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MITIGATING RISKS TO SHALLOW TRENCHLESS PIPELINE CROSSINGS USING GEOPHYSICS AND TEST PITTING

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ABSTRACT
Shallow linear infrastructure, like roads, rail and existing pipelines, are common obstacles for new pipeline projects. For these relatively short and shallow crossings, pipelines can usually be installed using a range of available boring methods. Although the value of detailed engineering assessment often conducted for larger scale Horizontal Directional Drill (HDD) or Pipe Thruster Installation crossings is not often perceived for these shallow crossings, they are not without risks associated with complex subsurface geology, largely pertaining to intersection of bedrock or coarse granular material. In this case study, we show how a combination of geophysical profiling and test pitting can provide a cost-effective means to characterize shallow subsurface geology with minimal ground disturbance. We demonstrate this approach for a series of 10 road and pipeline crossings spread over a 23-kilometre-long section of a proposed 42-inch natural gas pipeline in a previously glaciated area of Northeast British Columbia. A combination of seismic refraction and electrical resistivity tomography (ERT) profiles were acquired to non-invasively map the subsurface geology, from which select locations were proposed for targeted test pitting to ground truth the geophysical survey results. The results of the geophysics and test pitting surveys were used primarily to evaluate the risks of the 10 proposed track bore and auger bore crossing alignments. At crossing locations where the combined investigation results identified potential risk with the preliminary bore path (e.g., in and out of shallow bedrock), the results were then used to optimize the depth profile of the bore path, and to select the best-suited crossing configuration and tooling.

RÉSUMÉ
Les infrastructures linéaires peu profondes, comme les routes, les voies ferrées et les pipelines existants, sont des obstacles courants aux nouveaux projets de pipelines. Pour ces traversées relativement courtes et peu profondes, les pipelines peuvent généralement être installés en utilisant une gamme de méthodes de forage disponible. Bien que la valeur d'une évaluation technique détaillée souvent effectuée pour des franchissements par forages horizontaux à grande échelle (HDD) ne soit pas souvent perçue pour ces franchissements peu profonds, ils ne sont pas sans risques associés à la géologie souterraine complexe, se rapportant en grande partie à l'intersection de substratum rocheux ou de matériau granulaire grossier. Nous montrons ici que la combinaison de profilage géophysique et de puits d'essai peut dans certains cas fournir un moyen rentable pour caractériser la géologie souterraine peu profonde avec une perturbation minimale du sol. Nous démontrons cette approche pour une série de 10 croisements de routes et de pipelines répartis sur une section de 23 kilomètres relatif à un projet d’installation de pipeline de gaz naturel de 42 pouces dans une zone auparavant glaciaire du nord-est de la Colombie-Britannique. Une combinaison de profils de réfraction sismique et de tomographie par résistivité électrique (TRE) a été acquise pour cartographier de manière non invasive la géologie du sous-sol, à partir de laquelle des emplacements ont été sélectionnés pour des puits d’essai ciblés de manière à calibrer les levés géophysiques au mieux. Les résultats des levés géophysiques et des sondages ont été utilisés principalement pour évaluer les risques associés aux dix franchissements sans tranchée proposés. Dans les cas où les résultats combinés de l'étude ont identifié un risque potentiel associé à la trajectoire préliminaire de forage (par exemple, si parallèle au contact avec un substratum rocheux peu profond), les résultats ont été utilisés pour optimiser trajectoire, configuration et outillage.

1 INTRODUCTION

1.1 Project Description

TC Energy Ltd. (TC) is constructing the North Montney Mainline (NMML) in northeastern British Columbia (BC). The NMML is a 206 km long, 42-inch diameter natural gas pipeline separated into two sections with the 182 km long Aitken Section to the south, and the 24 km long Kahta Section to the north. The NMML crosses other infrastructure (roads and buried utilities) which, in several cases, required ‘bored’ shallow trenchless crossing methods to install the pipeline. Construction on the Aitken Section began first and the shallow trenchless crossings associated with that section were undertaken without previous site-specific assessment.

