Role of geophysics in optimizing Light Rail Transit track design for Edmonton's Valley Line LRT

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ABSTRACT
The Valley Line LRT in Edmonton is currently being constructed, extending from the downtown core to the community of Millwoods in the southeast of the City. Tetra Tech Canada Inc. (Tetra Tech) was retained by TransED LRT Design Build (TransED) to conduct multichannel analysis of surface waves (MASW) testing at two locations within the Millwoods section of the alignment. The objective of the investigation was to determine ground flexure/stiffness along the centre of the alignment. Both shear and compression wave velocities were collected, which along with density values provided through materials testing, allowed for calculation of the small strain shear and Young's moduli continuously along the testing locations. Using the calculated values from the MASW testing, the track design was optimized for localized site conditions, and provided cost savings for the project.

RÉSUMÉ
La ligne Valley de train léger (SRL) est en cours de construction à Edmonton afin de prolonger le tracé du centre-ville jusqu'à la communauté de Millwoods dans le sud-est de la ville. Tetra Tech Canada Inc. (Tetra Tech) a été retenue par TransED Design Build (TransED) pour conduire une analyse sismique d'exploration (AMOS) sur deux zones à l'intérieur de la section Millwoods du tracé. L'objectif de l'analyse était de déterminer la flexion et rigidité du sol le long du tracé central. Les vitesses des ondes de cisaillement et de compression ont été recueillies, ce qui a permis, avec les valeurs de densité fournies par les essais de matériaux, de calculer le cisaillement de petite déformation et de modules d'Young en continu le long des sites de tests. En utilisant les valeurs calculées à partir des analyses AMOS, la conception du tracé a été optimisé aux conditions du site, en plus de permettre des économies de coûts pour le projet.

1 INTRODUCTION

Geotechnical investigations analyzing subgrade soils along light rail alignments are common. However, boreholes are often not drilled along the final alignment, due to existing infrastructure, or are spaced far apart in variable terrain. Soil strength and stiffness of the subgrade have a considerable influence on the track and ballast design, and therefore gathering additional information in an efficient manner can help reduce the conservatism in the design (Selig and Waters, 1994).

Tetra Tech Canada Inc. (Tetra Tech) was retained by TransED LRT Design Build (TransED) to conduct multichannel analysis of surface waves (MASW) testing at two locations within the Millwoods section of the Valley Line LRT project in Edmonton, AB. Borehole drilling for the project had already been completed, but not all boreholes had been drilled on the final alignment, and additional information regarding soil properties could yield significant cost savings in finalizing the track design. The objective of the investigation was to determine soil moduli continuously along the survey areas, while following the final alignment as closely as possible, providing additional information in areas with limited borehole data.

MASW is a non-destructive technique that utilizes the dispersion properties of surface waves to model the shear wave velocity. The survey setup can also measure the compression wave velocity, through refraction analysis of the data under proper conditions. Using both collected shear and compression wave velocity information, along with density values provided through materials testing and drilling investigations, the small strain shear modulus and Young's modulus can be calculated at each sounding location.

2 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 P- (primary, compression) 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 a parameter that is directly proportional to the shear modulus of a material. It is a measure of stiffness (or rigidity) of that material, and therefore is a parameter often used in geotechnical engineering.

In addition to body waves, there are also surface 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. MASW is a seismic technique based on the dispersion characteristics of retrograde motion Rayleigh waves (Park et al. 2007). The waves are generated by a seismic source such as a sledgehammer hitting a metal plate on the ground, or a passive source such as construction and traffic noise. The Rayleigh waves propagate through the ground at a speed of 90% of the shear wave velocity of the near surface. They are detected by an array of geophones (receivers), which measure the vertical displacement of the ground surface. By analyzing the phase velocities of the Rayleigh surface waves detected by the geophones, a 1-D vertical shear wave velocity can be modelled.

