SSJV

EVERGREEN LINE RAPID TRANSIT PROJECT

TUNNEL GEOPHYSICS INVESTIGATION REPORT (CHATEAU PL.)

Reviewed by:	Ardalan Hamidi P.Eng, Technical Manager	
Approved by:	Marco Moccichino, Project Manager	
	Name, Title	Signature

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December 12, 2014

SNC-LAVALIN Constructors (Western) Inc.
SELI Canada Inc., Joint Venture
2120 Vintner Street
Port Moody | British Columbia | Canada | V3H 1W8
Attention: Ardy Hamidi, P.Eng.

Project: Evergreen Line Rapid Transit: Tunnel
Port Moody, British Columbia, Canada

Subject: Geophysical Exploration: Results

Hello Ardy,

This letter presents the results of the geophysical exploration recently completed to address over excavation issues related to a specific interval. This letter describes the approach, objective, theory, interpretation, and limitations of the geophysical effort. Prior to this submittal, preliminary results were delivered to the engineer and contractor for review and comment. The work that was completed was done so in general accordance with details presented in the Work Plan prepared and submitted by Siemens & Associates (SA) on November 15, 2014.

As described in the Work Plan, the geophysical methods recommended for this exploration have been applied successfully for many years to address myriad types of geotechnical problems. However, this project may be the first application conducted deep underground from the ceiling of a lined tunnel. The application is considered experimental and as described in this letter successful with a few cautions.

Project Understanding

SA understands that the 10 m diameter tunnel is advancing through glacial formations. In the vicinity of the geophysical exploration, the tunnel was at an average depth of roughly 45 meters. Over excavation has resulted in the creation of voids above the tunnel that offer potential for upward migration and subsequent surface disruption. Soils that have been loosened as a result of over excavation will be improved through a remediation program involving compaction grout methods applied from the surface.

The geophysical exploration is intended to confirm and/or identify targets for remedial grouting and, the exploration will be repeated following the completion of the remediation to support an opinion regarding success.

Scope

Although two geophysical methods were originally proposed, due to time constraint, only one method was approved. Electrical resistivity tomography as described in the Work Plan was not done. A single seismic method was applied known as Refraction Microtremor (ReMi). Data were collected at the surface in the conventional fashion and within the tunnel with receivers fastened to the ceiling near the crown in a very unconventional fashion.

The locations for the surveys were prescribed by the client to explore specific zones of interest related to TMB records where volumetric measurements during tunnel advancement indicated potential for over excavation.

Geophysical Methods

Refraction Microtremor (ReMi)

In support of various engineering endeavors, surface wave analysis is widely utilized for obtaining near surface shear-wave velocity models to define geologic conditions. The analyses provide information about the shear-wave velocity variations along the seismic array in broad terms gaining insight regarding geologic changes through long sections that can be very difficult to detect through alternative methods. ReMi is a passive method using ambient vibrations (background noise) sometimes augmented by an untimed, active seismic source to generate higher frequency input.

How it works: The ReMi analysis develops the shear-wave velocity/depth profile using an engineering seismograph, low frequency receivers (geophones) and straight line array aperture. Surface wave energies (Rayleigh Waves) are recorded using relatively long sample window (30 seconds) recording the ambient wavefield. For this project, quality low frequency signal was consistently recorded from both the surface and within the tunnel, and mid-range frequency was enhanced by striking a sledge hammer on the tunnel ceiling and on an aluminum plate at the surface.

In processing, the microtremor records are transformed as a simple, two-dimensional slowness-frequency (p-f) plot where the ray parameter "p" is the horizontal component of slowness (inverse velocity) along the array and "f" is the corresponding frequency (inverse of period). The p-f analysis produces a record of the total spectral power in all records from the site, which plots within the chosen p-f axes. The trend within these axes, where a coherent phase has significant power is "picked". Then the slowness-frequency picks are transformed to a typical period-velocity diagram for dispersion analysis. Picking the points to be entered into the dispersion curve is done manually along the low velocity envelope appearing in the p-f image. From a select group of receivers, a 1D shear-wave velocity vs depth model is developed by trial to match the field data. For this project, many 1D profiles were generated and then combined as a pseudo 2D shear-wave velocity model through the area of study.

Each line utilized a 24 channel receiver array with 4.5 Hz. geophones set on 5 meter spacing. Data were recorded using a DAQ III seismograph manufactured by Seismic Source in Ponca City, Oklahoma, USA, connected to a HP laptop computer manufactured in China.

