves that are used in many other applications but can transmit sound waves [99]. A disadvantage to using this method is that it can be very expensive due to the data processing requirements [54].

Appendix X – Safety and Regulations for Geophysical Surveys

Safety and regulatory research was conducted for geophysical surveys proposed in the solution. The relevant information and value it provided to the project can be found below in Table 48.

Table 48: Safety and regulatory guidelines for geophysical surveys and the value they provide.

Topic of Interest	Relevant Information	Value
Land Regulations		
Training Required [61]	• Training should include hazard identification, use of PPE, first aid, emergency response procedures, company and client policies, governmental regulations, and hands-on training for particular tasks. • Crew should maintain training records. • Timing of Training: 1. Pre-Employment: records of prior training should be considered in planning for new employees' training needs. 2. Orientation: hazards and PPE should be understood prior to starting a new job. 3. On-The-Job-Training: coaching, hands on demonstration of tasks. 4. Regulatory Training: provided as required by law or contract. 5. Verification of Competency: competency should be verified upon conclusion of the training. 6. HSE Meetings: departmental HSE meeting should be held of the crew weekly, and crew HSE meetings monthly. Daily tailgate meetings of 5-10 minutes duration for all crews. 7. Refresher Training: refresher training may be needed if a job task content changes. • Training and competency assessment programs should be aligned with OGP M3 - HSE competence assessment training guidelines for the geophysical industry Report No: 6.78/292 - June 1999.	• Outlined training required for geophysical investigations and steps for implementation.
Incident Reporting and Investigation [61]	• All incidents (accidents and near misses), hazardous situations, unsafe acts and conditions should be reported as per the company procedures, client or regulatory requirements. • All incident reports and high potential events should be investigated, reviewed, and actioned in an effort to prevent future occurrence of a similar event.	• Outlined how to report an incident during geophysical surveys.
Lightening Protection [61]	• Suspend all explosive operations. If carrying explosives, lay them down and move at least 30m away. Wait 30 minutes after the storm has passed over to continue the task.	• Outlined how to conduct geophysical

Topic of Interest	Relevant Information	Value
	• Disconnect all lines from recording instruments. Make sure all recording cables and geophones are not touching fences. Disconnect all cable lines at as many places as practical. • Lay all metal tools, loading and survey range poles, pipe or drill stems on the ground and away from you. • Suspend operations and move clear of flammable and explosive materials. • Suspend small boat operations; personnel get off the water.	surveys that uses explosives.

Ice Safety [61]	• Plan your work with the following in mind:
	  o What you plan to do, where and for how long.
	  o Conditions and limits on the ice cover.
	  o Weight of the load you plan to put on the ice cover.
	  o Sudden changes in temperature (±20°C in 24 hours).
	  o Be trained on self-rescue in freezing water.
	• Wear warm clothing, rubber-soled shoes, insulated waterproof gloves, a whistle, high visibility flotation suit and carry ice rescue picks.
		• Outlined how to conduct geophysical surveys that are completed on ice.

Boreholes [62]	• Work plan should be developed prior to implementing the logging program. • Equipment decontamination is required before, after and between individual boreholes. • Personnel conducting the survey should have specialized training or experience with borehole geophysics. • Personnel operating logging equipment should have an understanding of the theory, field procedures and methods of log interpretation. • A geoscientist, with experience in borehole geophysics, who understands the project objectives and local geohydrology may need to be available to examine logging results during logging operations when consistent with objectives of the program. This geoscientist is responsible for determining whether the instructions selected in the prelogging conference are being followed and whether changes should be made. • Log interpretation should be performed by a geoscientist with experience in borehole geophysics and knowledge of the site geology and hydrology. • A documentation plan for both the analog plot and digital data file should be established and become part of the work plan. Documentation of the following procedures is needed: calibration of logging probes, field operation of geophysical logging equipment, applicable decontamination, and format for presenting geophysical well log data. Repair, standardization, and calibration information should also be documented.	• Outlined regulations to follow when drilling boreholes.

Topic of Interest	Relevant Information	Value
	• Document all field problems including equipment malfunctions. This should include the steps taken to solve the problem and how the logs might have been affected. Repeat runs and field standardization should be more frequent when equipment problems occur. The use of one borehole on the project to check the probe response may aid in the identification of equipment or other problems. Probes should be recalibrated in a physical model after major repairs have been made. • Equipment Required: o Logging probes. o Logging cable. o Draw Works- moves logging cable and probe up and down borehole. o A depth measurement system which provides probe depth information for the interfaces and surface controls and recording systems. o Surface interfaces and controls that provide some or all of the following: electrical connection, signal conditioning, power, and data transmission between the recording system and probe. ▪ Recording system includes the digital recorder and an analog display or hard copy device.	
Electrical Resistivity Tomography	• Cables should be monitored by an operator in real-time during a survey to ensure safety on the job of everyone on site and in surrounding area. [63] • If cable is left for a time-lapse survey, it is buried or attached to a non-conductive borehole. [63] • Equipment Required: [64] o Electrodes. o Transmitter (power supply). o Receiver (acquisition). o Cables.	• Outlined regulations to follow when conducting an ERT survey.
Seismic Refraction [65]	• Information from previous seismic refraction surveys in the area, knowledge of the geology, published references containing the seismic velocities of earth materials, and published reports of seismic refraction studies performed under similar conditions should be used. • Numerous approaches are used to quantitatively interpret seismic refraction data; however, the most commonly used interpretation methods are classified into two general	• Outlined regulations to follow when completing a seismic refraction survey.

