Appendix C

Geophysical Report

July 26, 2021

ISSUED FOR USE
FILE: ENG.GEOP03198-03
Via Email: Kirby.McRae@tetratech.com

Tetra Tech Inc.
400, 161 Portage Avenue
Winnipeg, MB R3B 0Y4

Attention: Kirby McRae, P.Eng., Senior Design Lead

Subject: Ferry Road and Riverbend CSR – Rutland Trunk Sewer – Geophysical Survey
Winnipeg, MB

1.0 INTRODUCTION

Tetra Tech Canada Inc. (Tetra Tech) was retained by the City of Winnipeg to conduct geophysical profiling along Rutland Street for the proposed Ferry Road and Riverbend Combined Sewer Relief (CSR) tunnel in Winnipeg, MB. Previous geotechnical investigations and sewer projects in the area have identified the likelihood of hard glacial tills being encountered along an 800 m section of the alignment between Bruce Avenue and Silver Avenue.

Geophysical seismic data was collected along approximately 2 km of the alignment, including the noted 800 m section, in order to identify the location and elevation of harder subsurface material that could be problematic for tunnelling construction.

2.0 SEISMIC METHODOLOGY

2.1 Seismic Methodology

Two different seismic methods were utilized for this project: seismic refraction and multi-channel analysis of surface waves (MASW). Both data sets can be collected at the same time but use different properties of seismic wave train record.

Seismic refraction investigations rely on the generation of acoustic waves from a source and measurement of the ground response using acoustic receivers, called geophones, at a known geometry. The relative geometry of the source and receiver locations are known and can be related to the travel time of the acoustic wave travelling to each receiver. By identifying the first arrival of the compression (P-) wave, a modelled velocity cross-section can be generated.

Multichannel analysis of surface waves (MASW) is an alternate seismic technique based on the measurement of surface waves, specifically the dispersion characteristics of retrograde motion Rayleigh waves as these waves travel past the geophones. MASW data is analyzed by phase velocity-frequency based transformation. The dispersion curves are interpreted and solved through a least squares modelling process to obtain a one-dimensional vertical model of the average shear wave (S-wave) velocity across the seismic line at various depths, at each spread location. The MASW source can either be an active source (such as a sledgehammer striking a metal plate) or a passive source (such as ambient site noise caused by construction activities or traffic). MASW is often collected at the same time as refraction data and provides additional information along the profile to assist with interpretation of the refraction data.

A detailed description of seismic refraction and MASW methodology, including limitations, is included in Appendix B.

3.0 DATA COLLECTION

Seismic data was collected by David McBean, P.Geo. (Alberta), and Jordan Augruso, P.Geo. (Alberta), between August 16 and August 18, 2020. The seismic system used for the survey was a Geometrics' 24-channel seismograph with 4.5 Hz geophones at a 1 m spacing. A sledgehammer striking a metal plate was used as the seismic source. Data was collected using an off-end shot location of 10 m.

The geophones were mounted on a landstreamer, with ground coupling achieved through a metal plate. This setup allows the geophones to be moved along the line efficiently, increasing the speed of data collection. The survey setup is shown below in Photo 1.

Photo 1 – Landstreamer setup

Data was collected along a profile approximately 2 km in length, extending from the Assiniboine River at the south end of the alignment to the Winnipeg James Armstrong Richardson International Airport at the north end. Seismic data was collected at 5 m increments along the profile. No data was collected on active roadways; therefore, the seismic profile contains four gaps in data coverage at Portage Avenue, Bruce Avenue, Ness Avenue, and Silver Avenue. Figure 1 provides a plan view site map of the survey area.

Data was collected adjacent to Rutland Street, which remained open to traffic at the time of the survey. The noted avenues along the survey alignment likewise remained open to traffic at the time of the survey. The field crew timed collection of individual seismic data files to occur when there was minimal adjacent traffic, or when traffic was paused at stop lights, but in busier areas such as at between Bruce Avenue and Silver Avenue, roadway traffic did contribute noise to the dataset.

Geophone locations were surveyed by Tetra Tech using an RTK GPS system to provide position and elevation information.