Three (3) independent lines of ReMi data were recorded numbered RM-1 through RM-3. The first two lines represent data collected from the surface through alignments above zones of interest in an area known as Chateau Place and the locations are illustrated on the Site Plan presented as appendix to this letter.

At Chateau Place, the first line was laid out parallel and very near the existing apartment building in an effort to define conditions through a zone where TBM records indicated potential over excavation. The line was oriented on a strong oblique angle to the tunnel. The second line at Chateau Place was also on an oblique angle to the tunnel, necessary due to constraints posed by the apartment and steep topography. Topography along RM-1 and RM-2 was essentially flat.

RM-3 represents data processed from receivers connected to the ceiling of the tunnel near the crown. This was done using a coupling nut cemented to the top of the receiver fastened to a matching threaded stud set into the concrete tunnel liner. The 24 receiver array spanned Ring 251 to Ring 328, a distance of approximately 115 meters.

ReMi Processing

Dr. Satish Pullammanappallil, Ph.D. of Optim took the lead on processing the ReMi datasets. Dr. Pullammanappallil created a series of 1D shear-wave depth profiles along each line using 6 to 24 channels per analysis progressing one channel at a time (channels 1 to 12, 2 to 13, 3 to 14 and so on). All 24 channels were used to constrain the deepest parts of the model, and the data were judged to constrain depths of exploration on the order of about 35 meters. The procedure is arduous and involves judgment regarding velocity, layer thickness and transition boundaries. The solutions are not unique and a trial and error approach is utilized until a reasonable fit between the observations (data) and theoretical model is achieved.

The 1D ReMi profiles were then merged using SeisOpt® ReMi™ (© Optim) software to create the 2D models presented as Figures RM-1 through RM-3. The 2D models illustrate trends in the subsurface in terms of shear-wave velocity that correspond closely with observed over excavation records that were presented to SA.

As discussed, thin layers (small targets on the order of one half the receiver spacing) are not expected to be resolved and the depth to the various contact boundaries are also constrained by similar resolution such that the boundary is estimated to be accurate within about 15% or so (with respect to the total depth of the model). Model velocity is typically estimated to be within about 10 to 15% which would be calculated using more rigorous methods such as cross-hole techniques. Error can be plus or minus.

Conclusions

The Work Plan presented two geophysical methods to improve the confidence in interpretation. Since only one method was approved, SA must rely on priori data such as existing drilling records (exploration and TBM) to make judgment regarding data and interpretation quality as no independent geophysical measurements are available for consultation.

General

The shear-wave velocity is a direct measure of the strength of geologic materials and for this project, lower velocity regions that coincide with known zones of over excavation are judged to be related to disturbance (loosening) of the native soils as a result of over excavation and travel of voids from the top of the tunnel toward the surface. It is common to observe natural variations in shear-wave velocity distribution in most geologic conditions and not every low velocity region within the models that have been produced are necessarily related to tunneling activities. Each shear-wave velocity model is annotated to illustrate general interpretation of the findings with more detail presented through the following paragraphs.

When establishing locations for the lines at Chateau Place, SA placed emphasis on extending the line length as great as site constraints allowed in order to gain depth of exploration. This is why the lines are not parallel the tunnel. As discussed, ReMi is an averaging method using groups of receivers and small, isolated targets may go undetected. This is a limitation of the method; although, there are ways to improve the resolution and these involve trade-offs. As an example, smaller targets can be resolved using shorter receiver spacing with the sacrifice of depth of exploration. We chose 5 m spacing as a reasonable number to optimize both resolution and depth of exploration given the targets that were explained to us.

A shorter line oriented directly over the tunnel alignment was considered at Chateau Place; however, only a very short line length was available (receiver spacing of about 1.5 m) which was estimated to limit exploration depth to about 10 meters. This was considered too shallow a penetration and of limited value, and the data were not recorded.

Robust records were measured from both the surface at Chateau Place and from within the tunnel. There are differences though, as was expected. Most significant is the nature of the frequency spectra recorded from the different environments. Data from Chateau Place were reasonably normal with a full range of frequency leading to conventional processing and interpretation. Data from within the tunnel were especially rich in low frequency and especially poor in high frequency even though attempts were made within the tunnel to induce near receiver high frequency by striking the tunnel liner near the array with a hammer during the measurement sequence. As it turns out, measurement from the ground surface, when coupled with measurement from within the tunnel offer some compliment and together help to constrain a greater portion of the full depth of the section. That is, the surface data constrains the shallow environment best and the in-tunnel data is a slightly better measurement of the deeper geology.

