Imaging soil and rock along tunnel alignments with combined geophysical seismic techniques, case histories

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ABSTRACT

Recent advances in non-invasive geophysical techniques for tunnel pre-design have improved the resolution of mapping soil and rock stratigraphy and structural flaws. The detailed description of the subsurface continuously along a tunnel alignment, whether within the bedrock or the overburden, can identify problematic geology during the design phase. Two case studies are discussed that use combined seismic methods along proposed tunnel alignments to map geology.

RÉSUMÉ

L'innovation dans l'application de méthodes d'investigation géophysiques non-destructives, pour l'étude de projets de construction de tunnels, a permis d'améliorer la résolution de l'imagerie des dépôts meubles, de la stratigraphie du roc et des défauts géologiques structuraux. La description détaillée du sous-sol le long d'un axe de tunnel, dans les matériaux meubles ou le roc, peut permette d'identifier des problématiques au niveau géologique lors de l'avant-projet. Deux cas sont présentés, où une combinaison de méthodes sismiques est utilisée pour faire la caractérisation géologique le long de deux axes de tunnels proposés.

1 INTRODUCTION

The detailed description of the subsurface along a tunnel alignment, whether within the bedrock or the overburden, can identify problematic geology during the design phase. Geophysical techniques provide a cost effective, non-destructive means of collecting a near-continuous geologic profile. This paper presents two case studies using recent advances in seismic techniques.

The seismic methods applied to these case histories include traditional seismic refraction but rely predominantly on the technique Multi-Channel Analysis of Surface Waves (MASW) and a technique developed by our firm called Testing and Imaging using Seismic Acoustic Resonance (TISAR). TISAR was developed to create high-resolution stratigraphic images up to 70 m in depth.

2 SEISMIC METHODS

Seismic methods can be broken down into two categories from the users' point-of-view. There are methods that produce hard numbers such as depths and speed (Seismic Refraction and MASW) and there are methods that generate images of soil and rock structure that require interpretation of the images (Seismic Reflection and TISAR). Two of the former category and one of the latter categories have been combined to create a detailed cross-sectional profile of geology with certainty.

2.1 Seismic Refraction

This is one of the oldest seismic methods[1]. It relies on the fact that the fastest seismic pulse (also known as P-wave, Compressional waves or first arrivals) travels at different speeds in different materials. More importantly, it travels at faster speeds in more competent materials, with some exceptions (Hawkins, 1961). As well, materials tend to be better-consolidated and more competent with depth, again with some exceptions (Hawkins, 1961).

Figure 1 demonstrates the basic operating principle of the method. When a seismic pulse is initiated, the pulse travels along the surface to each of the receivers. The same pulse also propagates downward to a more competent (faster) formation and at some point it will overtake the pulse that travels along the surface. This is referred to as a *refracted* wave. After pulses are recorded from different locations, the depth and velocities for various geologic layers can be calculated. Typical geologic contacts that are often mapped include the top of the water table, the top of bedrock and sometimes intermediate overburden layers. The reader is referred to Redpath,(1973) for a detailed overview of the technique.

Although the P-wave is used more commonly for mapping geologic structures, the shear wave (S wave) is extremely interesting to engineers as it is more representative of the strength of a material. The S-wave, however, is slower than the P-wave and is more difficult to generate and measure in the field at

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[1] In 1909, Andrija Mohorovicic used travel-times from earthquake sources to perform a seismic refraction experiment and discovered the existence of the crust-mantle boundary now called the *Moho*.

sufficient strength in order to perform shear wave refraction. The solution is a relatively new technique that can generate a vertical profile of shear wave speeds non-intrusively called MASW.