Topic of Interest	Relevant Information	Value

	groups: methods that are used to define planar refractors and methods that are used to define nonplanar refractors.
	• Personnel not having specialized training and experience should be cautious using this technique and get assistance from qualified professionals.
	• Equipment Required:
	  o Logging probes.
	  o Logging cable.
	  o Draw Works- moves logging cable and probe up and down borehole.
	  o A depth measurement system which provides probe depth information for the interfaces and surface controls and recording systems.
	  o Surface interfaces and controls that provide some or all of the following: electrical connection, signal conditioning, power, and data transmission between the recording system and probe.
	    ▪ Recording system includes the digital recorder and an analog display or hard copy device.	

	Marine Regulations	
Small Boat Operations [61]	• Consider hazards such as predators, floating debris, low hanging limbs, shallow water, currents, tides, tidal bores, flash floods etc. • Boat should be equipped: approved flotation devices, fire extinguisher, extra line or rope, paddles, first aid kit, extra prop, shear pins, flashlight, ample fuel, kill-cord, and waterproof radio. • Personal flotation devices should be worn when operating. • Do not operate equipment and watercraft at night unless sufficient lights enable safe operations. • All personnel boarding a small boat should have been given the necessary HSE job-specific training in compliance with the contractor’s HSE policy and procedures. • The training should comply with the OGP /IAGC Safety Training Guidelines for Geophysical Personnel. • All members of the small boat crew should have been trained in basic first aid/CPR and overboard rescue and retrieval.	• Outlined how to conduct geophysical surveys using small boats.
Safety Training [66]	• Each company shall have a defined minimum level of training for all personnel. All employees should have completed this minimum training before travelling offshore.	• Provided guidelines for safety training

Topic of Interest	Relevant Information	Value
	• All personnel shall attend a Basic Offshore Sea Survival (BOSS) training course prior to working offshore.	for workers on an offshore project.
Incident Reporting [66]	• All accidents, incidents, near misses, hazardous situations, unsafe acts and conditions should be reported as per your company procedures, client or regulatory requirements. • All reports should be analyzed and actioned. Reports referring to serious accidents and reports referring to incidents with high potential risk shall be investigated, reviewed, and actioned in an effort to prevent future occurrence of a similar event.	• Outlined how to report an incident during geophysical surveys in a marine environment.
Personal Protective Equipment [66]	• Hard hats and protective footwear must be worn as required by company policy, crew procedures and by posted instructions.	• Outlined PPE required for offshore projects.
Deployment and Recovery of In-Sea Equipment [66]	• Check the operation and condition of all components of the In-Sea equipment system before starting work. • A check on the expected weather conditions, water depth, and vessel traffic should be made before commencing any marine or geophysical operation. • All In-Sea handling equipment should be operated only by or under close supervision of, a properly trained person. • Care should be taken when stopping the cable to attach or maintain depth controllers or similar attachments. • When cable guiding devices/heads are used, personnel should be aware that they may move due to the stress applied by the seismic cable. They should be properly closed so that the seismic cable cannot come out violently and hit nearby personnel. The cables and ropes should be regularly monitored for excessive tension or stress. • All personnel must understand the procedures before recovery of any equipment. Check expected weather conditions, water depth, obstructions and vessel traffic before commencing any marine geophysical operation. • Ropes and cables under tension are potentially dangerous. All personnel should stand in a protected position. When recovering equipment, care must be taken regarding the tension of cables and ropes.	• Outlined how to deploy and recover hydrophones if a boat is used for a seismic refraction survey.
Environmental Mitigations [67]	• Minimize the sound energy employed to achieve the purpose of the survey. • Gradual start-up of a sound source to allow marine mammals, sea turtles and other species to move away.	• Outlined environmental considerations for

Topic of Interest	Relevant Information	Value
	• Immediate shutdown of the sound if endangered species are observed within 500m of the sound source. • Use of qualified observers to monitor the survey operations. • Avoidance of critical marine habitats, species migration routes and spawning areas.	projects near and in water.
General Safety and Regulations		
Alberta Occupational Health and Safety Regulation [40]	• Part 1: General. • Part 4: Records and Fees. ○ 34.1 Employer records of certificates and permits. • Part 5: Programs, Approvals and Designated Organizations.	• Provided safety requirements for all labour projects in Alberta.
Planning Horizontal Directional Drilling for Pipeline Construction [16]	• Section 6: Geotechnical.	• Outlined steps to conduct a geophysical survey.