ReMi #1 (RM-1)

This data set was collected over a zone where TMB records indicated over excavation estimated to be less than 20% through a short interval. The results did not reveal low velocity regions where the line crossed the tunnel alignment. The line was very near and parallels an existing apartment building and the data is judged to have been partially influenced by the structure. The influence is most profound in the shallow environment where it is possible that an isolated, low velocity region could have gone undetected, being masked by the structure itself.

ReMi #2 (RM-2)

This line was extended along the existing surface disruption ("sinkhole") through a segment where over excavation in excess of 20% was recorded. The line is oriented on an oblique angle to the tunnel alignment necessary to achieve the desired line length. The model velocity profile clearly illustrates a natural increase in shear-wave velocity ranging from about 16 to 18 m below grade. In the vicinity of the known segment of over excavation (roughly Ring 293 to 297) a vertical, lower velocity anomaly is identified. SA interprets this feature as plausible indication of a void path working its way to the surface. This area has also been the location of many exploration holes that may also have promoted disturbance of the same area. It is possible that the shear-wave velocity is somewhat over estimated through this narrow, vertical zone since the position of the cable was not directly over the tunnel at this location and adjacent, undisturbed geology has contributed to the recorded data.

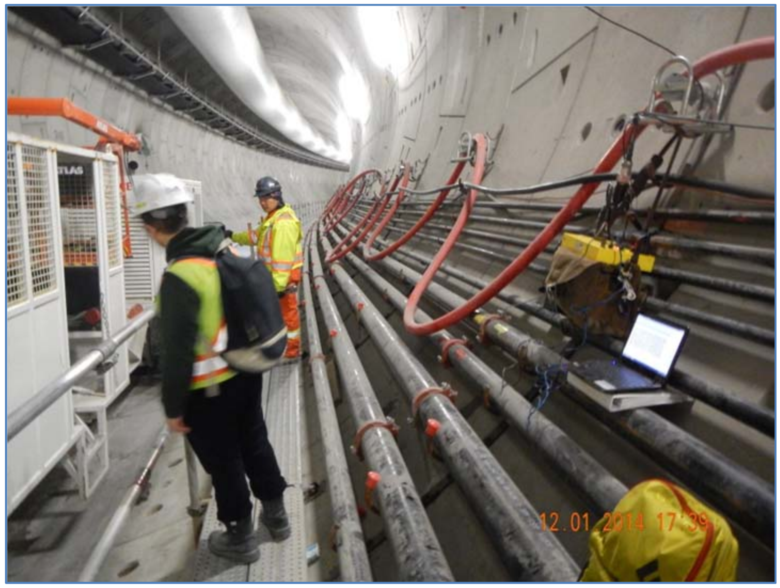
A significant low velocity region is shallow (about 5 to 14 m depth) where velocities on the order of 200 m/s are interpreted. This low velocity region is related to a known segment of over excavation and is adjacent the concrete backfilled surface disruption. Nearby regions (not over the tunnel) indicate that the typical shear-wave velocity at this depth is on the order of 380 m/s. As a result, SA interprets the low velocity regions illustrated above Rings 293 to about 298 are likely representative of disturbance near the surface promoted by tunneling activity. Similar low velocity is illustrated for a few meters farther along the line including the location where RM-3 actually crosses the tunnel at about Ring 303. SA does not have any information regarding TBM records in this area and cannot conclude on the validity of this interpretation.

Higher velocity regions near the surface of RM-2 are judged to reflect influence from shallow concrete that was placed in the open void as the line crossed very near this area (although not directly over it). Again, the velocity interpreted along this line that are judged to measure disturbance related to tunneling are likely to be overestimated due to influence from higher velocity, undisturbed geology along the obliquely oriented line.

ReMi #3 (RM-3)

The interpretation of RM-3 data, although recorded from deep underground, is based on the same surface wave (Rayleigh wave) theory similar to data recorded in the traditional fashion with receivers at the surface. Due to the depth, the records held a strong low frequency content and higher frequency was less coherent. Further, the tunnel itself influenced the wavefield such that information very near (within 5 to 10 meters) the tunnel was not available. This is probably due to the tunnel liner thickness, high strength and the presence of a surrounding strong grout layer.