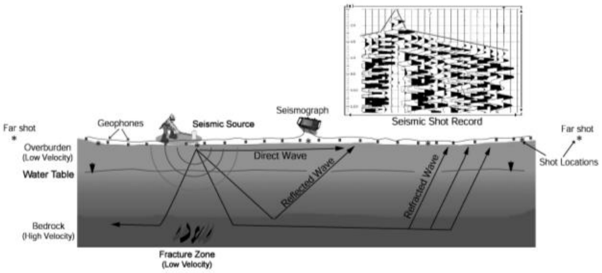
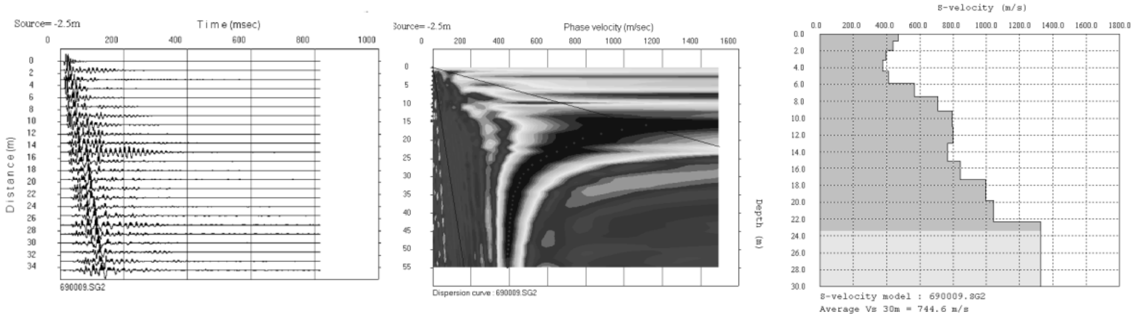


Figure 1: Refraction Seismic Operating Principle

2.2 Multi-channel Analysis of Surface Waves (MASW)

A simple seismic impact, such as a hammer, actually generates a multitude of different waves. One of the waves that arrive after the P and S-waves is called the Rayleigh wave[2]. This wave, when combined with the Love[3] wave, travels along the surface, is very strong and moves in an elliptical motion, which is why it is commonly known as “ground roll”. It was discovered that the wave always traveled at approximately 92% of the speed of a shear wave but was much easier to recognize because it was very strong (Viktorov, 1967). The Multi-channel Analysis of Surface Waves (MASW) is a seismic method used to evaluate the shear-wave velocities of subsurface materials through the analysis of the dispersion properties of Rayleigh surface waves (“ground roll”). Park et al. first introduced the technique in 1999, and the reader is referred to their paper for a detailed discussion (Park et al. 1999).



Raw Seismic Shot Record

Phase Velocity-Frequency Transformation indicating Dispersion Curve

1D Shear-Wave Velocity Profile from Inversion of Dispersion Curve

Figure 2: MASW Processing procedure

Essentially, the dispersion properties are measured as a change in phase velocity with frequency. Surface wave energy will decay exponentially with depth. Lower frequency surface waves will travel deeper and thus be more influenced by deeper velocity layering than the shallow higher frequency waves. Inversion of the Rayleigh wave dispersion curve yields a shear-wave (V_s) velocity depth profile (sounding). Figures 2 and 3 outline the basic operating and processing procedure for the MASW method.

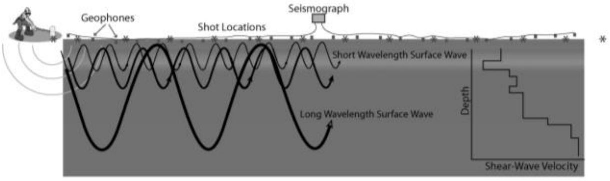


Figure 3: MASW Wave Motion Principle

2.3 Testing and Imaging of Seismic Acoustic Resonance (TISAR)

The method is similar to MASW in the sense that it utilises the frequency content of seismic waves. Certain frequencies will resonate between the surface and geologic contacts with a strong acoustic impedance difference. At the interface between two materials with different acoustic impedance, the seismic signal is partially reflected back to the surface. Under specific conditions, the repetition of such reflections leads to the build-up of a resonance signal, whose frequency is related to the depth of the interface and the seismic velocity of the upper material (Arsenault, 2001). The relative strength of those frequencies can be plotted in time. Figure 4 outlines the basic operating principle and applications for the method.

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[2] Named for Lord Rayleigh who predicted its existence.

[3] Particularly damaging because it moves laterally

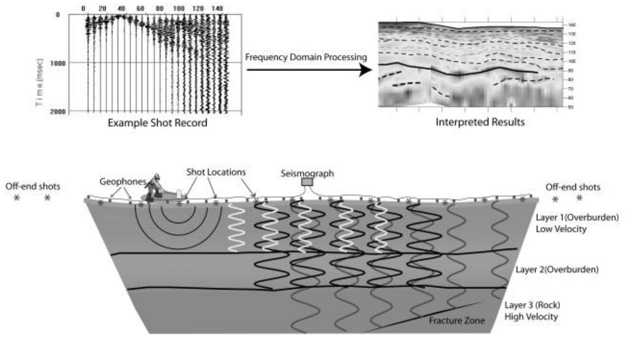

Figure 4: TISAR Operating Principle

In order to get the actual depth of a reflector, a velocity must be applied to the images. These values can be extracted from another data set, namely the refraction seismic data set.