Appendix XI – Geophysics Failure Modes and Effects Analysis

Table 49 below outlines the 19 identified failure modes related to the proposed solution. The failure modes have been scored on their severity, occurrence, and detection capabilities to output an RPN. Rankings have been created according to each mode's RPN score to identify the most critical modes with rank 1 being high and 19 low. Recommended actions have been developed for the 5 highest scoring modes. These actions will help to mitigate risks during field implementation.

Table 49: FMEA completed on the new proposed solution of ERT and seismic refraction.

Part Name, Number, & Function (Brief)		Potential Failure Mode	Potential Effect(s) of Failure	Severity	Potential Cause(s) of Failure	Occurrence	Design Verification	Detection	RPN	Rank	Recommended Actions
Seismic Refraction	Geophysics method for imaging subsurface conditions that measures the velocity of refracted waves.	Geophones do not detect the waves.	This could create inconclusive data results and require more tests/money.	7	There could be blockage in the ground of the waves due to large boulders or objects.	8	Complete ERT and boreholes alongside seismic refraction to have more data to interpret and make conclusions.	5	280	1	Review the data on-site to ensure collection was successful and all required inputs were retrieved. Review possible faults so that mitigation strategies can be implemented to reduce the risk of failure occurring.
Seismic Refraction	Geophysics method for imaging subsurface conditions that measures the velocity of refracted waves.	Cables get caught along water crossing.	This could possibly destroy the equipment, delay the survey, or cause for a hydrophone to be lost.	8	The current could be strong enough so that the hydrophones cannot stay in place or the survey equipment could be set up poorly.	7	Analyze the vegetation in the river prior to the survey as well as test if the current is too strong for accurate results.	3	168	2	Study the area prior to conducting the survey and have people prepared with rods on the river sides to untangle the hydrophones if it occurs.
Data Processing and Analysis	Converting the gathered data from the geophysics methods into useful outputs.	Even after completing all the surveys, anomalies could occur in the subsurface conditions and cause complications.	HDD project could still experience some complications due to unplanned for ground conditions.	8	Since using the spreads attached to boats only map areas perpendicular to the crossing, there are still sections under the water body that are not surveyed.	4	Complete as many surveys in the water body as possible using the boats to make the data gathered as continuous as possible.	4	128	3	If all data points to an anomaly, consider doing additional investigations to prevent further complications in the construction process. A borehole can be utilized to verify results.
Seismic Refraction	Geophysics method for imaging subsurface conditions that measures the velocity of refracted waves.	Geophone that is used on ice gets water damage and breaks.	This could destroy the equipment, require money to replace the geophone, and delay the survey.	7	Ice is not stable enough or the geophone is not installed correctly.	4	Test the thickness of the ice days prior to conducting the survey to ensure it is at least 10 inches so that it is safe to walk on.	3	84	4	Ensure contracting crew is equipped to handle conditions on-site and brings all required equipment in case of accidents.

Part Name, Number, & Function (Brief)		Potential Failure Mode	Potential Effect(s) of Failure	Severity	Potential Cause(s) of Failure	Occurrence	Design Verification	Detection	RPN	Rank	Recommended Actions
Boreholes	A narrow shaft bored in the ground used to analyze the soil conditions along the drill path.	Boreholes do not go as deep as required for the crossing.	Not able to gather the required data regarding soil types/concentrations and bedrock information.	9	Unclear instructions sent to geotechnical investigation team. Inaccurate drill path calculations.	3	Ensure drill path is accurate and required boreholes are mapped on the path. Have an engineer on-site when boreholes are being drilled, verifying the depth requirements.	3	81	5	Review construction plan and worst-case scenario for depth to ensure boreholes collect all required data.
Seismic Refraction	Geophysics method for imaging subsurface conditions that measures the velocity of refracted waves.	Boats cannot access water crossing.	This can affect the validity of results as data cannot be collected over the required area.	8	River is too small for a boat or current is too strong.	9	Measure the current, width, and depth of river prior to conducting the survey to decide the best way to collect the data.	1	72	6	
Seismic Refraction	Geophysics method for imaging subsurface conditions that measures the velocity of refracted waves.	Spread of hydrophones becomes detached and lost in the water.	This could destroy the equipment and delay the survey while also costing more money to replace the hydrophones.	8	The current could be strong enough so that the hydrophones cannot stay in place or the survey equipment could be set up poorly.	4	Analyze the vegetation in the river prior to the survey as well as test if the current is too strong.	2	64	7	
Boreholes	A narrow shaft bored in the ground used to analyze the soil conditions along the drill path.	Borehole contacts ground water flow and water floods out of hole.	Damage to the surrounding land and potential fines from the government and landowners.	7	Unknown locations of water flow beneath the land. Improper desk studies.	2	Proper desk studies should be conducted before borehole process. Only experienced and reputable geotechnical companies should be contracted.	4	56	8	
Boreholes	A narrow shaft bored in the ground used to analyze the soil conditions along the drill path.	Boreholes completed too close to drill path and frac-out could occur.	Drilling fluid contamination to the surrounding land.	8	Not following the regulations set out regarding borehole proximity.	2	ERT and seismic refraction results should be used in conjunction with regulatory guidelines to optimize borehole placement.	3	48	9	
Boreholes	A narrow shaft bored in the ground used to analyze the soil conditions along the drill path.	Boreholes may not capture an accurate representation of the drill path.	Inaccurate data about soil types and locations can lead to many construction problems such as fluid loss, improper tooling usage, and collapse of borehole.	9	The boreholes may be located too far away from the drill path and no longer are an accurate representation of the crossing. Anomalies in the earth interfere with the borehole results.	2	ERT and seismic refraction can help verify the results of a borehole investigation and flag any variances for further examination.	2	36	10	