RM-3 is in near perfect orientation with the tunnel since the data were recorded from geophones connected to the ceiling very near the crown. Given that, the interpretation is judged to be more representative of conditions directly over the alignment minus a "blind zone" in near proximity to the tunnel.



RM-3 illustrates a vertical, lower velocity column directly associated with the location of known over excavation. The data clearly respond to this region and the zone is judged to be associated with tunneling activities. Again, the actual shear-wave velocity is likely to be overestimated since the ReMi "average" will include influence from surrounding, undisturbed soil.

For RM-3, the near surface velocity interpretation (elevations greater than about 75 m) is judged to be less constrained or less certain when compared to measurement at the surface from RM-1 or RM-2. This is due to a dearth of high frequency content in the recorded data. As a result, the higher velocity concrete plug interpreted from RM-2 is not apparent in RM-3. As discussed in the Summary, SA has some ideas about ways to improve the results of future surveys.

Summary

The results are interpreted to represent plausible conditions through the exploration zones. The work at Chateau Place is complicated by orientation of the arrays that is necessarily oblique to the tunnel alignment and this muddles the result to some degree. Nevertheless, valuable data are presented through specific zones of interest. The experimental array connected to the tunnel ceiling is promising and clearly provides reason to conclude that only one significant disturbance was measured along the array.

RM-2 and RM-3 offer low velocity regions that are anticipated to be targeted for remediation using compaction grout techniques and ReMi data collection along these same lines are anticipated following the remedial effort. The follow-up ReMi surveys are expected to provide confirmation of the compaction grout program and will be performed in the same manner.

In future application in the search for disturbed soil associated with tunneling unconsolidated formations, improved resolution could possibly be achieved by using a more ambitious effort. This would include shorter spaced receiver array and more receivers. If this effort is to be repeated in another section of tunnel, SA will recommend 48 channel arrays with receiver spacing on the order of 2.5 to 3 m. This will result in similar depth of exploration although double the receiver count can be used to constrain the multiple 1D ReMi profiles that are generated to produce the 2D image. To improve the opportunity to measure high frequency content from within the tunnel, efforts to generate seismic "noise" at the surface would be helpful. This could be done by driving heavy equipment on roads above the tunnel, drilling, and inducing other types of construction activities. Given what we have learned in this effort, such an approach is very likely to improve the end result.

Limitations

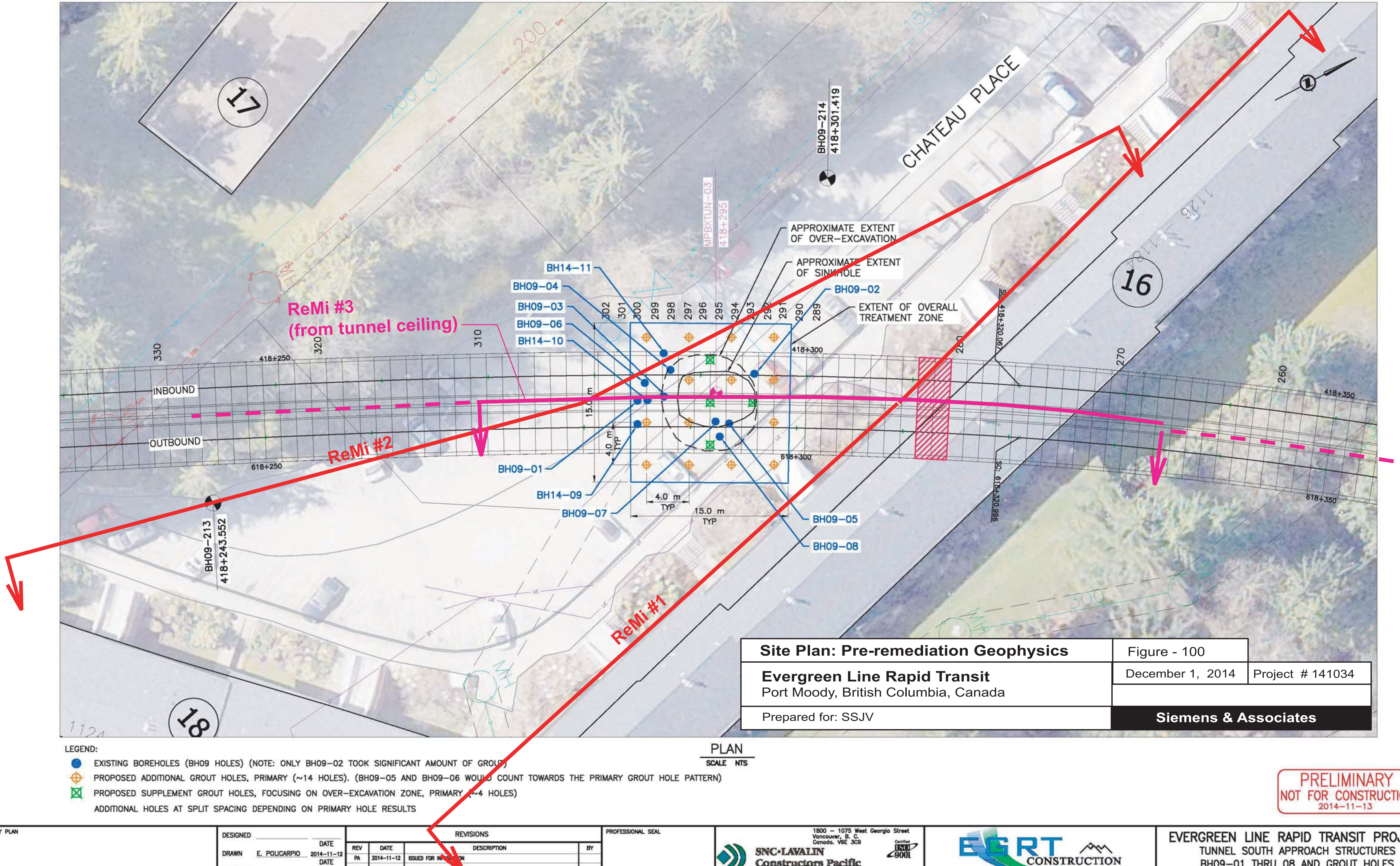
This letter presents our professional opinion based upon geophysical measurement and interpretation delivered as an endeavor to conform to the standard of practice currently employed by area geoprofessionals conducting similar work in Port Moody, British Columbia, Canada, at this time. We make no other warranty express or implied.

