Near surface S-wave seismic reflection profiling—new approaches and insights

André J.-M. Pugin,1* Kevin Brewer,1 Timothy Cartwright,1 Susan E. Pullan,1 Perret Didier,2 Heather Crow1 and James A. Hunter1

Abstract
Multi-component high resolution seismic reflection profiling has been extensively tested over a wide variety of ground surfaces across the southern provinces of Canada, showing new potential for applications of the method in groundwater and natural hazards research. The near-surface shear-wave reflection method using vibratory sources and short spacing land streamers equipped with three-component receivers is an excellent tool for accurately characterizing shear-wave velocities and recording optimal, non-aliased shear-wave data in the most polarized direction. A small portable multi-component vibrator developed at the Geological Survey of Canada (GSC) named ‘Microvibe’ provides higher frequency S-wave and P-wave signals than can be acquired with a Minivib I. In this paper we show that the shear-wave polarization can vary with depth and it may be necessary to combine multiple components together to achieve an optimized stacked section. Significant velocity anisotropies of up to 15% have been observed between the horizontal and vertical directions when using this multi-component Microvibe source. We make key recommendations based on time and space sampling recording windows for successful near surface PP-wave, PS-wave and SS-wave seismic reflection surveys. Using field examples and velocity measurements, we show the complexity of velocities in non-homogeneous media in the near surface.

Introduction
Three-dimensional subsurface data are critical to the development of predictive models for issues such as groundwater reservoir assessment and management, environmental assessments, and geohazards such as landslides and earthquake hazard assessments. Shallow seismic reflection profiling is one tool that can provide this subsurface information, to a variety of depths and at a variety of vertical and lateral resolutions. Pioneer research and applications in near-surface seismic reflection used P-waves (e.g., Doornenbal and Helbig, 1983; Hunter et al., 1984; Miller et al., 1989). The more recent development of shallow shear-wave (S-wave) reflection techniques is greatly expanding the potential of shallow seismic reflection, especially in the near-surface regime (0 to ~100 m depth). Sh-wave reflection investigations have mostly used hammer sources (e.g., Woolery et al., 1993; Harris, 1996; Inazaki, 2004; Pugin et al., 2004), portable vibrators (e.g., Ghose et al., 1996; Pugin et al., 2004), or larger vibrators (e.g., Clark et al., 1994; Pugin et al., 2009a). While the theoretical potential for Sh and Sv polarization determination was identified by Douma and Helbig (1987), evidence of shear-wave splitting and anisotropy has rarely been documented in the near surface (e.g., Harris, 1996). The purpose of this paper is to present some new approaches and new insights into shallow S-wave reflection methods using data acquired with three-component receivers and vibrating sources operating in various directions. These data highlight polarizations and velocity anisotropy in the near surface, and provide the basis for further applications and increased understanding of the potential for near-surface compressional-wave (PP), shear-wave (SS), and converted wave (PS) reflection methods.

Over the past five years, our group at the Geological Survey of Canada (GSC) has acquired more than 800 km of high resolution seismic reflection profiles across Canada (Figure 1). We have acquired data in a broad variety of geological environments, ranging from very soft marine clays in the St. Lawrence Lowlands in eastern Canada to very hard and compacted tills sealing buried valley groundwater reservoirs in the Canadian Prairies and over-deepened valleys in the western Canadian Cordillera (e.g., Pugin et al., 2009b; Hunter et al., 2010; Oldenborger et al., 2012). These areas may be considered representative of various environments present around the globe.