Part Name, Number, & Function (Brief)		Potential Failure Mode	Potential Effect(s) of Failure	Severity	Potential Cause(s) of Failure	Occurrence	Design Verification	Detection	RPN	Rank	Recommended Actions
Boreholes	A narrow shaft bored in the ground used to analyze the soil conditions along the drill path.	Inconclusive borehole data.	Inconclusive data about soil types and locations can lead to many construction problems such as fluid loss, improper tooling usage, and collapse of borehole.	9	Inexperienced contractors may lead to unclear results and in turn inconclusive data. Anomalies in the land may also present inconclusive data.	2	The ERT and seismic refraction results should be used to optimize borehole locations to avoid anomalies and only highly experienced contractors should be hired.	2	36	10	
ERT	Geophysics method for imaging subsurface conditions using resistivity measurements.	Electrode array becomes detached and lost in water.	Not able to gather data. This could destroy the equipment and delay the survey while also costing more money to replace the equipment.	6	Did not securely attach the spread to either the boat or the sides of the river. The current could be strong enough so that the electrodes cannot stay in place or the survey equipment could be set up poorly.	3	Ensure the attachment of the array is secure prior to completing the survey. Analyze the vegetation in the river prior to the survey as well as test if the current is too strong.	2	36	10	
Seismic Refraction	Geophysics method for imaging subsurface conditions that measures the velocity of refracted waves.	Machinery used as a sound source malfunctions and does not produce waves.	This could delay the survey and cause more money to acquire new equipment.	6	This technology could be outdated or affected by the weather.	3	Run tests with the equipment beforehand and calibrate it.	2	36	10	
Data Processing and Analysis	Converting the gathered data from the geophysics methods into useful outputs.	Data is not clear, and the soil layers cannot be mapped.	Not being able to use the information to help with the HDD process.	8	Surveys not completed correctly, or the equipment malfunctioned.	2	Ensure high quality and new equipment is used. Make sure the geophysics team is skilled and reputable.	2	32	14	
ERT	Geophysics method for imaging subsurface conditions using resistivity measurements.	Electrodes cannot go far enough through the ice.	Not able to gather the correct data or any data regarding the subsurface.	6	The ice is thicker than expected. Incorrect tools to plant the electrodes.	2	Be knowledgeable of the ice thickness prior to the survey.	2	24	15	
ERT	Geophysics method for imaging subsurface conditions using resistivity measurements.	Ice breaks.	Could damage or lose electrodes. Electrodes could be in incorrect position for gathering data.	6	The ice was thinner than expected.	2	Be knowledgeable of the ice thickness prior to the survey.	2	24	15	
ERT	Geophysics method for imaging subsurface conditions using	Electrode array gets caught along crossing.	The data collected may be affected as the electrode could be in the wrong location. May not	3	Not being cautions enough of surrounding environment or when deploying the spread.	2	Scan the area before the survey to make sure there are no large branches etc. that the	2	12	17	

Part Name, Number, & Function (Brief)		Potential Failure Mode	Potential Effect(s) of Failure	Severity	Potential Cause(s) of Failure	Occurrence	Design Verification	Detection	RPN	Rank	Recommended Actions
	resistivity measurements.		be able to retrieve the spread.				spread could get caught on.				
Boreholes	A narrow shaft bored in the ground used to analyze the soil conditions along the drill path.	Cannot get the equipment to do the boreholes on-site.	Unable to get borehole data and in turn soil types, formations, and ground conditions.	9	Location of HDD crossing is remote, and the location is unable to be graded to bring in equipment.	1	Only locations capable of supporting required equipment should be considered as it will also be pivotal for the construction.	1	9	18	
Data Processing and Analysis	Converting the gathered data from the geophysics methods into useful outputs.	Discontinuity in ground that causes data to be affected.	Images produced from the surveys have large areas of unknown material.	4	There could have been unknown utilities or existing pipelines in the way.	1	Ensure to gather information on utilities and pipelines in the area prior to completing the surveys.	1	4	19	

Appendix XII – Project Management

A work breakdown structure and Gantt chart were created and utilized to identify upcoming milestones and required deadlines for the project duration. These tools also helped to evaluate the critical path and task dependencies for contingency planning. These can be found below in Appendix XII—B Work Breakdown Structure and Appendix XII—C Gantt Chart.