We appreciate the opportunity to conduct this exploration and trust that the services are in line your expectation.

Prepared by,
Siemens & Associates

J. Andrew Siemens, P.E., G.E.

Addressee: 1 electronic
Encl. Site Plan (Figure 100)
RM-1 through RM-3



Site Plan: Pre-remediation Geophysics	Figure - 100	
Evergreen Line Rapid Transit Port Moody, British Columbia, Canada	December 1, 2014	Project # 141034
Prepared for: SSJV	**Siemens & Associates**	

PLAN
SCALE NTS

LEGEND:
- EXISTING BOREHOLES (BH09 HOLES) (NOTE: ONLY BH09-02 TOOK SIGNIFICANT AMOUNT OF GROUT)
- PROPOSED ADDITIONAL GROUT HOLES, PRIMARY (~14 HOLES). (BH09-05 AND BH09-06 WOULD COUNT TOWARDS THE PRIMARY GROUT HOLE PATTERN)
- PROPOSED SUPPLEMENT GROUT HOLES, FOCUSING ON OVER-EXCAVATION ZONE, PRIMARY (~4 HOLES)
- ADDITIONAL HOLES AT SPLIT SPACING DEPENDING ON PRIMARY HOLE RESULTS

PRELIMINARY
NOT FOR CONSTRUCTION
2014-11-13

LAYOUT: MONITORING
PLOT DATE: 2014-11-13 8:52 AM POLICARPIO, EDWIN
FILE LOCATION: C:\USERS\POLIE\DOCUMENTS\WORKING_DRAWINGS\511328-BOREHOLE_BH09-01-08_AND_GROUT-HOLES_PA.DWG

KEY PLAN	DESIGNED		DATE
	DRAWN	E. POLICARPIO	2014-11-12
	CHECKED		DATE
	APPROVED		DATE
	SCALE BAR AS PER 1:1 ANSI D-SIZE SHEET EGL-TITLEBLOCK.dwg		

REVISIONS

REV	DATE	DESCRIPTION	BY
PA	2014-11-12	ISSUED FOR INFORMATION	

PROFESSIONAL SEAL

SNC·LAVALIN Constructors Pacific
1800 – 1075 West Georgia Street
Vancouver, B. C.
Canada. V6E 3C9
Certified ISO 9001