Much of these data have been acquired using an IVI Minivib coupled with a landstreamer made of 48 sleds mounted with three-component (3-C), 30 Hz geophone sensors spaced at 0.75 m, 1.5 m, or 3 m (e.g., Pugin et al., 2009a; Figure 2a). Depending on the target depths and the distance to be covered, shot spacing has varied from 1.5 m to 6 m. The IVI Minivib is an excellent and versatile shallow seismic

1 Geological Survey of Canada, 601 Booth Street, Ottawa, ON, K1A, 0E8, Canada.
2 Geological Survey of Canada, 490 Rue de la Couronne, Quebec, QC, G1K 9A9, Canada.
* Corresponding author, E-mail: Andre.Pugin@NRCan-RNCan.gc.ca

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Various models of portable vibrator have previously been developed (e.g., Ghose et al., 1998; Haines, 2006; Polom...
Seismic data acquisition and processing

In the surveys presented here, we adopted similar acquisition and processing parameters. The Minivib I source used a linear sweep of length 7 s from 20 Hz to 300 Hz with the 140 kg mass vibrating in either the in-line horizontal or the vertical direction. The Microvibe used a sweep length of 9 s and was vibrated from 20 Hz to 350 Hz in the transverse horizontal direction, and from 20 Hz to 500 Hz in the vertical direction. The data were recorded uncorrelated, though with a correlation display visible to the operator. The shot spacing was either 3 m or 4.5 m and was chosen to optimize the data quality and the line coverage in the survey time available. The 48 3C receivers mounted on a landstreamer were spaced at either 0.75 m or 1.5 m, and the nearest offset for the first geophone was 3 m for the Minivib and 1.5 m for the Microvibe.

The seismic processing sequences are presented in Table 1. We apply an AGC of 1 s on uncorrelated data because it both whitens the signal spectrum and decreases random noise such as wind or rain noise or small movements related with tension release in the streamer. A band-pass filter centres the signal to its optimum frequency band. Deconvolution is sometimes needed for removing reverberations that occur within the unsaturated near surface zone. The bandwidth of SS and PS data over the clay basins is 40–300 Hz, while over harder typical glacial sediments the bandwidth drops to 30–120 Hz. PP data in these sections have frequency content starting at 90 Hz and reaching ~250 Hz for the Minivib I, or as high as ~500 Hz for the Microvibe. Migration is needed when steep slopes are present in the subsurface, or when diffractions are observed. It has been found that static corrections are only required for PP-wave seismic reflection profiles as lateral thickness variations of the unsaturated zone affect P-waves more significantly than S-waves. In general, near surface S-wave velocity distributions are much more homogeneous and do not require sophisticated static corrections, not even residual

<table>
<thead>
<tr>
<th>PP-wave processing</th>
<th>SS-, PS-wave processing</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEG2 to KGS-SEGY conversion</td>
<td>Band pass filter</td>
</tr>
<tr>
<td>AGC: 1s</td>
<td>Trace normalization</td>
</tr>
<tr>
<td>Correlation</td>
<td>Velocity semblance analysis</td>
</tr>
<tr>
<td>3-C separation</td>
<td>NMO correction</td>
</tr>
<tr>
<td>Geometry edition</td>
<td>Stack</td>
</tr>
<tr>
<td>CMP sorting with binning at half of the shot spacing</td>
<td>Band pass filter</td>
</tr>
<tr>
<td>*First break picking for statics corrections</td>
<td></td>
</tr>
<tr>
<td>Band pass filter</td>
<td>*Migration</td>
</tr>
<tr>
<td>Trace normalization</td>
<td>Topography statics on a datum plane</td>
</tr>
<tr>
<td>Noise surgical mutes</td>
<td>Time–depth conversion</td>
</tr>
<tr>
<td>Velocity analysis</td>
<td></td>
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<tr>
<td>*Refraction statics application</td>
<td></td>
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<tr>
<td>NMO correction</td>
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</tr>
<tr>
<td>Stack</td>
<td></td>
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<td>*Deconvolution</td>
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<td>Band pass filter</td>
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<td>Time–depth conversion</td>
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Table 1 Seismic processing sequences used for the stacked sections presented here.

Figure 3 Body waves acquired with a Minivib in horizontal inline (H1) vibrating mode and a 3C landstreamer. Data are shown for the vertical component receivers (V). From left to right: raw PP-wave field record (0–0.15 s); raw field record showing the PP-wave, PS-wave, and SS-wave reflections (0–1.2 s); PP-wave stacked section; PS-wave stacked section; SS-wave stacked section.
Statics. However, special care and attention must be given to velocity analyses when processing shallow S-wave data, as low velocities produce steep reflection hyperbola curves.