1.2 Background

Challenging ground conditions (unexpected shallow bedrock) were encountered on a subset of the NMML Aitken section trenchless crossings. This experience prompted TC to consider ways to reduce the geotechnical uncertainty for the shallow trenchless crossings on the subsequent Kahta Section, with particular focus on assessing depth to bedrock and presence of large clasts in the overburden. Therefore, TC commissioned a post construction geophysical survey at a completed crossing site where unexpected shallow bedrock had caused cost and schedule overruns to determine if this was a method that could be applied for upcoming planned crossings. Geophysical methods are commonly used for crossings of major infrastructure (e,g., highways and rail lines) and water bodies (Henderson et al., 2004; Bauman and Nahas, 2007), but is rarely considered for shallow crossings of secondary infrastructure, where the risk profile is often perceived to be much lower for any individual crossing.

The soil conditions at the completed crossing were known from boring records and detailed logging of the bore bays. Both electrical resistivity tomography (ERT) and seismic refraction (seismic) methods were carried out, and a reasonable correlation between inferred depth to bedrock from the geophysical study and logged ground conditions was found. The positive outcome from this study was taken by TC as sufficient proof of concept and it was decided to implement the approach for the 10 planned shallow trenchless crossings on the Kahta Section.

1.3 Site Description

The Kahta Section is located within the Alberta Plateau physiographic region of northeastern British Columbia (Church and Ryder, 2010). The pipeline route crosses terrain comprising broad, rolling plateaus incised by small streams. Geological mapping of the surficial deposits in the Trutch area (NTS94G) indicates that the soil along the pipeline route consists mainly of till, containing a mixture of clay, silt, and sand, as well as minor pebbles, cobbles, and boulders overlying sub-horizontally bedded sedimentary bedrock (Bednarski, 2000). Drift thickness is indicated to be relatively thin (i.e., less than 10 m bgs) along much of the route.

The bedrock geology underlying the glacial deposits along the pipeline comprise Cretaceous sedimentary rocks that include:

- Dunvegan Formation: massive conglomerate, fine- to coarse-grained sandstone, carbonaceous shale (marine and non-marine)
- Fort St. John Group Sully Formation, which comprises marine shales, siltstone and sandstone (Stott, 1982; B.C. Ministry of Energy and Mines, 2013)

2 METHODOLOGY

The geohphysical methods used included Electrical Resistivity Tomography (ERT) and Seismic Refraction (seismic) supplemented with test pitting for ground truthing.

2.1 Electrical Resistivity Tomography

ERT is a technique for mapping the distribution of subsurface electrical resistivity (or its inverse, conductivity) in a cross-sectional format. Electrical resistivity is a measure of how resistive a unit volume of material is to the flow of electrical current. In typical electrical resistivity surveys, a low frequency alternating current is injected into the ground through a pair of electrodes, and a potential (i.e., voltage) difference is measured between a separate pair of receiver electrodes. By using an array of electrodes, and by measuring voltages from various combinations of electrode pairs, multiple subsurface current paths can be sampled. An inversion technique is then used to reconstruct an electrical resistivity tomogram (or geoelectric cross-section) of the subsurface that best fits all the measurements made from all of the different electrode combinations. All of the ERT profiles for this study were acquired with a uniform spacing between electrodes of 1.5 metres (m) and a minimum profile length of 120 m. A multi-channel gradient array acquisition sequence was used for all measurements, resulting in a minimum of 838 measurements per profile.

Resistivity inversion is the process of converting measured apparent resistivity to true earth resistivities (e.g., RES2DINV; Loke and Barker 1996). The process produces a 2-D model, or cross-section, that represents the best fit to the measured apparent resistivity values. The resolution of the model is a function of the number of data points measured and the depth of the current paths through the ground. The highest resolution is obtained at shallow depths, where there are multiple crossing current paths close to the electrodes, and the resolution decreases with increasing depth. Layer boundaries with strong resistivity contrasts are more likely to be resolved effectively than layers with weak resistivity contrasts (e.g., boundaries between clay and sand layers are usually distinguished, whereas soil layers with similar grain sizes are often indistinguishable).