The TISAR method was developed by necessity as a means of replacing Ground Penetrating Radar technology in shallow unfavourable environments (e.g. clay rich soils), and to complete the near-surface portion of the traditional Seismic Reflection method (top 50 m). The upper 50 m, which tends to be the area of interest for most engineering problems as opposed to exploration, which tended to interested in depths greater than 100 m. It has the advantage of generating images from surface down to depths up to 70 m with much higher resolution (layers as thin as 10 cm) while using a simple seismic source.

3 CASE HISTORY - KUGLUKTUK

The community of Kugluktuk needs a reliable non-frozen water source and the obvious source is the Coppermine River adjacent to the community. The problem is the river is frozen to the bottom for most of the year. There could however be a groundwater source under the river. The client conceptualized drilling a well into the rock from the shore that would emerge under the river into some coarse material that remains unfrozen. Ideally there would be a dip in the bedrock that could be filled with coarse material.

Early in May 2008, the combined seismic approach was used to map the top of bedrock and map the variation in the overburden material. Geophones were placed on the ice at a spacing of 6.25 m. Seismic data is collected in “spreads”. Each spread consists of 24 geophones in a row, thereby producing almost 144 m of profile. A profile consists of any number of spreads. For this project almost 1400 m of data was collected on three profiles.

A typical seismic refraction spread includes seven records (shot locations). Initially it was hoped to auger down through the ice and fire a “buffalo gun” into the water. A gunshot consists of 12-gauge shotgun shell full of powder. However, the ice thickness was too deep for the auger. The second option was to fire the gun into the ice surface.

A typical TISAR spread consists of 18 records. A 10-lb sledgehammer was used for this source. The location of the shots was between every second geophone and 10, 30 and 50 m off of each end of the spread.

Three profiles were produced; two perpendicular to the river and the third profile was a short profile parallel to the river. The report was submitted recommending three drill targets in order of priority.

The ideal target would include a dip in the bedrock as derived from the seismic refraction data and a strong TISAR reflector (black), which would indicate a coarse material near the bedrock surface. Unfortunately this combination could not be found so a compromise was a dip in the bedrock and a strong reflector higher in the overburden stratigraphy. The seismic refraction data indicated that the bedrock was relatively flat and P-wave speed was in the 3400 to 4400 m/s range. This suggests that the bedrock was a competent sedimentary rock rather than the igneous rocks outcropping near shore. Also, there was no indication of a fracture zone along any of the profiles.

The following year the two highest priority targets were drilled. Figure 5 is only a segment of the first profile where Nuna Burnside Engineering and Environmental Ltd collected the drill holes. The “outcrop” is the shoreline.

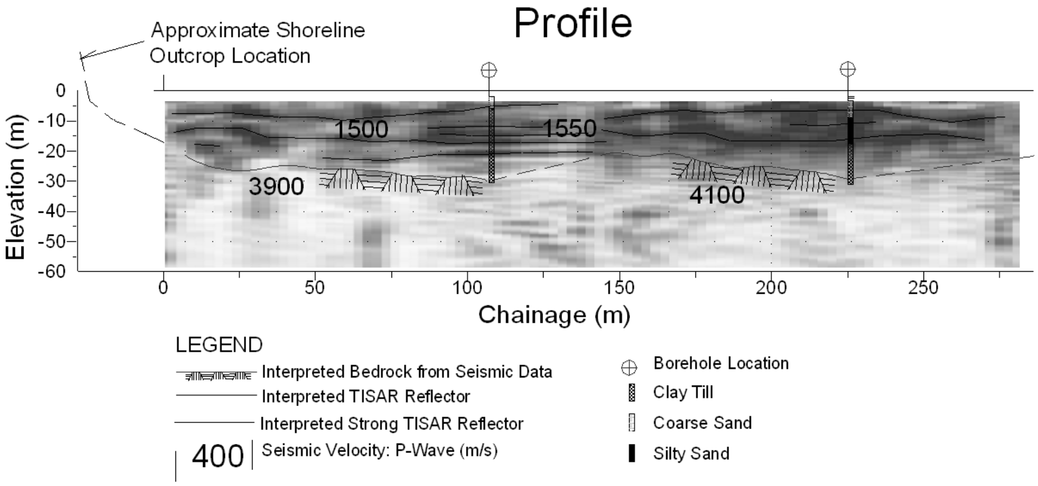

Figure 5: Segment of a Profile Showing Two Priority Drill Locations

The results from the drill holes correlated very well with the geophysical data.