JV LOGO: SSJV
DESIGNER: SELI

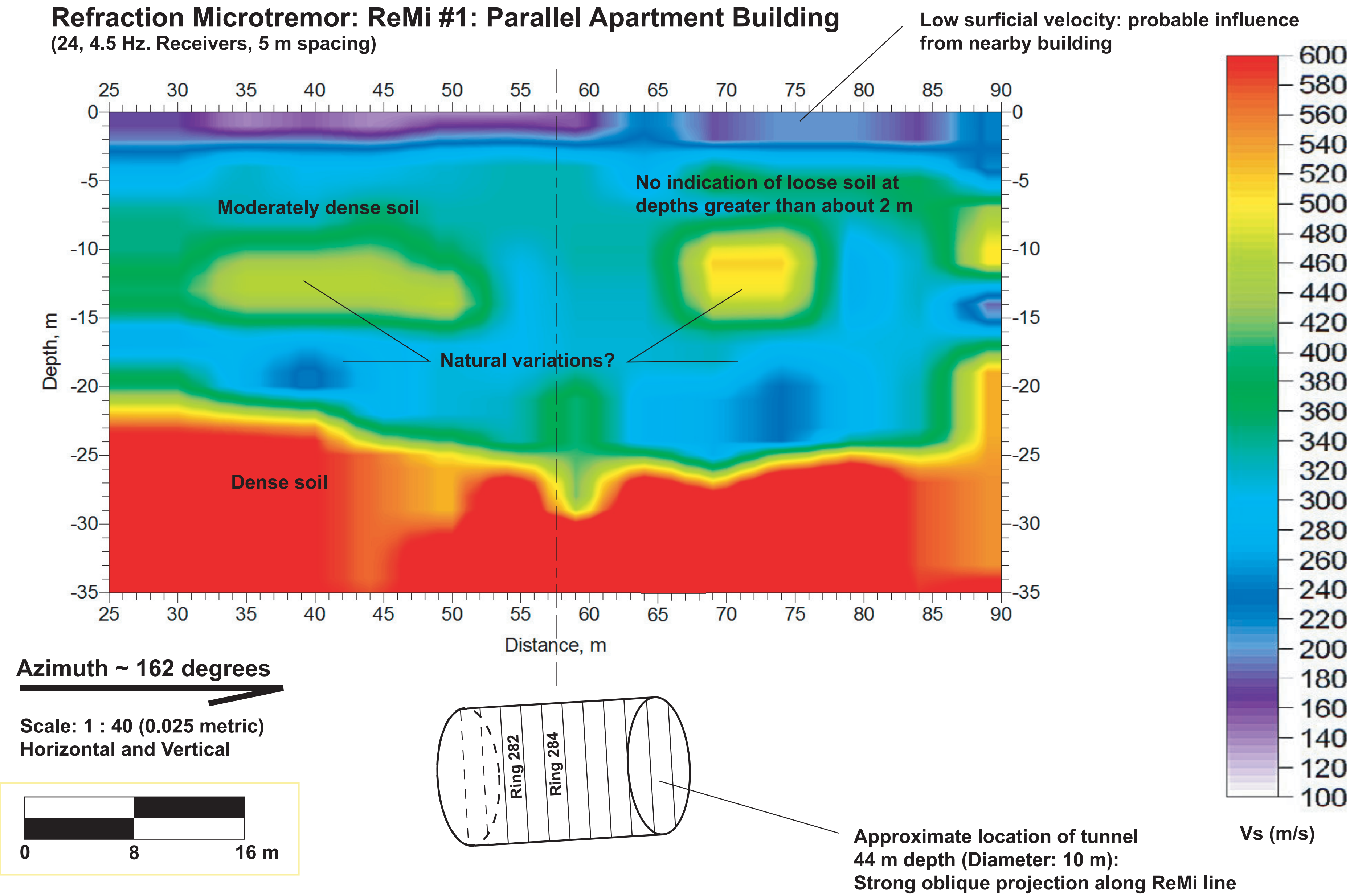
EGRT CONSTRUCTION
British Columbia Ministry of Transportation and Infrastructure
SCALE NTS
0 10 m
SCALE BAR