We are aware that a normal moveout application on CMP gathers is not the optimum method to stack PS converted waves (Frasier and Winterstein, 1990); however, the CMP stacked sections presented here show good stacked quality, possibly because the offset range is rather short after muting, and the effective CMP stack fold is low. We plan to test common reflection point binning as a better method for stacking PS sections.

**Compressional (PP), converted (PS), and shear (SS) waves in marine sediments in eastern Canada**

The marine deposits of the St. Lawrence Lowlands and Ottawa River valley in eastern Canada provide an ideal environment for seismic reflection work (e.g., Hunter et al., 1984; Pugin et al., 2009a). Due to the uniformity of the fine-grained marine sediments, PP-waves, PS-waves, and SS-waves, polarized in various directions, are easily recorded with 3C geophones with minimal interference from surface waves or ground roll. Figure 3 shows data acquired with the Minivib source vibrating in the inline horizontal mode. In this case, with the source operating in shear mode, the vertical component receivers have recorded excellent PP-wave, SS-wave, and converted PS-wave phases from the bedrock surface and layers within the overlying marine sediments. We have observed that the polarization of the PP-wave reflections is always vertical with very little energy in the horizontal plane; however, S-waves can be polarized in various directions depending on the site conditions. In this geological environment, the SS-wave and PS-wave reflections are best observed with the vertical receivers. However, we will show other examples in this paper S-wave reflections show various directions of polarization.

The processing of SS-wave sections requires great accuracy in the determination of stacking velocities. In this example, where very high-frequency shallow S-wave reflections are observed, the velocity must be determined within a range of less than 5 m s\(^{-1}\) to optimize the quality of the sections. At this site, S-wave velocities are 100–300 m s\(^{-1}\), while P-wave velocities are 1200–1500 m s\(^{-1}\). As the different types of reflected arrival interfere in some time–offset windows, judicious use of surgical mutes is required to ensure that stacked sections are produced using only PP, PS, or SS reflections, as required.

The stacked sections shown in the three central panels of Figure 3 demonstrate the range of subsurface resolution and depths of penetration that are characteristic of the three different wave types. The PP-wave section shows the lowest subsurface vertical resolution (longest wavelength) but the deepest penetration. The PS-wave section is much higher resolution than the PP-wave section and also displays better penetration into harder sediments than observed with SS-waves. The SS-wave section is characterized by very high subsurface resolution (shortest wavelength).
Sections for the three different wave types, acquired with a Minivib along a 5 km transect over a buried channel containing an esker, a coarse gravel, and sand feature are compared in Figure 4. The sand feature formed in a subglacial melt-water tunnel and is now a valuable aquifer. In this example, the main subsurface features can be seen on the PP-wave section, but reflection wavelengths are at least 10 m, resulting in relatively poor subsurface resolution. In contrast, the top and the bottom of the esker can be very accurately defined in the PS-wave section, though little of the depositional structure of the overlying fine-grained marine sediments can be observed. Detailed structures, such as synsedimentary slumps within the mud and fine sand, can only be seen in the SS-wave section where reflection wavelengths are less than 1 m. This comparison clearly demonstrates the benefit and additional information that can be obtained from multi-component recording and multi-phase processing.

**S-waves in heterogeneous and harder ground**

While the soft, marine sediments of the St. Lawrence Lowlands are an ideal environment for observing all types of body wave reflections, S-wave reflections are also present in harder sediments, such as over-compact sand, gravel, or harder glacial sediments which are common in the Canadian Prairies (e.g., Pugin et al., 2011) or in the western Canadian Rockies. However, in these environments S-waves are often obscured by interfering surface waves, i.e., Rayleigh and Love waves. The main challenge in processing S-wave data here is to remove this interfering energy. Careful use of low-cut filters commonly removes a good part of the surface wave energy (Figure 5). However, some surface wave energy may still be present with an overlapping frequency band. Filtering in the frequency–wavenumber domain can then remove most of any remaining dispersive energy.