- Coarse sand and silty sand was encountered within the TISAR grey areas.
- The geophysical bedrock depth was within a meter of the boreholes results.
- The bedrock was a shale rock.
- The geophysical results were correct in assessing a clay till at the bedrock surface and not coarse material.

4 CASE HISTORY - TORONTO

A tunnel has been proposed within the shale bedrock that underlies Toronto. The final design depth has not been finalized because ideally the tunnel is entirely within competent shale. More information was needed along the alignment in order to map the following:

- Small bedrock valleys, the survey actually crossed two topographic valleys.
- Deep bedrock fracturing or deeper weathering in the shale.

Unfortunately, the project is still ongoing so the specific intent and location of the tunnel cannot be revealed. Given the density of the urban environment there was only a limited number of locations where boreholes could be collected and not always on the alignment.

The survey combined MASW results with 1350 m of TISAR images. Typically the TISAR results rely strongly on seismic refraction data in order to adjust the time scale in the TISAR images and identify clearly the top of bedrock. Unfortunately the seismic refraction data could not be easily collected in the urban environment. The bedrock depth of 30 or more metres requires a substantial energy source such as explosives. In addition, the “far shots” (see Figure 1) must be very far from the spread on real estate often inaccessible to the survey. As a result the TISAR images relied on correlation with MASW data and borehole data on this project.

Figure 6 presents only one segment of the alignment with TISAR images, two boreholes and two MASW soundings. The basic borehole logs provided by Geoterre Ltd. are included. The following observations were made in the report.

- The sand and silt just above the bedrock correlates very well with the orange-red reflectors in the TISAR images.
- There is a tremendous amount of layering indicated in the TISAR images, which is corroborated by the variety of overburden layering in the logs.
- The logs end at the bedrock surface. The top of rock from the boreholes matches very well with the TISAR transition zone from multiple layering to the quiet “blue” areas.
- The MASW data agrees with the bedrock identification, as there is an upward spike in the shear-wave velocity over 600 m/s at the bedrock surface.
- There were a number of anomalous areas identified in this survey where some reflectors could be identified penetrating into the bedrock. These areas are likely not related to large fractures but rather preferential weathering to depths of 3 to 6 metres into the bedrock surface.

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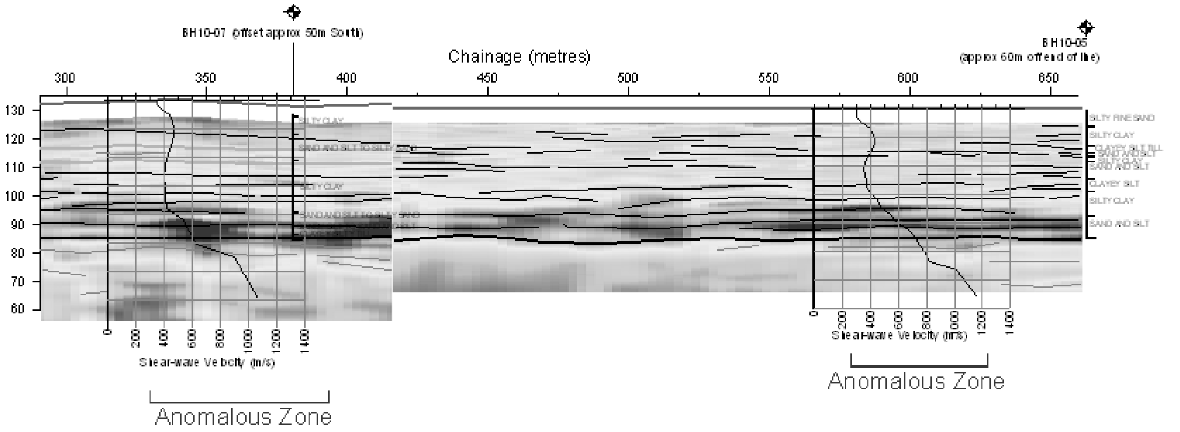

Figure 2: Segment of Tunnel Section with MASW and TISAR Images

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