In a layered medium, surface waves have dispersion properties that are not observed with body waves. Dispersion occurs because surface waves are comprised of different wavelengths propagating at different velocities. The propagation velocity of each wavelength is called the phase velocity. For a given wavelength, there are multiple phase velocities at which the surface waves can travel. The slowest possible phase velocity for a given wavelength is known as the fundamental mode; it is this mode which MASW analysis is based upon. By analyzing the fundamental mode at different frequencies, a dispersion curve can be generated. Shorter wavelengths have shallow penetration depths, while longer ones have deeper penetration. Therefore, analysis of the fundamental wave energy distribution of the dispersion curve provides a profile of near-surface shear wave velocities.

The result of a MASW survey is a series of one-dimensional sounding, providing stiffness parameters at discrete locations, roughly analogous to a series of penetrometer measurements. 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.

2.1 Refraction

Refraction analysis can also be carried out on data collected for a MASW survey, to provide additional information beyond shear wave values. This method relies on knowing the relative geometry of the source and receivers, (i.e. distance between sledgehammer strike and the geophone array). By identifying the first arrival times of the compression (P-) wave, a modelled velocity cross-section can be generated for the wave, thereby obtaining the modelled P-wave velocities along the cross-section.

The technique is governed by Snell's Law and utilizes the refraction of P-waves on layers beneath the subsurface. Refractions typically occur at layer interfaces where velocities increase with depth. In situations where velocities decrease with depth, the lower velocity layer cannot be successfully modelled. For this project, refraction data was collected in areas where the geophones and source were on soil (velocities increase with depth). In areas with pavement (velocities decreasing with depth), refraction data was not obtained.

3 DATA COLLECTION

Data was collected by Tetra Tech's Edmonton office between October 31, 2017 and November 2, 2017. At the time of the survey, air temperatures ranged from -12°C to +4°C, and ground conditions ranged from wet soils to snow cover. It should be noted that although air temperatures during data collection were near or below freezing, ground conditions remained unfrozen during testing.

Data was collected over two areas of the Millwoods section of the Valley Line LRT: Northbound chainage 620+510 to 621+010 (Area A); and Northbound chainage 623+100 to 623+300 (Area B).

All MASW data was collected using a Geometrics' 24 channel Geode seismograph. The 24 geophones were arranged at 1 m spacing on a landstreamer, with ground coupling being established through metal plates at the base of each geophone. All positioning information was obtained with a Trimble R8 RTK GPS system, and reported in 3TM-114 (NAD83, CGVD28) coordinate system, tied to ASCM 57885. This yielded an absolute positional accuracy of ±2.5 cm in both the vertical and horizontal direction.

The objective of the survey was to collect MASW data as close to the centerline of the final alignment as possible within the two survey areas. Ongoing construction activities caused some obstructions and required Tetra Tech to deviate from the centerline at some locations. In only one location (Area B NB 623+130 to NB 623+180) was data collection prevented; this was due to the presence of an active access road that could not be closed at the time of the survey. Figures 1 and 2 show site maps of the two survey areas along with the MASW sounding locations overlain on the proposed alignment.