Additionally, a table was used to track project risks throughout the project, an outline can be found in Table 51. This table was updated on a weekly basis to ensure all risks had been identified and a mitigation strategy defined. Completing this exercise helped to keep the project on track and plan for required resources. In addition to this risk table an upcoming actions table was used to plan each task over a two-week period and the resources required (Table 52).

Appendix XII—A Project Progression

Effective project management has been a top priority during the course of the project. Planning all tasks in addition to their risks and required resources helped the project to progress smoothly with limited delays and hiccups. The project was able to remain on schedule by utilizing the resources outlined below. These were found to be particularly effective as the nature of the project was multifaceted, requiring lots of research and organization. As outlined throughout the report, meetings with professionals were leveraged to ease and support the required level of research. This is where Table 52 was valuable as it allowed required meetings to be identified in advance and in turn allow for scheduling time. Scheduling meetings with professionals was one of the more challenging aspects of time management as busy schedules limited both email response times and available meeting times.

One of the larger hurdles of the project was the various changes to the project scope outlined in Section 1.3 Evolution of Project Scope. These changes resulted in significantly more research than initially anticipated and therefore put pressure on the projects' timeline. This was managed by utilizing the work breakdown structure, specifically the late start and end dates to identify when the absolute latest a task could be completed was. This table played a pivotal role in the success of keeping the project on schedule. Ultimately, these changes to scope altered the predicted result of the project but allowed for the best solution possible to be output.

Appendix XII—B Work Breakdown Structure

The work breakdown structure outlines all tasks completed over the project course. Beside each task, it lists the scheduled start and finish dates that were assigned. Next to these dates are the late start and finish dates which represent the latest date a task could be started to be completed before a succeeding task required results. The righthand column was used to identify if a task had been completed to track the progress being made. Table 50 outlines the work breakdown structure for the project duration.

Table 50: Table outlining work breakdown for the project year.

Task Name	Start	Finish	Late Start	Late Finish	Completed
Auger Boring research	Fri 09/18/2020	Fri 10/02/2020	Fri 09/18/2020	Fri 10/03/2020	Yes
Microtunneling research	Fri 09/18/2020	Fri 10/02/2020	Fri 09/18/2020	Fri 10/03/2020	Yes
HDD research	Fri 09/18/2020	Fri 10/02/2020	Fri 09/18/2020	Fri 10/03/2020	Yes
Project considerations and scope analysis	Fri 09/18/2020	Fri 10/02/2020	Fri 09/18/2020	Fri 10/03/2020	Yes
Preliminary stakeholder analysis	Wed 09/23/2020	Thur 10/08/2020	Sun 10/04/2020	Sun 10/18/2020	Yes
Problem definition research	Fri 09/18/2020	Fri 10/02/2020	Fri 09/18/2020	Fri 10/03/2020	Yes
Writing of brief 1	Wed 09/23/2020	Fri 10/02/2020	Fri 09/18/2020	Fri 10/03/2020	Yes
Editing of brief 1	Sat 10/03/2020	Sun 10/04/2020	Sun 10/04/2020	Sun 10/04/2020	Yes
Second iteration of Stakeholder Analysis	Wed 09/23/2020	Thur 10/08/2020	Sun 10/04/2020	Sun 10/18/2020	Yes
Value and market analysis	Wed 09/23/2020	Thur 10/08/2020	Sun 10/04/2020	Sun 10/18/2020	Yes
QFD Analysis	Wed 09/23/2020	Thur 10/08/2020	Sun 10/11/2020	Sun 10/18/2020	Yes
Writing of brief 2	Wed 09/23/2020	Thur 10/08/2020	Sun 10/11/2020	Sun 10/18/2020	Yes
Editing of brief 2	Tues 10/06/2020	Thur 10/08/2020	Sun 10/18/2020	Sun 10/18/2020	Yes
Third iteration of Stakeholder Analysis	Wed 09/23/2020	Thur 10/08/2020	Sun 10/11/2020	Sun 10/18/2020	Yes
TRIZ Analysis	Mon 10/19/2021	Wed 10/28/2020	Thurs 10/22/2020	Fri 10/30/2020	Yes
Force Fitting Technique for idea generation	Mon 10/19/2022	Wed 10/28/2020	Thurs 10/22/2020	Fri 10/30/2020	Yes
Failure analysis for idea generation	Mon 10/19/2023	Wed 10/28/2020	Thurs 10/22/2020	Fri 10/30/2020	Yes
Design for X analysis	Mon 10/19/2023	Wed 10/28/2020	Thurs 10/22/2020	Fri 10/30/2020	Yes
Continue to contact stakeholders	Mon 10/19/2020	Wed 10/28/2020	Thurs 10/22/2020	Fri 10/30/2020	Yes