4.0 DATA PROCESSING

4.1 Refraction

The data was processed using Geometrics' SeisImager seismic processing software. The software was used to filter and gain the data, select the first arrivals, and assign layers to the travel times and perform a time-term inversion. The results from the time-term inversion were used as the initial model for tomographic inversions.

Due to traffic noise, the refraction seismic data had a low signal to noise ratio in some locations, making it challenging to pick the P-wave first arrivals. In these areas, MASW was used as the primary method for interpretation.

4.2 MASW

The data was also processed using MASW methods, which involves creating a plot of the phase velocity vs. frequency, called a dispersion image. By selecting the highest amplitude energy at the lowest phase velocities (the fundamental mode), a dispersion curve is determined. In general, the data was sell-suited to the MASW method and yielded a well-defined phase dispersion curve. The MASW data was processed and inverted in Kansas Geological Survey's SurfSeis software. The back calculation of shear wave (S-wave) velocity was performed using an iterative inversion least-squares approach. MASW is less sensitive to background noise, well-suited in urban environments and works well in unconsolidated soils.

5.0 RESULTS AND INTERPRETATION

Figures 2 and 3 provide an interpreted seismic profile along the surveyed alignment. In general, the seismic data agrees well with the available borehole information along the entire alignment. Primarily the modelled S-wave velocity was used to map the till interface, with P-wave velocities being used to help refine the interpretation in non-traffic areas.

The modelled S-wave contours have been shown on the figures along with an interpreted top of till interface, simplified borehole data, and proposed tunnel elevation. Locations along the alignment where either no data was collected (for example on roadways), or where the data quality and thus confidence in the data was poor have been shown as dashed lines (inferred).

The till interface fits well with a modelled S-wave velocity of between 190 m/s to 250 m/s and a modelled P-wave velocity of 1,000 m/s. The S-wave velocity used for the till interface changes as one moves north, away from the Assiniboine River. Since till is a geological deposition description, the actual composition of the material can, and does, change over the course of the alignment both in terms of material composition, density (N blow counts), and water content, which will affect seismic velocities.

From approximately 50 m north of the Assiniboine River (profile chainage 0 m) to the running track in Bourkevale Park (profile chainage 220 m), the till interface correlates better with a higher modelled S-wave velocity (220 m/s to 250 m/s) than the rest of the alignment. This could be due to the higher silt and less clay composition in the till relative to the rest of the alignment.

Over the running track (profile chainage 250 m) to Portage Avenue, the till is interpreted to be at its deepest point, over 12 m from surface, and is close to the modelling extent of the data. The engineered surface of the track does change the dispersion behavior of the surface waves and there is evidence of a velocity reversal (fast layer over a slow layer) in the refraction data that prevents accurate depth modelling from the refraction data set. The till interface correlates better with a modelled S-wave velocity of approximately 200 m/s.

From Portage Avenue to the end of the alignment past Silver Avenue, the till interface correlates well with a slower modelled S-wave velocity between 190 m/s and 200 m/s. The till interface elevation is shown as a gradual ascent, with several localized crests and troughs, to a high point around profile chainage 1,900 m past Silver Avenue. The till interface is at its shallowest point of only about 4 m from the surface at this furthest surveyed chainage.

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We trust this document meets your present requirements. If you have any questions or comments, please contact the undersigned.

Tetra Tech Canada Inc.

PROVINCE OF MANITOBA
N. S. PARRY
Member
34186G
REGISTERED PROFESSIONAL GEOSCIENTIST

July 26, 2021

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ENGINEERS GEOSCIENTISTS MANITOBA
Certificate of Authorization
Tetra Tech Canada Inc.
No. 6499