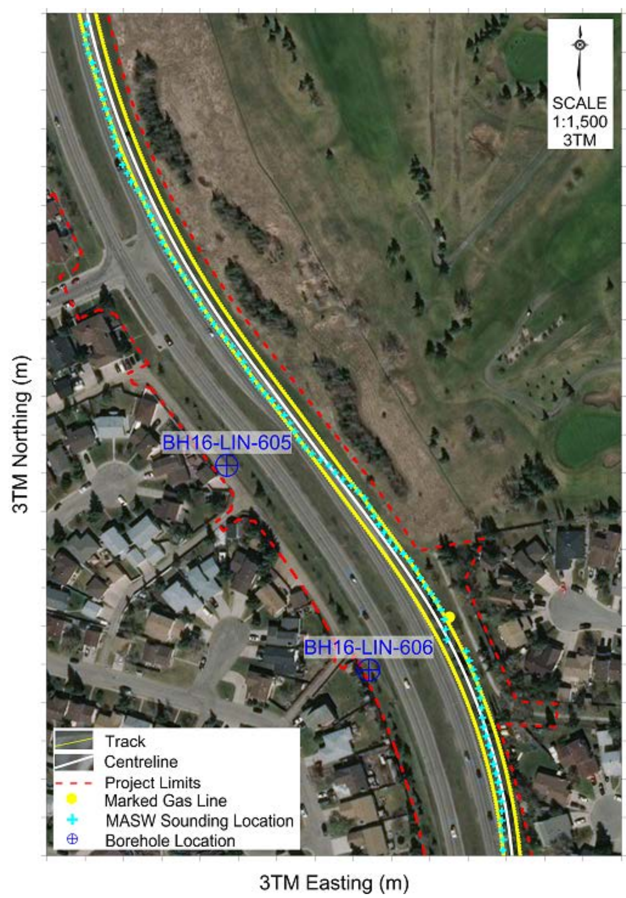

Figure 1. Area A Sitemap.

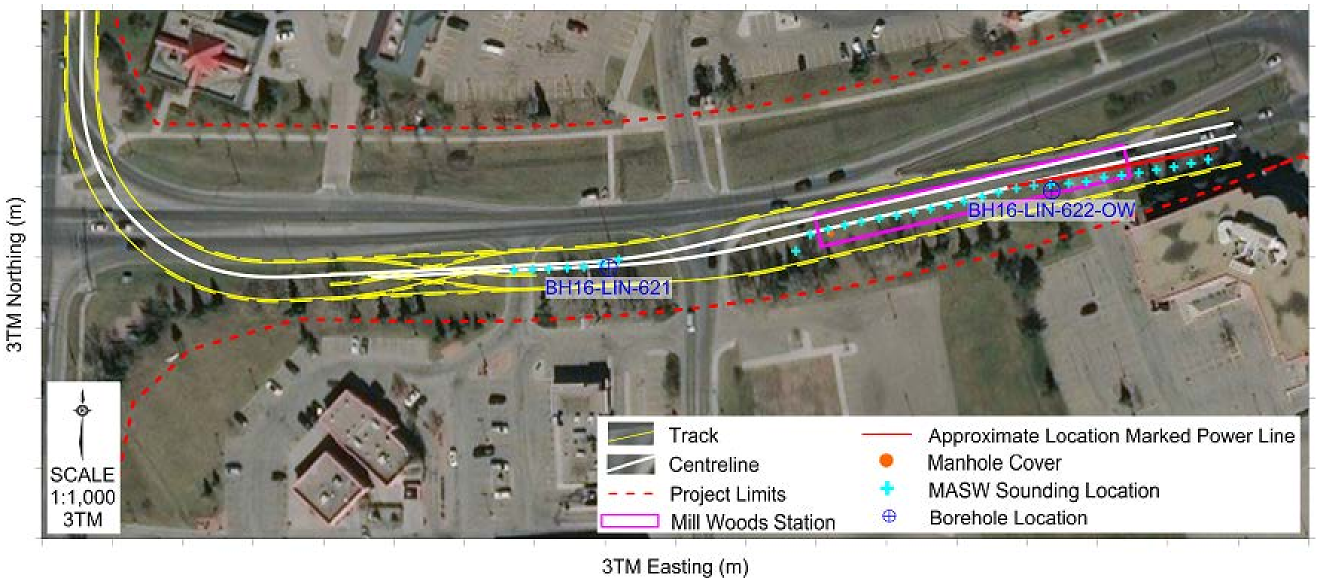

Figure 2. Area B Sitemap

3.1 Active Data

Active data is MASW data that is collected using an active source, such as a sledgehammer hitting a metal plate on the ground. Sledgehammer sources are quick to employ and provide a high frequency surface wave, which is good for achieving high resolution data in the near surface to a depth of approximately 10 m in typical Edmonton area soils. For this project, only 0 to 5 m depth have been provided as these were the depths of interest.