Task Name	Start	Finish	Late Start	Late Finish	Completed
Katia Greco Interview (Geotechnical Engineer at TC Energy)	Thurs 10/29/2020				Yes
Rob Purcell Interview (PM at TC Energy)	Fri 10/30/2020				Yes
Timeline Analysis	Fri 10/30/2020	Sun 11/01/2020	Sun 11/01/2020	Tues 11/03/20	Yes
Post-It Note Method	Sun 11/01/2020	Thurs 11/05/2020	Thurs 11/05/2020	Sat 11/07/2020	Yes
Mind Map on HDD	Sun 11/01/2020	Thurs 11/05/2020	Thurs 11/05/2020	Sat 11/07/2020	Yes
Mind Map on project outputs	Sun 11/01/2020	Thurs 11/05/2020	Thurs 11/05/2020	Sat 11/07/2020	Yes
Mind Map on project assumptions	Sun 11/01/2020	Thurs 11/05/2020	Thurs 11/05/2020	Sat 11/07/2020	Yes
Mind Map on large costs	Sun 11/01/2020	Thurs 11/05/2020	Thurs 11/05/2020	Sat 11/07/2020	Yes
Mind Map on timely processes	Sun 11/01/2020	Thurs 11/05/2020	Thurs 11/05/2020	Sat 11/07/2020	Yes
Reverse Solution Breakdown	Fri 11/06/2020	Fri 11/06/2020	Sat 11/07/2020	Sat 11/07/2020	Yes
Reflection on idea generation completed	Thurs 11/05/2020	Thurs 11/05/2020	Fri 11/06/2020	Sat 11/07/2020	Yes
Writing of brief 3	Fri 10/30/2020	Fri 11/06/2020	Sun 11/08/2020	Mon 11/09/2020	Yes
Editing of brief 3	Sat 11/07/2020	Sun 11/08/2020	Mon 11/09/2020	Tues 11/10/2020	Yes
Select crossing point for pseudo project	Tues 11/10/2020	Tues 11/10/2020	Thurs 11/12/2020	Thurs 11/12/2020	Yes
Download and learn AutoPIPE	Wed 11/11/2020	Thurs 11/12/2020	Thurs 11/12/2020	Fri 11/13/2020	Yes
Begin creating pipe simulation in AutoPIPE	Fri 11/13/2020	Mon 11/16/2020	Mon 11/16/2020	Wed 11/18/2020	Yes
Create performance measurements for design objectives	Fri 11/13/2020	Mon 11/16/2020	Mon 11/16/2020	Wed 11/18/2020	Yes
Update House of Quality	Fri 11/13/2020	Tues 11/17/2020	Tues 11/17/2020	Thurs 11/19/2020	Yes
Research time requirements for site restoration	Fri 11/13/2020	Tues 11/17/2020	Tues 11/17/2020	Thurs 11/19/2020	N/A

Task Name	Start	Finish	Late Start	Late Finish	Completed
Research amount of drilling mud required per metre of HDD crossing length.	Fri 11/13/2020	Tues 11/17/2020	Tues 11/17/2020	Thurs 11/19/2020	Yes
Writing of brief 4	Mon 11/16/2020	Wed 11/18/2020	Mon 11/16/2020	Sat 11/21/2020	Yes
Editing of brief 4	Wed 11/18/2020	Fri 11/20/2020	Sat 11/21/2020	Sun 11/22/2020	Yes
Determine upper bound on cost as well as target cost for project	Sun 11/22/2020	Tues 11/24/2020	Wed 11/25/2020	11/28/2020	Yes
First pass of research on validity of assumptions made	Sun 11/22/2020	Tues 11/24/2020	Wed 11/25/2020	11/28/2020	Yes
Research forces on the pipe and how to calculate them	Sun 11/22/2020	Tues 11/24/2020	Wed 11/25/2020	11/28/2020	Yes
Research how crew size affects timelines.	Wed 11/25/2020	Sat 11/28/2020	Sat 11/28/2020	Mon 11/30/2020	Yes
Design crossing in AutoPIPE	Wed 11/25/2020	Sat 11/28/2020	Sat 11/28/2020	Mon 11/30/2020	Yes
Research typical costs for renting of equipment, raw materials required, and determine average contractor prices	Wed 11/25/2020	Sat 11/28/2020	Sat 11/28/2020	Mon 11/30/2020	Yes
Meeting with Katia Greco	Mon 11/30/2020				Yes
Researching feasibility of cost reduction ideas	Thur 11/26/2020	Sat 11/28/2020	Sun 11/29/2020	Wed 12/2/2020	Yes
Interim presentation development	Thur 11/19/2020	Mon 11/23/2020	Thu 11/26/2020	Mon 11/30/2020	Yes
Interim report writing	Sun 11/29/2020	Fri 12/04/2020	Tues 12/01/2020	Fri 12/04/2020	Yes
Interim report editing	Sat 12/05/2020	Mon 12/07/2020	Mon 12/07/2020	Wed 12/09/2020	Yes
Complete House of Quality from another stakeholder's point of	Wed 12/16/2020	Sat 12/19/2020	Fri 12/18/2020	Wed 12/23/2020	Yes