FIGURES

LEGEND

SEISMIC READING LOCATION

BOREHOLE

0+000 TUNNEL PATH CHAINAGE

TUNNEL PATH

SCALE 1:7,500
NAD83
UTM z14

CLIENT

Winnipeg

TETRA TECH

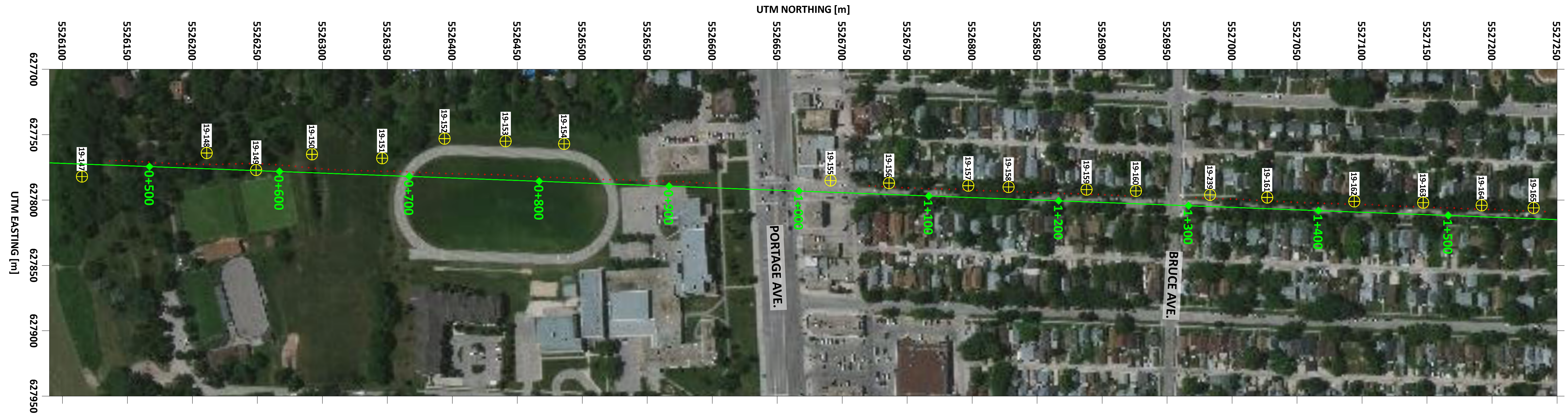
Ferry Rd. & Riverbend CSR Rutland Trunk Sewer

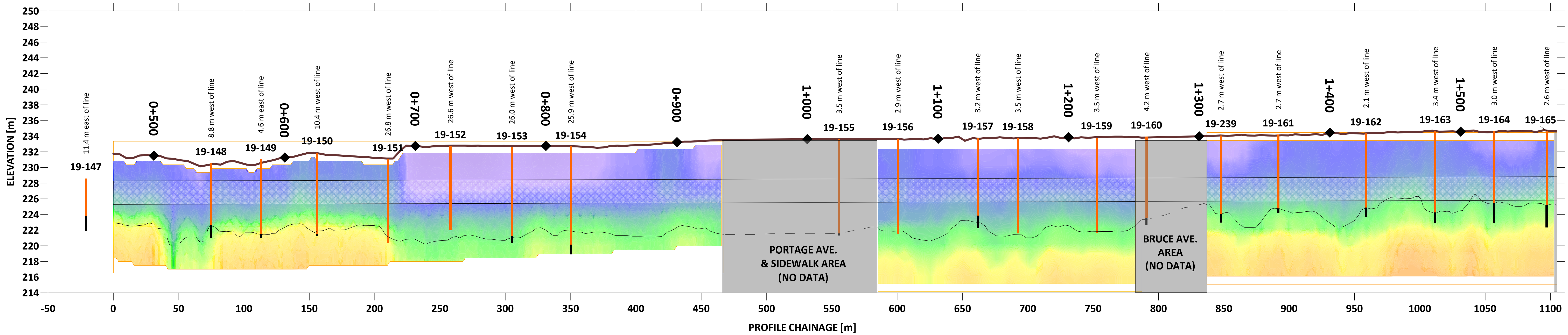
Seismic Data Coverage Overview Map

PROJECT NO.	DWN	CKD	APVD	REV
ENG.GEOP03198-03	JA	PF	PF	1

OFFICE	DATE
EBA.EDM	May 28, 2021

Figure 1





LEGEND

- ◆ TUNNEL CHAINAGE MARKER
- PROPOSED TUNNEL LOCATION
- BOREHOLE RESULT - NON-TILL MATERIAL
- BOREHOLE RESULT - TILL MATERIAL
- NO GEOPHYSICAL DATA
- GROUND SURFACE
- INTERPRETED TILL INTERFACE (FROM GEOPHYSICAL AND BOREHOLE RESULTS)
- INTERPRETED TILL INTERFACE (INFERRED)