EVERGREEN LINE RAPID TRANSIT PROJECT
TUNNEL SOUTH APPROACH STRUCTURES
BH09-01 THRU 08 AND GROUT HOLES
PLAN

PROVINCE CONTRACT No.	03902	SUB-CONSULTANT No.	
DRAWING No.	511328-BH09_01-08_&_GROUT_HOLES		PA

SUPERCEDES PRINTS OF THIS NUMBER WITH LETTERS PREVIOUS TO

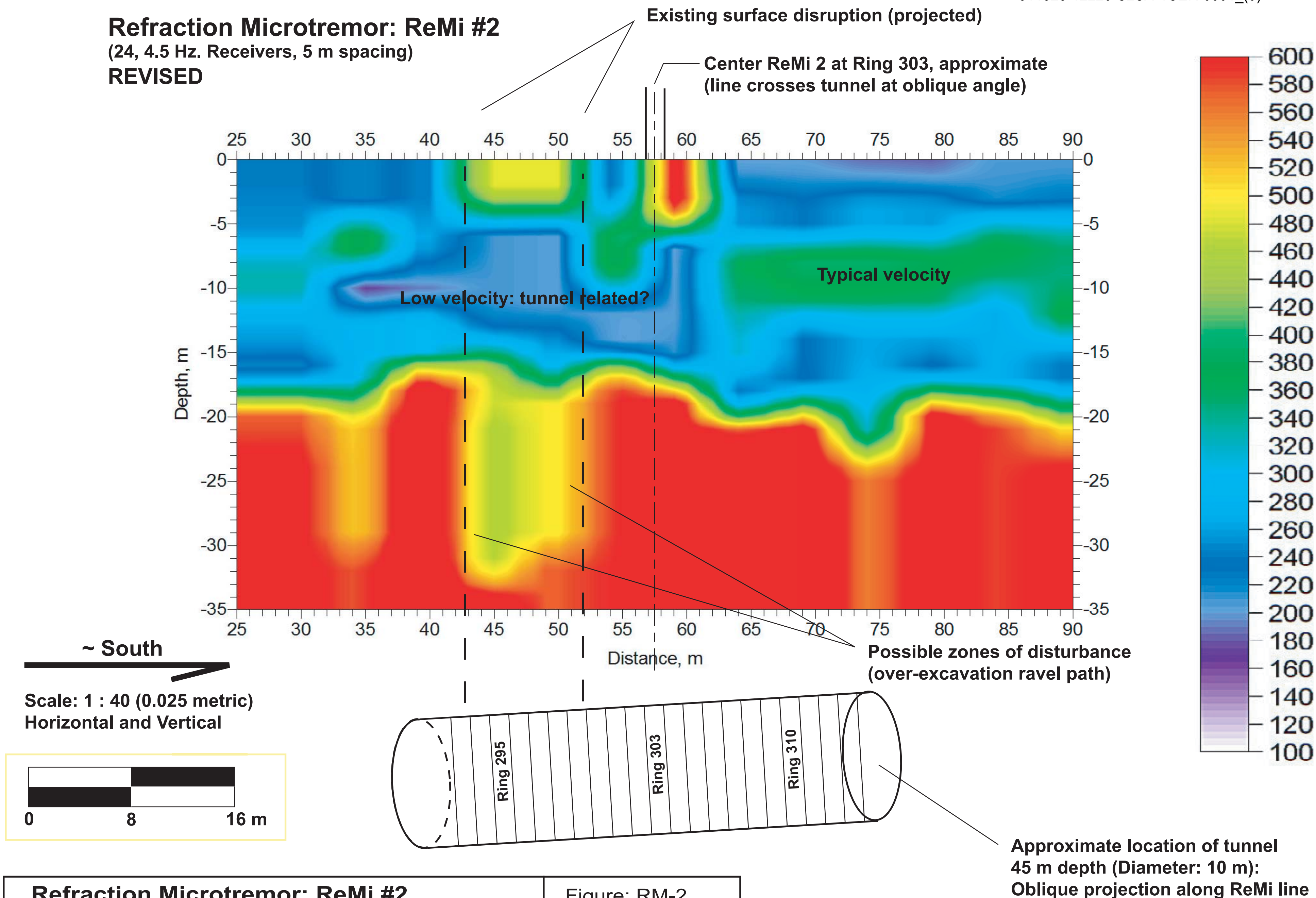
TRA-2015-00010



Refraction Microtremor: ReMi #1	Figure -RM1	
Evergreen Line Rapid Transit Port Moody, British Columbia, Canada	November 19, 2014	Project # 141034
Prepared for: SSJV	**Siemens & Associates**	

Refraction Microtremor: ReMi #2
(24, 4.5 Hz. Receivers, 5 m spacing)