Task Name	Start	Finish	Late Start	Late Finish	Completed
view to gain further insight					
Bust or develop assumptions declared throughout project	Wed 12/16/2020	Yes	Fri 12/18/2020	Wed 12/23/2020	Yes
Develop multiple crossing designs in AutoPIPE and run stress analyses	Wed 12/16/2020	Yes	Fri 12/18/2020	Wed 12/23/2020	Yes
Meet with Paul Kelly to discuss costs associated with HDD crossings. Validate current economic analysis	Wed 12/16/2020				Yes
Meet with Jamie McClennon to discuss validity of cost reduction options	Tues 01/12/2021				Yes
Plan design review	Tues 01/05/2021	Yes	Thurs 01/07/2021	Sun 01/10/2021	Yes
Create presentation for design review	Sat 01/09/2021	Yes	Sun 01/10/2021	Wed 01/13/2021	Yes
Writing of project review 1	Mon 01/11/2021	Yes	Sat 01/16/2021	Sat 01/23/2021	Yes
Conduct design review	Wed 01/13/2021				Yes
Assumption busting	Thurs 01/14/2021				Yes
Research drilling mud as a cost reduction opportunity	Wed 01/13/2021	Yes	Fri 01/15/2021	Sun 01/24/2021	Yes
Research subsurface mapping technologies	Wed 01/13/2021	Fri 01/22/2021	Fri 01/15/2021	Sun 01/24/2021	Yes
Editing of project review 1	Wed 01/20/2021	Fri 01/22/2021	Sat 01/23/2021	Sun 01/24/2021	Yes
Finalize AutoPIPE and run stress analyses	Wed 01/20/2021	Fri 01/22/2021	Wed 01/20/2021	Fri 01/22/2021	Yes
Complete 2D crossing profile	Mon 01/25/2021	Sat 01/30/2021	Wed 02/03/2021	Thu 01/28/2021	Yes
Make economic analysis more detailed and accurate	Mon 01/25/2021	Sat 01/30/2021	Wed 02/03/2021	Sat 01/30/2021	Yes
Create general construction plan for the Wapiti River crossing	Mon 01/25/2021	Sat 01/30/2021	Wed 02/03/2021	Sat 02/02/2021	Yes

Task Name	Start	Finish	Late Start	Late Finish	Completed
Complete more research on drilling mud	Mon 01/25/2021	Sat 01/30/2021	Wed 02/03/2021	Fri 02/08/2021	Yes
Complete more research on technologies that are used to determine subsurface conditions	Mon 01/25/2021	Sat 01/30/2021	Wed 02/03/2021	Fri 02/08/2021	Yes
Discuss cost reduction ideas with industry professionals	Mon 01/25/2021	Sat 01/30/2021	Wed 02/03/2021	Tues 02/12/2021	Yes
Select one of the cost reduction ideas to pursue	Mon 01/25/2021	Sat 01/30/2021	Wed 02/03/2021	Tues 02/12/2021	Yes
Finalize how output will be delivered	Mon 01/25/2021	Sat 01/30/2021	Wed 02/03/2021	Tues 02/12/2021	Yes
Writing of Project Review 2	Wed 01/27/2021	Wed 02/03/2021	Sat 01/30/2021	Sat 02/06/2021	Yes
Editing of Project Review 2	Wed 02/03/2021	Fri 02/05/2021	Sat 02/06/2021	Sun 02/07/2021	Yes
Develop design solution using subsurface mapping techniques	Sat 02/06/2021	Sun 02/17/2021	Mon 02/08/2021	Sat 02/20/2021	Yes
Writing of Project Review 3	Sun 02/17/2021	Wed 02/24/2021	Sat 02/20/2021	Sat 02/27/2021	Yes
Editing of Project Review 3	Wed 02/24/2021	Fri 02/26/2021	Sat 02/27/2021	Sun 02/28/2021	Yes
Interview with Choon Park	Fri 03/12/2021				Yes
Interview with Kshama Roy	Fri 03/12/2021				Yes
Interview with Ben McClement	Fri 03/12/2021				Yes
Interview with Paul Kelly	Mon 03/15/2021				Yes
Interview with Sam Wilson and Craig Lenderbeck	Tues 03/16/2021				Yes
Interview with Jamie McClennon	Wed 03/17/2021				Yes
Writing of Project Review 4	Mon 03/08/2021	Mon 03/15/2021	Thu 03/11/2021	Thu 03/18/2021	Yes
Editing of Project Review 4	Mon 03/15/2021	Wed 03/17/2021	Thu 03/18/2021	Fri 03/19/2021	Yes
Finalize geophysical process flow chart for clients	Mon 03/29/2021	Yes	Fri 04/02/2021	Mon 04/12/2021	Yes

Task Name	Start	Finish	Late Start	Late Finish	Completed
Quantify cost savings associated with risk from geophysical surveys	Mon 03/29/2021	Yes	Fri 04/02/2021	Mon 04/12/2021	Yes
Further research on safety and regulations for ERT and seismic refraction processes	Mon 03/29/2021	Yes	Fri 04/02/2021	Mon 04/12/2021	Yes
Review process flow chart with industry professional	Mon 03/29/2021	Yes	Fri 04/02/2021	Mon 04/12/2021	Yes
Writing of final report	Fri 04/02/2021	Yes	Mon 04/12/2021	Tues 04/13/2021	Yes
Final presentation practice	Fri 04/09/2021	Yes	Sun 04/11/2021	TBD	Yes
Editing of final report	Mon 04/12/2021	Yes	Tues 04/13/2021	Fri 04/16/2021	Yes
Submit final report for review	Fri 04/16/2021				Yes
Complete all other project documentation	Fri 04/16/2021				Yes
Present solution to Client	Fri 04/19/2021				Yes

Appendix XII—C Gantt Chart

Figure 35 below is a Gantt chart outlining the major project deliverables at a high-level throughout the project duration.