A comparison test between the Minivib and the Microvibe sources has been performed over a complex glacial environment of till, sand, and gravel on Vancouver Island (Figure 6). The S-wave velocity in these sediments ranges from 350 m s⁻¹ to more than 500 m s⁻¹. To introduce high frequencies into the ground, the Minivib data were acquired with a vertical linear sweep from 20 Hz to 240 Hz. The Microvibe was oriented in the transverse horizontal direction with a linear sweep from 20 Hz to 300 Hz. Based on borehole data and velocity analyses, the main reflection at 0.2 s and 0.25 s is associated with the bedrock–sediment interface at a depth of 50–70 m. Even though the Minivib mass was vibrated vertically, the bedrock reflection can be observed in all receiver orientations with very similar energy. This is less the case with the smaller Microvibe source which generates a very polarized S-wave. In this case, the best subsurface image is obtained when the source and receiver orientations are both horizontal transverse, resulting in clear reflections within the upper sedimentary column. These shallow reflections can be seen because the Microvibe generates and transmits higher frequency energy into the ground.

In Saskatchewan, we have conducted a successful 3C survey over highly consolidated sediments filling a buried bedrock valley. The buried valley is sealed by hard, compacted tills with P-wave velocities exceeding 2500 m s⁻¹ and S-wave velocities of 500–800 m s⁻¹. Figure 7 shows a raw field record from the centre of this valley, which is ~170 m deep, where the Minivib source was used with a non-linear sweep from 20 Hz to 240 Hz. The sweep parameter was adjusted to increase the time of the sweep in the low frequency range, based on observations that the optimum frequency range for S-wave signals at this site was 20–110 Hz. The sweep was continued into the higher frequencies to produce the energy range for P-waves (see also Pugin et al., 2011). In this...
example, a dry layer of sand in the upper few metres strongly limited the frequency band of the P-wave energy that was able to penetrate deeper into the sedimentary column. As a result, the stacked PP-wave section (Figure 8) is very poor. In contrast, the SS-wave section shows much clearer reflection returns both from the shallow subsurface and from within the buried valley. The layered reflections from depth suggest that coherent stratified sediments, such as lacustrine sediments, fill this buried valley.

While the case study presented here did not result in much usable PP-wave reflection data, elsewhere in the Canadian Prairies PP-wave sections can provide better results than the SS-wave data. In our experience, this is often an indication of very coarse-grained lithologies where large boulders act to disperse and scatter the shorter wavelength S-wave energy and induce incoherent S-wave returns (Pugin et al., 2011).

**S-wave polarization**

The polarization and splitting of S-waves in shales has been documented by Crampin (1985, 2003), who used differences in stacking velocity and velocity discrepancies between P-waves and S-waves. Further precise measurements have been made in boreholes (Winterstein et al., 2001) with the estimates of horizontal birefringence ranging from 0% to 21%. Anisotropy has been documented in the near surface by Bates et al. (1996); however, to our knowledge, Harris (1996) is the only author to have documented S-wave splitting in near-surface unconsolidated sediment. All these cited papers documented S-wave anisotropy in the horizontal plane. However, now that we are routinely recording 3C data, we have acquired considerable evidence that S-wave

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*Figure 7* Effect of filtering for enhancing PP-wave and SS-wave reflections in raw, trace-normalized, 2C field records. The records were obtained with the Minivib source vibrating in horizontal inline (H1) direction. Top panels: raw records obtained with (left) vertical (H1,V) and (right) horizontal inline (H1,H1) receivers. Central panels: low frequencies are filtered out to enhance PP-waves, which are only clearly seen on the vertical receivers. Bottom: high frequencies are filtered out to enhance the PS-waves, are more clearly seen on the horizontal receivers.

*Figure 8* Comparison of PP-wave and SS-wave seismic sections over a buried valley sealed by hard compacted tills overlain, at the surface, by several metres of dry sand. The PP-wave data here are poor, but the SS-wave section provides a clear image of the buried bedrock valley infilled with stratified sediments.
vertically polarized reflections in the upper 0.37 s. Some horizontal energy from these shallow reflectors is recorded by the inline receivers SS(V,H1), but very little exists in the transverse plane SS(V,H2). In contrast, the deeper reflections (0.37–1.2 s) are best observed using the horizontal transverse vibrating mode and receivers SS(H2,H2). A birefringence effect explains why some reflections can be seen in the vertical receivers, SS(H2,V), at the time of 0.37 s.