2.2 Seismic Refraction

The seismic refraction method uses the propagation of compressional waves (P-waves) in the subsurface to determine the velocity structure of the ground. Seismic energy is produced by a source (e.g., sledgehammer, as used for this study) which spreads downward and laterally through the earth. An array of receivers (geophones) measures the arrival of that energy at points along a survey line. Increasing vertical velocity gradients with depth will cause seismic energy to refract back to the surface. Decreasing vertical velocity gradients are rare but, where present, will bend rays away from the surface and create shadow or blind zones that cannot be imaged. The travel path that the energy takes from the shot location to each receiver can be represented by a curved ray path.

Typically, seismic energy that has propagated through bedrock material will arrive with faster apparent P-wave velocities along the seismic array than seismic energy that has travelled through overburden (e.g., sand, till, etc.). The picked travel times of the first-arriving energy can be used as input for seismic inversion software, which solves for the velocity model of the subsurface that best fits the observed travel times. The accuracy of each travel-time pick is determined by the frequency of the first-arriving energy and the signal-to-noise (S/N) ratio. Factors that can reduce the frequency and/or S/N ratios include soft or spongy soils, wind noise, turbulent rivers, traffic noise, and the distance between the shot and the receiver (signal strength will reduce proportionally with increasing length of the ray path). The maximum depth of investigation is determined by the deepest refracted ray path. As a general rule, the longer the horizontal offset between a shot and a receiver, the greater the depth of penetration. A minimum of 48 geophones at intervals of 2 m were used for each seismic refraction profile, with shot points located every 4 m.

2.3 Overall Approach

The intended crossing assessment method relied on combined use of geophysical data and test holes to provide calibration for interpretation of the geophysical models. This work was timed to coincide with the end of grubbing and beginning of clearing on the construction right-of-way. This timing yielded significant logistical and cost advantages: all permitting, ground disturbance checks, and accesses were in place, and equipment required for test pitting was already mobilized to the area, working concurrently on other tasks.

In general, the seismic method is the most useful for detecting boundaries between material of contrasting elastic properties and densities, such as overburden and bedrock (with higher velocities measured within substrata of higher unit weight). The ERT technique can be useful in detecting boundaries between materials that have contrasting electrical resistivities, which is a function of porosity, mineralogy and porewater composition. Clays and water saturated materials are known as generally electrically conductive and contrast sharply with more electrically resistive materials such as gravels, coarse glacial till, and bedrock.

At the onset of the geophysical survey program, both ERT and Seismic were utilized. While both methods were deemed useful given the geological setting, an evaluation of early survey results revealed that the seismic method would be most useful at delineating the elevation of the top of bedrock. The method was preferred and implemented on its own as the program progressed because the location of bedrock was more of a concern and few boulders were anticipated. The lengths of the geophysical survey lines were designed by Advisian to extend past the extents of the bore bays on each side of the crossing in order to obtain data definition to target depth for the entirety of the crossings.

Test pitting was the most cost-effective approach to ground truthing and provided calibration in support of the interpretation of the geophysical survey data. In addition, periodic visits of the sites were carried out by BGC Engineering Inc. (BGC) during the boring of the shallow trenchless crossings to log the soil conditions from the walls of the excavated bore bays.

Given the limited time between the investigation and the execution of the bores, BGC and Advisian worked together in delivering working files crudely but effectively conveying the key results in support of decision making.

Following the completion of the crossings, BGC also solicited feedback from the mainline contractor on the overall accuracy and value of the pre-construction data at each location. Table 1 provides a brief description of the crossings with associated site investigation effort.