The majority of data collected for this survey was active data, utilizing a sledgehammer seismic source. An active MASW sounding was collected at every 5 m along the alignment within each survey area. Active data requires a high signal to noise ratio, which was achieved through stacking and the timing of data collection (i.e., waiting for "quiet" traffic adjacent to the survey site before collecting a reading).

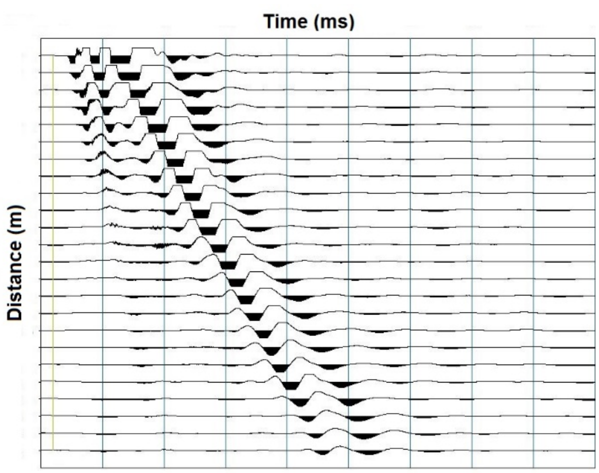

Figure 3. Example MASW shot record at NB 621+035

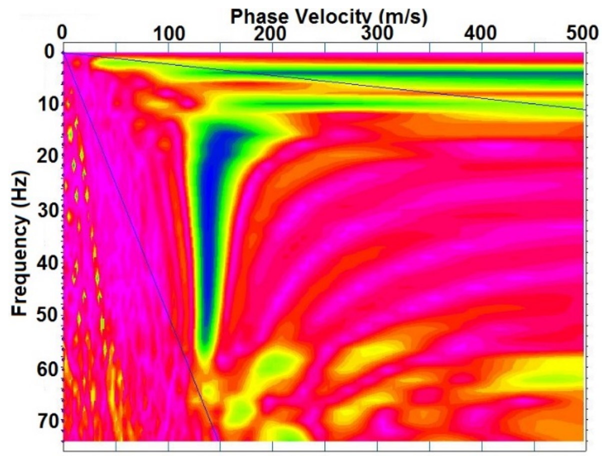

Figure 4. Example MASW Dispersion curve at NB 621+035

3.2 Passive Data

In addition to active data, two passive MASW soundings were collected for this survey – one in Area A and one in Area B. Passive MASW data utilizes background seismic noise (i.e. traffic, construction, etc.) as the wave source and generally provides deeper information than active data. For this survey, the passive data was collected and used as a quality control check to the active data.

4 DATA PROCESSING

All MASW data was processed using the SeisImager seismic processing software. For each sounding, both active and passive, a dispersion image was generated in the frequency-phase velocity domain. These images were used to interpret the dispersion curve, identifying and selecting the fundamental mode. The interpreted dispersion curves were used to calculate initial shear wave models, which were run through a least-squares inversion process to obtain final shear wave models.

Table 1. Example Soil Parameter Results from Area A

Station	Depth Range (m)	S-Wave Velocity (m/s)	P-Wave Velocity (m/s)	Soil Type	Density (kg/m^3)	Poisson's Ratio	Shear Modulus (MPa)	Young's Modulus (MPa)	Comments
NB 620+810	0.0 – 1.0	112	500	Clay	1806	0.473	23	67	• P-wave velocity from refraction data • Soils and density based on tri-axial testing from BH605, sample depth of 1.5-2.0 m. • Soil surface at array mid-point
	1.0 – 2.0	112	610	Clay	1806	0.483	23	67	
	2.0 – 3.0	137	716	Clay	1806	0.481	34	101	
	3.0 – 4.0	163	1029	Clay	1806	0.487	48	142	
	4.0 – 5.0	180	1232	Clay	1806	0.489	59	174	

For soundings collected on soil surface (as opposed to pavement), seismic refraction analysis was also completed using SeisImager software to obtain compression wave information. Data was filtered and gained before hand picking the first arrival times. This information was then used to generate a tomographic compression wave model along the profile. The results were exported into a spreadsheet format for each sounding location.