Our observations show that most of the S-wave reflection energy is in the horizontal plane when the near surface S-wave velocity is ~300 m s\(^{-1}\) or higher. However, in low-velocity sediments a significant amount of S-wave energy returns to the surface receivers in the vertical plane. Figure 9 shows a reflection section of 500 m length acquired with the Microvibe at a site where S-wave velocity data are available in a 96 m deep borehole (Medioli et al., 2012) drilled into clayey silts. P-wave and S-wave VSP profiles were acquired in the borehole with a receiver spacing of 1.5 m and a shot spacing of 3 m. At each shot station, a linear sweep of length 9 s was applied using the Microvibe, over 20–500 Hz in the vertical mode and 20–250 Hz in the horizontal transverse mode. This 6C dataset has been stacked into six S-wave sections corresponding to each combination of source and receiver components. The six sections show a clear progression from the SS(V,V) (i.e., SS-wave section with vertical source and receivers) to the SS(H2,H2) (i.e., SS-wave section with horizontal transverse source and receivers). The SS(V,V) section is characterized by very high quality, high resolution, vertically polarized reflections in the upper 0.37 s. Some horizontal energy from these shallow reflectors is recorded by the inline receivers SS(V,H1), but very little exists in the transverse plane SS(V,H2). In contrast, the deeper reflections (0.37–1.2 s) are best observed using the horizontal transverse vibrating mode and receivers SS(H2,H2). A birefringence effect explains why some reflections can be seen in the vertical receivers, SS(H2,V), at the time of 0.37 s.

Also shown for comparison in Figure 9 are the PP-wave section and a Minivib SS-wave section acquired with the mass vibrating in the horizontal inline mode. In this SS-wave section, data from both the vertical and horizontal inline receivers have been stacked together to integrate shallow and deeper reflections in the same section.

To illustrate the importance of 3C data acquisition for integrating changes in polarization as a function of time, the complete ‘John Shaw Road’ section, of 3.5 km length, is shown in Figure 10. Figure 9 is a detailed 500 m section in the vicinity of the borehole and its location is marked on Figure 10. The John Shaw Road section crosses a buried valley filled with coarse sediment (highlighted in blue) deposited in a sub-glacial melt water tunnel. These coarse sediments features are targeted as shallow groundwater reservoirs in glacial sedimentary basins (e.g., Pugin et al 2009a). The data were acquired with the Minivib, vibrating in the horizontal inline direction with a linear sweep of
20–300 Hz. Vertical and horizontal inline receivers spaced at 0.75 m were towed on a landstreamer array. The upper panel in Figure 10 shows a PP-wave section processed with the vertical component of this 2C recording. The wavelength at 140 Hz, the centre frequency of the wavelet, is approximately 10 m. The centre panel shows the SS-wave section obtained by stacking the two receiver components in order to integrate the vertically polarized shallow reflections with the horizontal deeper S-wave reflections. The wavelength of these S-wave reflections varies from ~1.2 m in the near surface to ~3 m at a depth of 100 m. The lower panel displays the polarization angle between the horizontal inline and vertical directions obtained using principal component analysis for a sliding time window of 0.07 s. Light shades show a more vertical polarization and dark shades correspond to more horizontal polarization of the S-wave. The pattern of polarization clearly identifies the major stratigraphic units on this section. Where there are very soft clays near the surface, the S-wave polarization is essentially vertical. In some shallow areas on this section, more horizontally polarized energy is observed, perhaps implying the presence of harder sediments such as sand layers. The polarization then returns to a vertical orientation beneath these layers. Reflections
from harder horizons (tills, gravels, bedrock surface) are horizontal across the entire section, irrespective of the depth to the layers. The only exception occurs where steep slopes and diffractions are present, e.g., on the steep slope at 600 m distance on the section.