PLAN MAP SCALE 1:3000

PROFILE SCALE 1:3,000
VE = 6

MODELLED S-WAVE VELOCITY [m/s]

0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360 380 400 420

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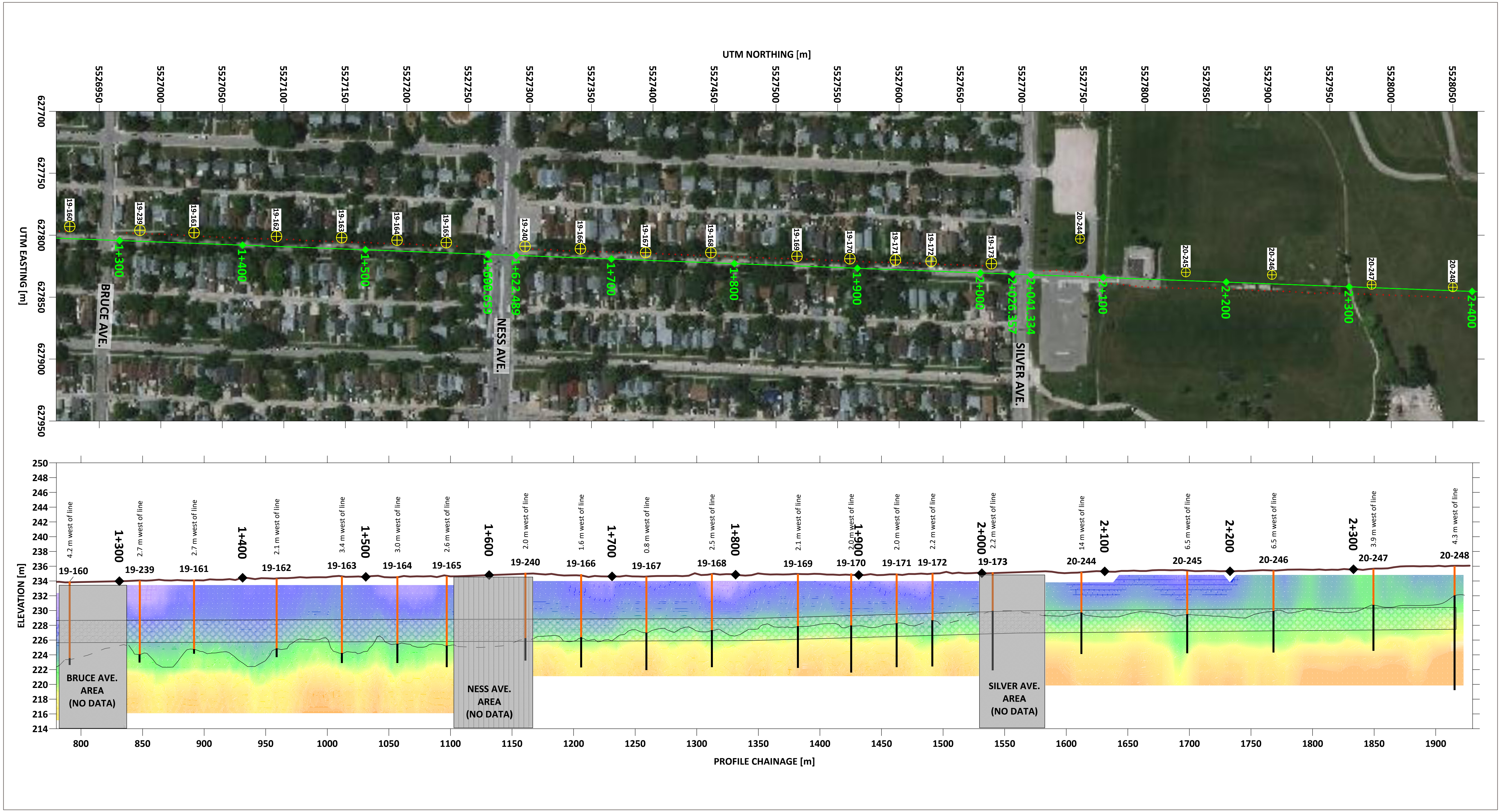
Ferry Rd. & Riverbend CSR Rutland Trunk Sewer