Using the shear wave (S-wave) and compressional wave (P-wave) velocities obtained from this investigation, as well as soil information provided by TransED, additional soil parameters were calculated. These include Poisson's Ratio, Shear Modulus, and Young's Modulus values.

In addition to these values, comments were provided indicating the surface type at the midpoint of each sounding, and which boreholes the soil types and density information were obtained from. Results were provided in table format for Areas A and B. An example of the results table is provided in Table 1. For soundings where the P-wave velocity could not be measured directly (where noted, soundings on pavement), a P-wave velocity was estimated based the S-wave and median Poisson's Ratio for the nearby data collected on soil.

Analysis of the passive data showed good agreement with the active data, and was primarily used as a backcheck to the active analysis.

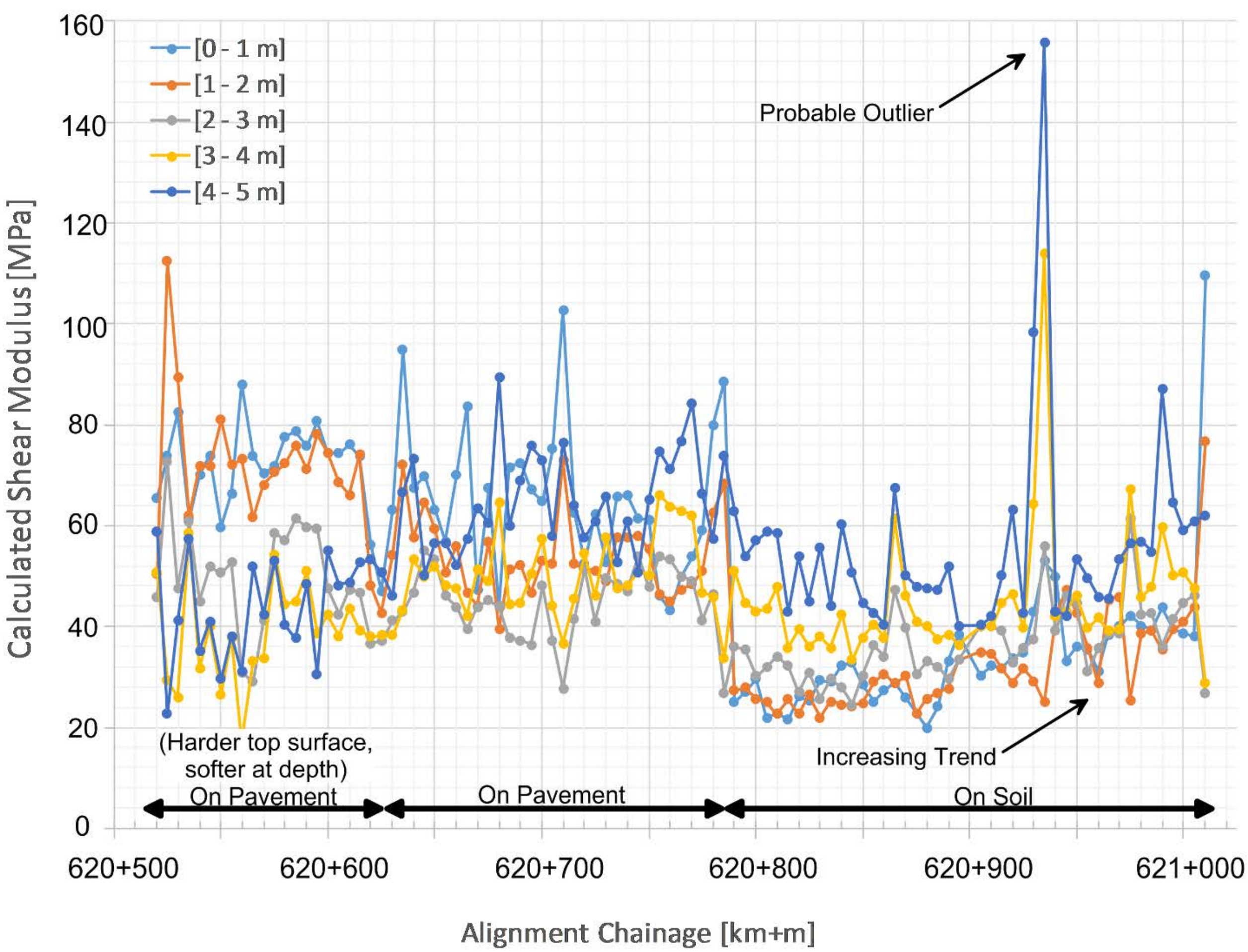

Figure 5. Calculated shear modulus values along alignment, Area A.

5 RESULTS

Line plots showing Shear Modulus values for each of the five depth intervals along Areas A and B are shown in Figures 5 and 6. In the sections of Area A where data was collected on pavement, higher ranging values were observed, approximately from 30 to 80 MPa. The surface wave dispersion and subsequent model shows a high contrast in velocity from the hard pavement to softer clay material (clay fill), then increasing again with depth as the material transitions back into a denser clay till.

Between NB 620+635 and NB 620+785 m, the subsurface properties change and the shear modulus range increases to approximately 45 to 85 MPa, with less of a contrast between soil shear modulus values and the overlying pavement. The shear modulus values also show a relatively consistent range in areas with a soil surface, with values ranging from 22 to 60 MPa and increasing in strength as depth increases. A slight increase in shear modulus values towards the south (up-chainage) was also noted within Area A, indicating a local trend.

In Area B, collected entirely on a soil surface, the shear modulus data shows a consistent range, with values ranging from approximately 30 to 80 MPa and increasing in strength as depth increases. A slight decreasing local trend was noted in shear modulus values to the south (up-chainage) of Area B.