Table 1. Shallow trenchless crossing description and associated investigation details

Crossing Number	Feature Crossed	Geophysical Survey		Number of Test Pits	
		Seismic	ERT	BGC Test Pits	Mainline Contractor Test Pits
1	Hotline	x	x	0	0
2	Hotline	x	x	0	0
3	Road/Hotline	x	x	1	1
4	Road	x		2	0
5	Road	x		2	0
6	Road	x		0	2
7	Road/Hotline	x		0	1
8	Road/Hotline	x		0	0
9	Hotline	x	x	2	2
10	Road	x	x	2	0

3 RESULTS

Results of the geophysical survey, test pitting program, and the encountered conditions are summarized in Table 2. A representative example of the cross-sectional profiles illustrating results from the geophysical surveys provided by Advisian is presented in Figure 1. The preliminary bore path is drawn on the cross-sections, along with the post-installation as-built top of pipe elevation. Locations of BGC and Mainline Contractor test pits are shown along the bore paths. Representative annotated photographs illustrating observations made at bore bays are provided in Figure 2.

4 DISCUSSION

4.1 Correlation between survey results and actual boring conditions

Out of the 10 crossings investigated through this assessment, seven stratigraphic profiles inferred from acquired data (geophysical survey and test-pitting) proved to accurately reflect the conditions encountered during the boring operations. Encountered conditions were observed to diverge from the inferred conditions at Crossing numbers 1, 2 and 8.

At Crossing 1, weathered siltstone was logged by BGC near the pipe invert at both bore bays, whereas the geophysical survey interpreted a shale/mudstone below the extent of the bore. Weathered, or fractured bedrock can often be difficult to distinguish from mineral soil in a geophysical survey due to the lower density compared to competent bedrock. In this case the bedrock was likely easily bored due to its weathered nature. No issues at the crossing were noted by the Mainline Contractor.

Table 2. Summary of results of the geophysical survey, test pitting program, and the encountered conditions

Crossing Number	Bedrock Along Bore Path		Notes	Summary of Mainline Contractor's Account of Boring Conditions
	Anticipated[1]	Encountered		
1	N	Y	Survey[3] data interpreted bedrock surface lower than base of bore bays.	No issues noted. Weathered siltstone logged in bore bays near pipe invert.
2	Y	N	Survey data interpreted bedrock surface near base of bore bays.	No bedrock encountered along bore path. No issues noted.
3	Y	Y	Test pit encountered bedrock. Survey data interpreted bedrock near base of exit bay.	No issues noted. Final bore path lower than preliminary bore path.
4	Y	?[2]	Test pits encountered bedrock. Survey data interpreted bedrock in entry bore bay.	No issues noted. Bore bays not logged by BGC, bore path may have encountered bedrock on the NW (exit) side based on the geophysical profile and TP results.
5	N	N	Survey data interpreted bedrock surface lower than base of bore bays. Test pits did not encounter bedrock.	No issues noted.
6	N	N[2]	Survey data interpreted bedrock surface lower than base of bore bays. Test pits did not encounter bedrock.	No issues noted. Bore bays not logged by BGC. Inferring that bedrock was not encountered based on no issues noted, test pit results, and geophysical profile.
7	Y	Y[2]	Survey data interpreted bedrock surface near base of bore bays. Test pit encountered bedrock.	No issues noted. No bedrock observed in exit bay by BGC after partial backfill. Entry bay not logged. Inferring that bedrock was encountered based on geophysical profile and test pit result.
8	N	Y	Survey data interpreted bedrock surface lower than base of bore bays.	Bedrock surface much higher than expected although general profile of density accurate based on drill response. Mainline Contractor had not planned for rock drill bit on-site causing minor delay. 12 m from exit side, encountered car-sized boulder which had to be removed. Final bore path higher than preliminary bore path.
9	Y	?[2]	Survey data interpreted bedrock surface near base of bore bays. Test pits did not encounter bedrock.	No issues noted. Bore bays not logged by BGC.
10	N	N	Survey data interpreted bedrock surface lower than base of bore bays. Test pits did not encounter bedrock.	No issues noted.

[1] Inferred from geophysical survey and test pit results.