Interpreted Seismic Profile Segment 1

PROJECT NO.	DWN	CKD	APVD	REV
ENG.GEOP03198-03	JA	PF	PF	0

OFFICE	DATE
EBA-EDM	October 06, 2020

Figure 2



LEGEND

PLAN MAP SCALE 1:3000

PROFILE SCALE 1:3,000
VE = 6

- TUNNEL CHAINAGE MARKER
- APPROX. PROPOSED TUNNEL LOCATION
- BOREHOLE RESULT - NON-TILL MATERIAL
- BOREHOLE RESULT - TILL MATERIAL
- NO GEOPHYSICAL DATA
- GROUND SURFACE
- INTERPRETED TILL INTERFACE (FROM GEOPHYSICAL AND BOREHOLE RESULTS)
- INTERPRETED TILL INTERFACE (INFERRED)

MODELLED S-WAVE VELOCITY [m/s]

0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360 380 400 420

CLIENT

Winnipeg

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Ferry Rd. & Riverbend CSR Rutland Trunk Sewer

Interpreted Seismic Profile Segment 2

PROJECT NO.	DWN	CKD	APVD	REV
ENG.GEOP03198-03	JA	PF	PF	1

OFFICE	DATE
EBA-EDM	May 28, 2021

Figure 3

APPENDIX A

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LIMITATIONS ON USE OF THIS DOCUMENT

GEOPHYSICAL

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The Client acknowledges that it has fully cooperated with TETRA TECH with respect to the provision of all available information on the past, present, and proposed conditions on the site, including historical information respecting the use of the site. The Client further acknowledges that in order for TETRA TECH to properly provide the services contracted for in the Contract, TETRA TECH has relied upon the Client with respect to both the full disclosure and accuracy of any such information.

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While TETRA TECH endeavours to verify the accuracy of such information, TETRA TECH accepts no responsibility for the accuracy or the reliability of such information even where inaccurate or unreliable information impacts any recommendations, design or other deliverables and causes the Client or an Authorized Party loss or damage.

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This Professional Document is based solely on the conditions presented and the data available to TETRA TECH at the time the data were collected in the field or gathered from available databases.

The Client, and any Authorized Party, acknowledges that the Professional Document is based on limited data and that the conclusions, opinions, and recommendations contained in the Professional Document are the result of the application of professional judgment to such limited data.

The Professional Document is not applicable to any other sites, nor should it be relied upon for types of development other than those to which it refers. Any variation from the site conditions present, or variation in assumed conditions which might form the basis of design or recommendations as outlined in this report, at or on the development proposed as of the date of the Professional Document requires a supplementary investigation and assessment.

TETRA TECH is neither qualified to, nor is it making, any recommendations with respect to the purchase, sale, investment or development of the property, the decisions on which are the sole responsibility of the Client.

1.7 ENVIRONMENTAL AND REGULATORY ISSUES

Unless stipulated in the report, TETRA TECH has not been retained to investigate, address, or consider and has not investigated, addressed, or considered any environmental or regulatory issues associated with the development of the site.

1.8 NATURE AND EXACTNESS OF SOIL AND ROCK DESCRIPTIONS

Classification and identification of soils and rocks are based upon commonly accepted systems and methods employed in professional geotechnical practice. This report contains descriptions of the systems and methods used. Where deviations from the system or method prevail, they are specifically mentioned.

Classification and identification of geological units are judgemental in nature as to both type and condition. TETRA TECH does not warrant conditions represented herein as exact, but infers accuracy only to the extent that is common in practice.

Where subsurface conditions encountered during development are different from those described in this report, qualified geotechnical personnel should revisit the site and review recommendations in light of the actual conditions encountered.