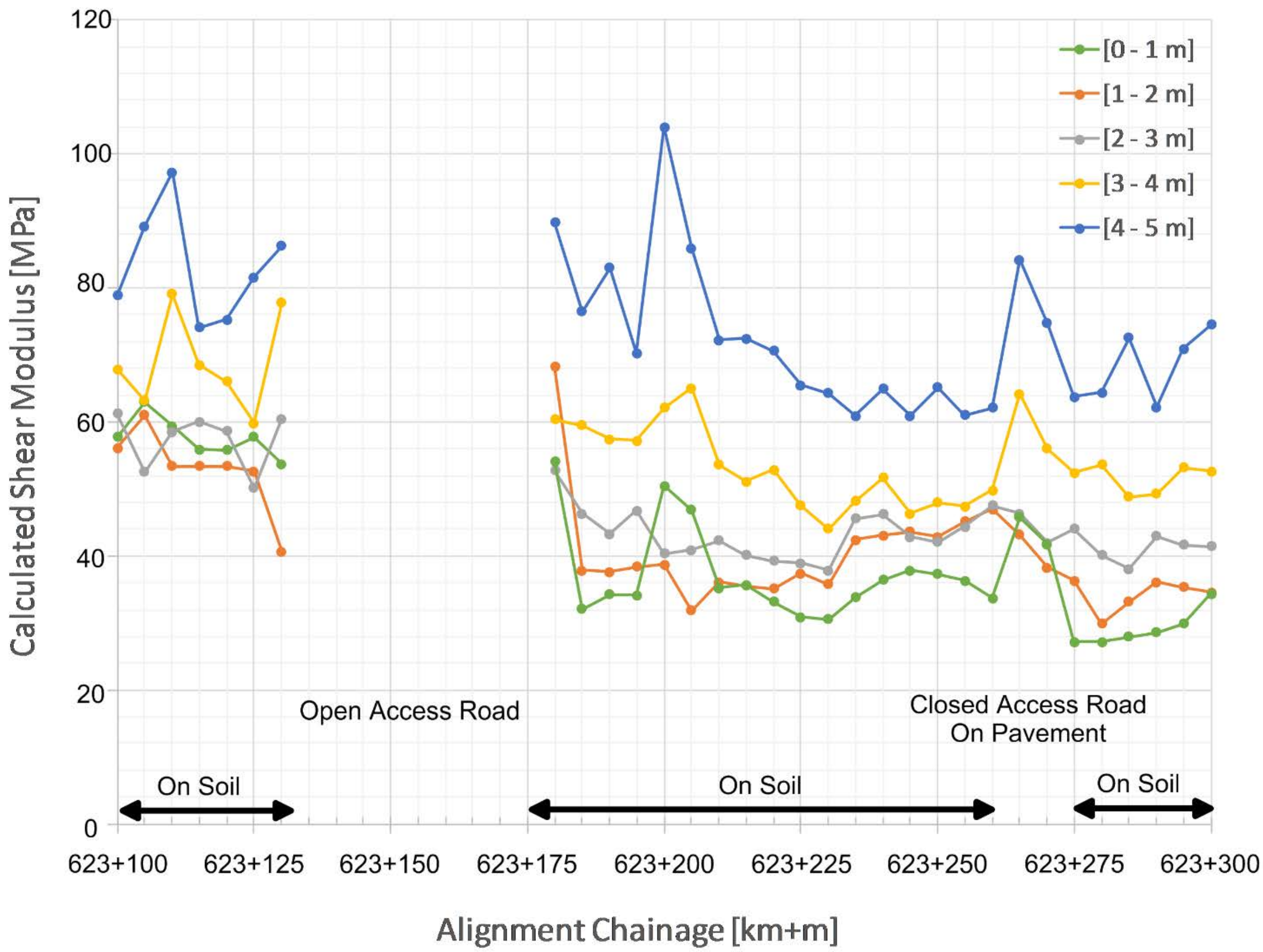

Figure 6. Calculated shear modulus values along alignment, Area B

5.1 Impact on Track Design

The track slab was analyzed by the designer as a two-way grillage model, with beam elements in both transverse and longitudinal directions. Soil-structure interaction was accounted for through springs generated in the structural software based on the geotechnical soil properties provided by the geotechnical team. The track slab has been assessed under three different limit states (FLS, ULS, and SLS).

The main geotechnical properties used as input parameters are the subgrade elastic modulus (high strain) and Poisson's ratio. The elastic modulus (low strain), Young's modulus, was calculated from the shear modulus (low strain) obtained from the MASW survey results and Poisson's Ratio. The elastic modulus was then converted from low to high strain. Initial elastic modulus value(s) used for the subgrade prior to the MASW survey were more conservative because there were some lower Standard Penetration Test (SPT) blow counts (N-Values) results from the subsurface investigation program. After using MASW to confirm the properties of these areas along the final alignment, the designer was able to use higher elastic modulus values in the structural model with higher confidence, thus reducing the rebar density by approximately 10 to 20 percent. The method of subgrade preparation and track slab thickness remained the same. The full extent of the cost savings for the project is still being analyzed.

6 CONCLUSION

Geotechnical investigations for LRT design are limited to a discrete number of boreholes, that can be situated in areas off the final alignment. This often results in the use of geotechnical parameters for track design, namely elastic modulus and Poisson's ratio, that are conservative. MASW is a geophysical seismic technique that can be used as an efficient way to model near surface shear wave velocities. In this study, both shear and compression wave data were continuously collected at a spacing of 5 m in two locations along Edmonton's Valley Line LRT alignment. This allowed the LRT track designers to use a larger input value for elastic modulus with a higher degree of confidence, yielding a reduction in the amount of track reinforcement required to meet the design criteria.

7 REFERENCES

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