[2] Bore bays not logged by BGC or not logged in detail.

[3] Results from the geophysical survey are referred to as survey data in this table.

At Crossing 2, the geophysical survey indicated that the bore was expected to intersect fine-grained bedrock near the base of the path, but none was encountered. This discrepancy did not cause any construction issues.

At Crossing 8, bedrock was not expected based on the geophysical survey, but sandstone was encountered throughout most of the path. The Mainline Contractor did not have a rock-bit on-site for the planned start of drilling since bedrock was not expected, and this caused a minor delay while a rock-bit was sourced. A large (approximately 3 m diameter) sandstone boulder was also encountered near the bore exit and had to be excavated. While the top of bedrock proved to be inaccurate at this crossing, the Mainline Contractor foreman on-site noted that the overall density profile shown on the seismic survey was accurate, in that more competent ground was encountered on the west side of the road corresponding to the noted rise in seismic density, which deflected the drill upwards by approximately 0.3 meters. The ERT survey method was not completed at the crossing and may have been able to identify the presence of the large boulder.

4.2 Outcome for the project

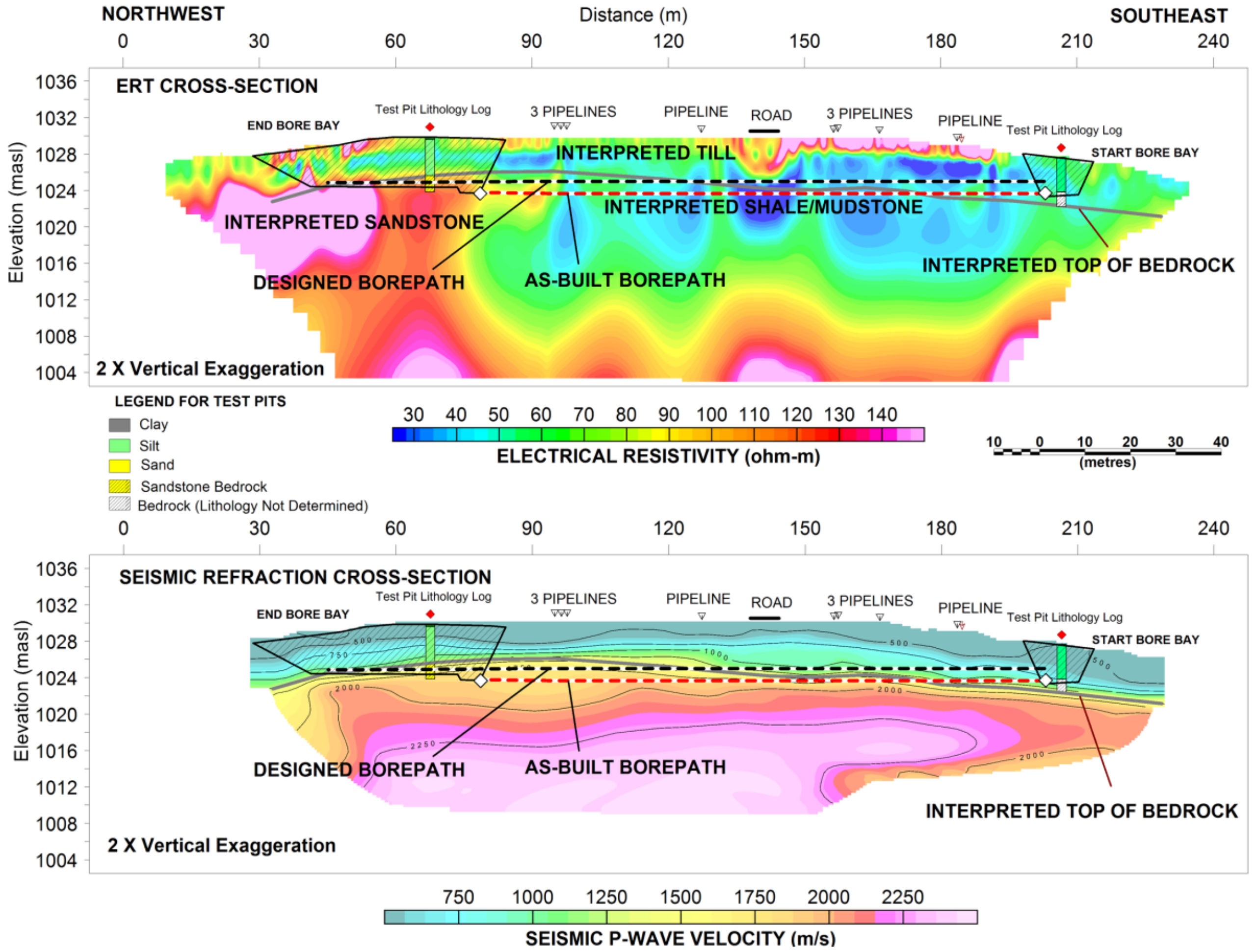
The overall the outcome of this investigation program was deemed by the parties involved to have brought value in assisting the mainline contractor with the repositioning/confirmation of the borepath, as well as selection of crossing configuration and tooling in a cost-effective way.