1.9 LOGS OF TESTHOLES

The testhole logs are a compilation of conditions and classification of soils and rocks as obtained from field observations and laboratory testing of selected samples. Soil and rock zones have been interpreted. Change from one geological zone to the other, indicated on the logs as a distinct line, can be, in fact, transitional. The extent of transition is interpretive. Any circumstance which requires precise definition of soil or rock zone transition elevations may require further investigation and review.

1.10 STRATIGRAPHIC AND GEOLOGICAL INFORMATION

The stratigraphic and geological information indicated on drawings contained in this report are inferred from logs of test holes and/or soil/rock exposures. Stratigraphy is known only at the locations of the test hole or exposure. Actual geology and stratigraphy between test holes and/or exposures may vary from that shown on these drawings. Natural variations in geological conditions are inherent and are a function of the historic environment. TETRA TECH does not represent the conditions illustrated as exact but recognizes that variations will exist. Where knowledge of more precise locations of geological units is necessary, additional investigation and review may be necessary.

1.11 SURFACE WATER AND GROUNDWATER CONDITIONS

Surface and groundwater conditions mentioned in this report are those observed at the times recorded in the report. These conditions vary with geological detail between observation sites; annual, seasonal and special meteorological conditions; and with development activity. Interpretation of water conditions from observations and records is judgmental and constitutes an evaluation of circumstances as influenced by geology, meteorology and development activity. Deviations from these observations may occur during the course of development activities.

APPENDIX B

SURVEY METHODOLOGIES AND LIMITATIONS

SURVEY METHODOLGIES AND LIMITATIONS

Seismic Refraction Methodology

Seismic investigations rely on the generation of acoustic waves from a source and measurement of the ground response using acoustic receivers, or geophones, at a known geometry. The relative geometry of the source and receivers are known and can be related to the time it takes for the acoustic wave to travel to each receiver. By identifying the first arrival times of the compression (P-) wave, a modelled velocity cross-section can be generated, thereby obtaining the modelled P-wave velocities along the cross-section.

The seismic refraction method is based on acoustic behavior controlled by Snell's Law and results in a cross-section model by analyzing the first arrival time of acoustic waves as received over an array of geophones. Where the apparent velocity of the first arrival wave changes (identified by a change in slope of the first arrival time versus geophone distance), a change in layer type and velocity can be identified.

Refractions can only occur at layer interfaces where velocities increase with depth. In situations where velocities decrease with depth, the lower velocity layer cannot be reliably modelled.

Seismic Refraction Limitations

Inverse Modelling – The inverse modelling process can produce many different valid, geologically realistic models that satisfy the initial conditions. The models used in this data analysis are considered the best models at the time of reporting based upon other available geophysical data and borehole data collected, as well as site observations.

Vertical Resolution – Layers with a vertical dimension that are small relative to the geophone spacing may not be detected due to insufficient horizontal sampling.

Hidden Layers – Governed by Snell's Law, the seismic refraction method can only resolve lithological layers if the velocities of the layers increase with depth. Sometimes this assumption is violated and results in 'hidden' or 'blind' layers that are low velocity layers between two higher velocity layers, or equally, layers that are too thin to be resolved given the velocity contrast present and the geophone geometry used.

Multichannel Analysis of Surface Waves (MASW) Methodology

When a stress is applied to an elastic body (such as a hammer hitting the ground), the corresponding strain propagates outwards as an elastic wave. There are two principal types of elastic waves: body and surface waves. Body waves consist of compressional or P- (primary) waves and S- (shear) waves. The velocities of P- and S-waves (Vp and Vs, respectively), are related to the bulk elastic properties and density of the material. Shear wave velocity is an important parameter that is directly proportional to the shear modulus of a material. It is a measure of stiffness (or rigidity) of that material and is a parameter often used in geotechnical engineering.

In addition to body waves that travel through an elastic medium, there are waves that travel only along the boundary of an elastic solid. There are two common types of surface waves in solids: Rayleigh waves (or ground roll) and Love waves. Rayleigh waves are of interest as their velocity behaviour is controlled by the shear strength of the material supporting the ground roll movement. Rayleigh waves are easily generated and constitute the majority of measurable seismic energy under normal ground conditions. Rayleigh waves have characteristic properties in that they travel in an elliptical retrograde motion in the vertical plane as they propagate along the surface of the elastic medium. The velocity of Rayleigh waves approximates 0.9Vs and can therefore be used to estimate the shear velocities of materials. Geophones are used to record the Rayleigh waves by measuring the vertical particle displacement at the ground surface.