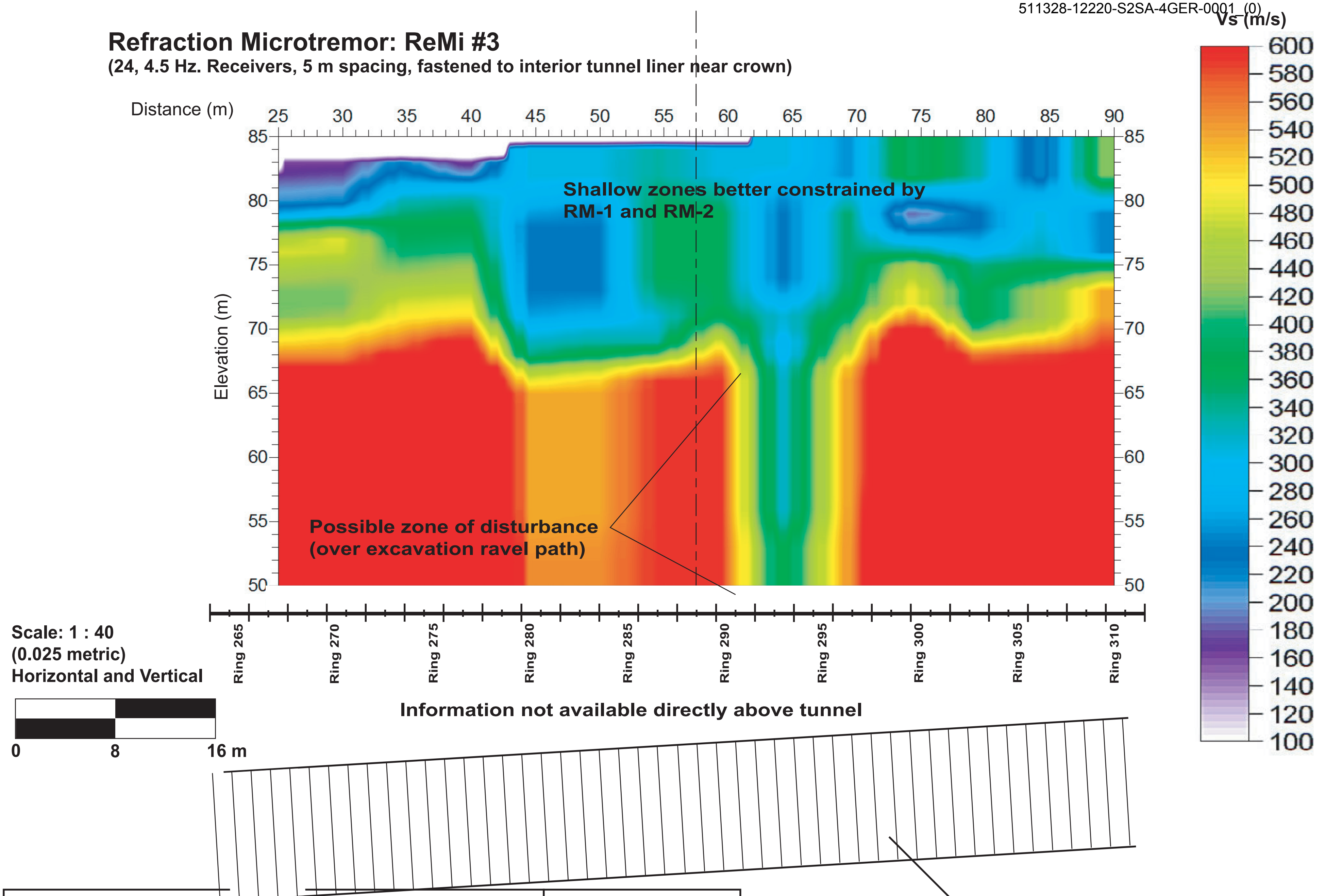
REVISED



Refraction Microtremor: ReMi #2	Figure: RM-2	
Evergreen Line Rapid Transit Port Moody, British Columbia, Canada	November 20, 2014	Project # 141034
Prepared for: SSJV	**Siemens & Associates**	

Refraction Microtremor: ReMi #3

(24, 4.5 Hz. Receivers, 5 m spacing, fastened to interior tunnel liner near crown)



Refraction Microtremor: ReMi #3	Figure: RM-3	
Evergreen Line Rapid Transit Port Moody, British Columbia, Canada	December 1, 2014	Project # 141034
Prepared for: SSJV	**Siemens & Associates**	