4.3 Considerations for optimum implementation

While the proposed methods of investigations are on the low end of the cost spectrum when considering geotechnical investigations, it should be stressed that the timing of the execution of the program (efficiencies related to the ongoing construction phase) was key to drastically minimizing associated costs. This implies that this approach is suited for field fitting of planned crossing but may not be suited to support front-end-engineering documentation (tendering or regulatory approval). However, in areas where relatively shallow bedrock is expected for a proposed pipeline alignment, borehole drilling for ground truthing at select shallow crossings (in lieu of test pitting) may be considered as part of the overall geotechnical program undertaken in support of pipeline and/or facility design.

It is also important to note that where discrepancy was observed between inferred conditions from investigation results and actual conditions encountered along the crossing, no pre-construction test pit information had been gathered to calibrate and adjust the geophysical survey data. However, despite the discrepancy between anticipated and encountered conditions at three of the crossings, the interpreted bedrock surface derived exclusively from the geophysics results showed that the bore bays and borepaths for these crossings would be in close proximity to bedrock, and that the risk of variable soil/bedrock conditions could not be ruled out.

Figure 1. Representative example of the cross-sectional profiles, illustrating results from the geophysical surveys and the test pits. The colour grid in the upper panel shows changes in electrical resistivities (warm colours show higher resistivities and cool colours show lower resistivities). The colour grid in the lower panel shows changes in p-wave seismic velocities. The gray line delineates the top of bedrock as interpreted for the most part from the from the resistivity data and the seismic refraction profile data (lower panel). The dashed black line shows the designed bore path prior to construction



A more consistent approach to conducting verification test holes and applying the full spectrum of recommended geophysical survey methods (in this case both seismic refraction and ERT, but survey configuration is typically customized to site conditions) is recommended for improved outcomes, as it allows for more calibrated and meaningful interpretation of the geophysical output.

4.4 Potential for use in the industry

Understanding that the quality and applicability of geophysical survey data is dependent on the geological conditions, this assessment method is recommended for consideration as a cost-effective approach to:

- minimizing risk of cost and schedule overruns for short trenchless (largely boring) crossing programs at the onset of the execution phase,

- providing definition for bidders and minimize embedded contingency at the planning and tendering stage,
- allowing an informed pre-planning process for the crossings and improving the overall field execution

5 ACKNOWLEDGEMENT

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Figure 2. Representative annotated photographs illustrating observations made at bore bays.

Crossing 8. Bore Entry, Sandstone bedrock at 3.3 mbgs, with overlying clay till.

Crossing 5. Test pit investigation. Clay till logged to final depth (5.2 m).

Crossing 8. Bore exit bay. Sandstone bedrock within pipe horizon, overlain by clay till.

Crossing 2. Bore entry bay. Clay till to depth.

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