In a layered medium, surface waves have dispersion properties that are not observed with body waves. Dispersion occurs as a result of surface waves being comprised of different wavelengths propagating at different velocities. The propagation velocity of each wavelength is called phase velocity. By analyzing the differing phase velocity characteristics at different frequencies, a dispersion curve can be generated. Short wavelengths have shallow penetration depths, while longer ones have deeper penetration. Therefore, analysis of the fundamental wave energy distribution of the dispersion curve maps a profile of near-surface shear wave velocities. The entire MASW technique thus consists of three fundamental steps: acquisition of ground roll data; imaging of the dispersion curves; and inversion (or back calculation) of shear wave velocities from the interpreted dispersion curves, thus obtaining stiffness parameters.

The end result of a MASW survey is a one-dimensional sounding, providing stiffness parameters at discrete locations, roughly analogous to a series of penetrometer measurements. Although the MASW technique makes use of the lateral dispersion of velocities along the surface (and thus is not a true point measurement), it is assumed to represent a point measurement that is representative of the soil conditions in the immediate vicinity of the array. In areas where a two-dimensional profile is required, a series of constant-offset one-dimensional soundings can be collected and processed together to build up a two-dimensional cross-section of shear wave velocities.

MASW Limitations

Due to the mathematical nature of inverse models, many possible models can satisfy the initial conditions and be considered equally correct in the absence of other data. In this case, the models chosen were deemed to be the optimal models given the available information. Therefore, modelling parameters were selected based on the expected lithology in the region of the survey. The models presented are considered reasonable, given the information available at this time, and represent the simplest interpretation that provides a good match to the measured field values. Other models with different layer thicknesses and seismic parameters may result in similar matches of the modelled data with the field data.

In geophysical modelling, the representation of the deepest layer of the model is referred to as a half-space. For this layer, only the top boundary is defined and the layer is treated mathematically as extending infinitely into the earth. The half-space is considered homogeneous and isotropic. In reality, there are subsequent seismic layers in the earth beyond the last model layer; however, due to geometric limitations of the survey and in situ contrasts between differing layers, they cannot be defined. As long as the seismic properties of the material beneath the final model layer do not differ substantially from those of the final model layer itself, the half-space approximation is considered to be mathematically sound, and the seismic model layers are considered to be a reasonable approximation of the seismic layers within the limits of the survey.

Topography – One of the assumptions of MASW theory is that the entirety of the array is in the same plane. This assumption has to do with the fact that one is measuring time differences with the use of geometry. As long as the changes in topography along the array's plane are less than 10 percent of the total line length, this holds true. Changes in topography did not exceed 10 percent of the total line length for the MASW profile at this site.

Fundamental Mode – An assumption used in the software is that the fundamental mode of the dispersion image is used for analysis. This mode can, at times, be difficult to pick out. It should be reviewed on a shot-by-shot basis to ensure correct interpretation as was done in this evaluation.

Layer Resolution/Aliasing – When spectra with poor low-frequency components are used in data collection over an area with stiff soils, a gradation of shear-wave velocities may be modelled where a sharp interface exists. This is due to the aliasing of these boundaries at depth as the lower frequency waves have too long of a wavelength to distinguish sudden boundaries.

Data Density – As with most surveys, data density should be considered when reviewing the results. Geophone spacing and survey methodology was recorded, reported on, and used in the interpretation process.

Data Coverage/Resolution – There are limitations on vertical resolution and maximum depth based on survey design and site conditions. The minimum vertical resolution (thus minimum depth of investigation) is directly proportional to the geophone interval and the highest frequencies generated by the source (and recorded by the receivers), while the theoretical maximum depth of investigation is proportional to the spread length between the first and last geophone, and the lowest frequencies generated by the source. Thus, maximum and minimum depths of investigation may vary between profiles collected with the same parameters and setups at the same site, because an impulsive, human-driven source, such as the one used in this project, does not guarantee a specific frequency content.