Tools for polarization analysis and phase and amplitude rotation, as described by Pugin et al. (2009a), are helpful to optimize the stacked section. However, to use such tools, it is preferable to acquire very near offset data. Here the trace spacing is 0.75 m and the maximum offset is of 39 m for a depth of ~100 m; this avoids large phase and amplitude changes that occur at large offsets. A similar test has been performed with geophones spaced at 1.5 m in a landstreamer, and the polarization analysis did not give coherent results.

The presence of the 96 m deep borehole on the John Shaw Road section has allowed us to conduct some detailed velocity analyses. A downhole velocity measurement has been compared with semblance analysis of surface reflection data acquired with the Microvibe (Figure 11). The downhole measurements were acquired with a 3C downhole tool and the Minivib as a source. The detailed velocity–depth profile obtained from these data reveal the presence of a 3 m thick high velocity layer at the surface underlain by a very low velocity mud layer where the S-wave velocity decreases to approximately 100 m s$^{-1}$. The velocity gradually increases with depth up to values of 400 m s$^{-1}$ at a depth of 96 m. In Figure 11, the purple crosses show the average velocities determined from semblance analysis of common midpoint (CMP) gathers of surface reflection data. These average velocities have been converted to interval velocities using the Dix equation. The results compare very well with the downhole measurements. Dix (1955) clearly outlined the restrictions governing the validity of his equation. One of them is that the velocity of each layer should be constant, which is clearly unrealistic in this case, and in general for unconsolidated sediments because S-wave velocity increases with total vertical stresses even when the lithology is unchanged (Budhu, 2007). We have found that using the Dix curve with averaging of the depths and velocities (see red curve in Figure 11) provides a more realistic velocity depth profile and a better match with the downhole measurements, even for the complex velocities observed at shallow depths.

Figure 12 Results of semblance analyses from 15 CMP gathers that show velocity anisotropy between $S_v$ waves and $S_h$ waves. The splitting occurs here within the uppermost 5 m of the sediment column where $S_v$-waves are observed to have slightly lower velocities than $S_h$-waves.

Figure 13 Example of semblance analysis that shows S-wave velocity anisotropy between $V$ and $H_2$. On the right side of the figure, a seismic cone penetrometer velocity measurement is compared with the results of the semblance analysis at CMP 450 (courtesy of the Ministry of Transportation of Quebec).
Figure 14 Migrated seismic sections acquired in an area with potential for landslides. PP(V,V): PP-wave section from data acquired with source in vertical mode and vertical receivers. SS(V,V): SS-wave section from data acquired with source in vertical mode and vertical receivers. SS(H2,H2): SS-wave section from data acquired with source in transverse horizontal mode and transverse horizontal receivers. The two lower panels show the stacking velocities obtained through semblance analyses for the vertical and horizontal (H2) shear modes.

Sh and Sv velocities

The polarized Microvibe source (with a shot spacing of 3 m and a receiver spacing of 1.5 m), has made it possible to measure velocity anisotropy of up to 15% using semblance analysis on CMP super-gathers (3 m bin size). Figure 12 shows a compilation of 15 picked velocity functions from semblance analysis extracted from a 400 m long profile over a clay layer. The average velocity graph clearly demonstrates that the stacking velocity is significantly lower for the Sv-wave than for the Sh-wave. After the application of an average-to-interval velocity transformation, as discussed above, one can observe that this anisotropy is limited to the uppermost 5 m of the sedimentary column.