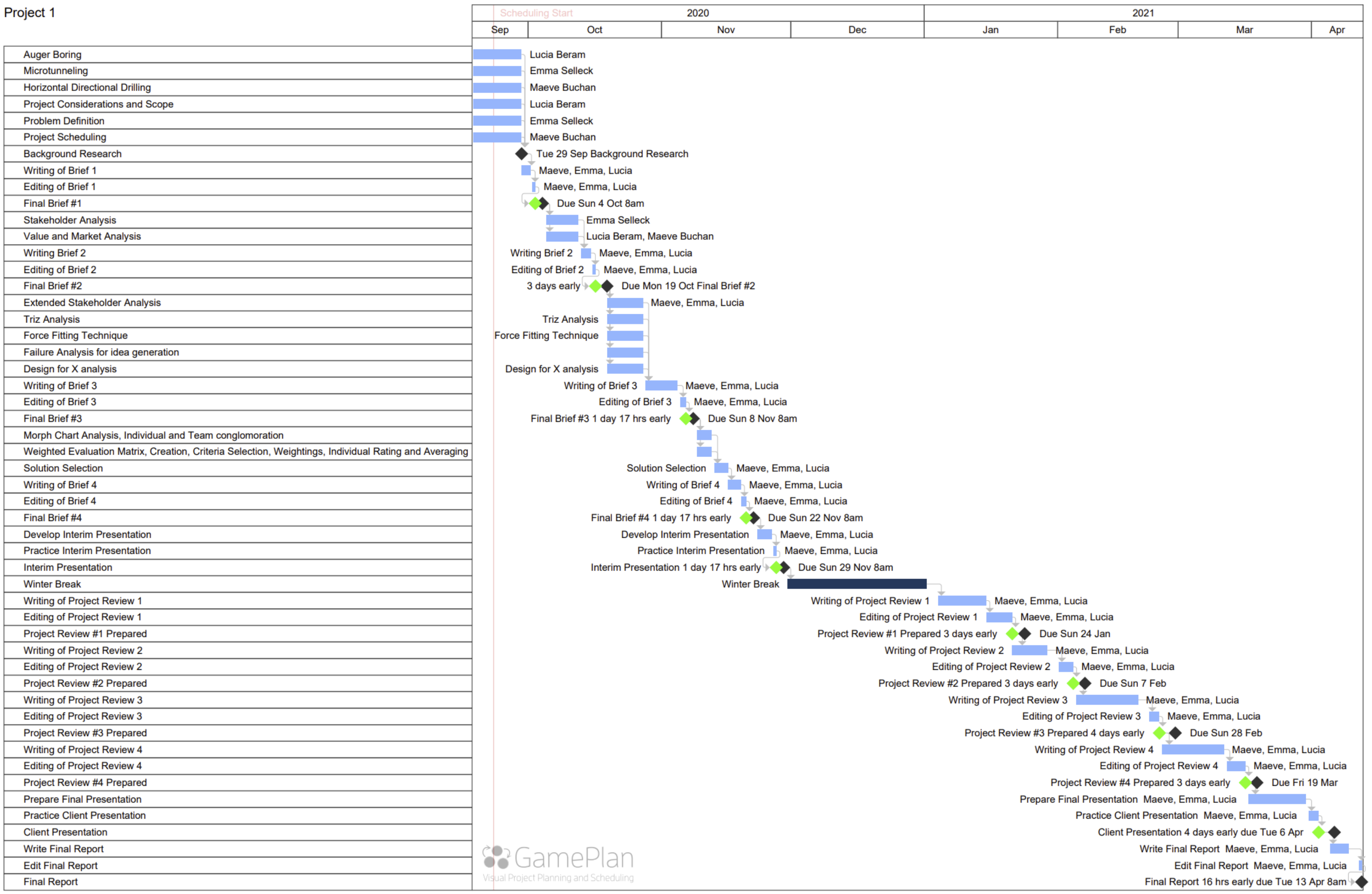

Figure 35: Gantt chart outlining the expected project timelines, milestones as well as task dependencies.

Appendix XII—D Other Project Management Resources

Table 51: Table used to identify project risks and how they will be mitigated.

Risk	Mitigation Strategy

Table 52: Table used to identify key next steps in the project and the resources required to complete them.

Action Item	Resources to Accomplish Action Item	Due Date for Action Item