From another test site, an example of a semblance analysis is displayed in Figure 13. This example is extracted from a survey related to a landslide study where accurate S-wave velocities were needed for soil stability prediction mapping. CMP 340 shows a near surface velocity anisotropy similar to that discussed in Figure 12. It is to be noted in this semblance analysis that the picking error at shallow depths is very small (3–5 m s⁻¹), so that an observed anisotropy of 10–20 m s⁻¹ is significant and beyond measurement errors. A comparison with a seismic cone penetrometer profile at the location of CMP 450 (Figure 13) again shows that the semblance method yields comparable velocity–depth profiles.
Some of the seismic reflection sections obtained in this landslide study are shown in Figure 14. The interpretation is greatly enhanced with the S-wave velocity information (lower panels). These data show a low velocity layer at the surface (100–130 m s\(^{-1}\)) evolving laterally to higher velocities (\(-160\) m s\(^{-1}\)) towards the right end of the section. A landslide did occur near the right end of this section and the higher S-wave velocity of this sediment may be the reason why the landslide did not affect that portion of the section. The structural and velocity information obtained by this survey suggest that the central part of the section (CMPs 150–350), where the S-wave velocity is anomalously low and the low velocity material sits directly on the bedrock surface, may be more prone to sliding. This is also an area where the Sv velocity is 10–20 m s\(^{-1}\) lower than the Sh velocity, which is a difference of up to \(-15\%\). This velocity difference seems low in comparison to the velocities observed by Jolly (1956), who found that Sh velocity exceed Sv velocity by up to 100%. Jolly (1956) could partly explain this observation in using a transversely isotropic model. Further complexity was being modelled by Levin (1979), who showed that Sv reflections are non-hyperbolic by definition, in particular as the offset is large, which is true for the shallow reflections at a few metres depth because they have a wide reflection angle even at what we would consider very short offsets. The problem becomes even more complex when the subsurface is anisotropic in all directions (e.g., Winterstein, 1986, 1990), which is very likely the case in complex glacial sediments. Further experiments with new 9C datasets are needed to better understand and better model such S-wave velocity anomalies in near surface media.

**Discussion: key parameters for a successful near-surface S-wave survey**

Our experience over the past five years in S-wave reflection profiling with vibrator sources has convinced us of the great potential of these techniques. S-waves offer a good alternative to P-waves for reflection imaging of the subsurface and can provide extraordinary resolution in some circumstances. Furthermore, S-wave techniques can work in some places where the more traditional P-wave methods fail. We are also learning that the transmission of seismic energy through the ground is a highly complex process related to anisotropy, but some of these complexities such as polarization changes and velocity anisotropy provide us with new insights and new ways to measure the physical properties of the near surface.

We offer the following suggestions to assist with the successful recording of S-waves in the near-surface environment. Based on our experience, S-wave reflections are almost always present in the data, and difficulties in observing them are usually related to simple errors in the spatial and time sampling of the survey.

To optimize the recording of S-waves, a receiver spacing of 1.5 m or less is recommended to sample steep, low-velocity, hyperbolic reflections. The use of 3C recording is crucial, as S-waves can be polarized in all directions and this polarization can change as a function of reflector depth and lithology, particularly in respect of the surface layers. A landstreamer greatly enhances the acquisition rate because of the need for small receiver spacings and multi-component recording. A very short offset from the source to the first receiver is recommended to pick the shallowest reflections. Survey on roads give significantly better results than surveys on rooted soils, where near-surface absorption is tremendous.

A long recording or listening time is required as the P-wave/S-wave velocity ratio can be as high as 10 in soft soils. We currently use listening times from 1 s up to 2 s, depending on the target depths. A vibrating source provides a means of shaping the signal, and the use of a non-linear sweep can help optimize the frequency ranges required for various body wave reflection signals. During processing, careful and judicious use of band-pass and spatial filters may be required to remove noise and surface wave interference.

If all these rules have been respected and no coherent S-wave reflections are observed, our experience suggests that the subsurface materials are either very complex or chaotic due to buried utilities or various sizes of ‘rubble-like’ concrete slabs or logs buried in the near surface, or the lithology itself is characterized by a chaotic distribution of various density contrasts, as can be the case with a bouldery till or gravel. In such difficult cases, the longer wavelength P-wave data can sometimes still be extracted and processed from the records. Out of the 800 line km of profile we have acquired over the past five years, only one or two kilometres of data did not provide any body-wave reflection signals, and that can be attributed to unfavourable near-surface conditions related to human activities.

Our experience with S-wave reflection surveying offers new perspectives for studies in hydrogeology, geotechnical investigations and earthquake hazard assessment. The use of the smaller Microvibe vibrator is greatly enhancing our understanding the properties of body waves in the near surface.

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