There is no pure P- or S-wave land seismic source

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Summary:

We conducted a field experiment at a soil site near Ottawa and recorded 9-C seismic data using a hand-held hammer and a receiver cable with 48 3-C 28-Hz geophones at 0.75-m intervals. The receiver spread length is 35.75 m and the near-offset is 0.75 m. We recorded three triplets of shot records with the impact source in vertical, inline horizontal, and crossline horizontal orientations. We identified several wave modes in the nine field records --- PP, PS, SP, and SS reflections, in addition to refracted waves. We then performed vertical sum of the three records associated with each of the three different source orientations (vertical, inline horizontal, and crossline horizontal) but with common geophone orientation, and computed the semblance spectra of the composite records. We ascertained the wave modes based on the semblance peaks.

This field test led to several important observations regarding characteristics of wave propagation in the near-surface. First and foremost, based on our experience in using impulsive and vibroseis sources, there is no pure P- or S-wave land seismic source --- any source type can generate any combination of wave modes. Second, a wave mode may not be present in a record acquired with a given source-receiver orientation which theoretically should give rise to that mode, but can appear unexpectedly in a record acquired with a given source-receiver orientation which theoretically should not give rise to that mode. Third, the combination of wave modes captured by a specific source-receiver orientation depends on the *V*p/*V*s ratio. Finally, these observations led to a realization that for a complete representation of the wavefield propagating within the near-surface, we need to record multicomponent data.

Introduction:

Consider a vertical-impact source applied to the free surface associated with an elastic half-space. The equations for P- and S-radiation patterns have been derived by Miller and Pursey (1953). Using these equations, F. Hilterman wrote a program to calculate the radiation patterns (personal communication). Figure 1 shows the radiated wave modes for two different *V*p/*V*s ratios --- typical of a soil column (Figure 1a) and a rock column (Figure 1b). Note that the vertical-impact source, which is mistakenly defined as an ideal P-wave source, contrary to common understanding, gives rise to a very small amount of P-wave radiation (the tiny green circle in Figure 1a); however, much of the source energy is consumed by the S-wave radiation in the supercritical region (the red lobes) contributing to surface waves. In the case of a lower *V*p/*V*s ratio (Figure 1b), note that the vertical-impact source gives rise to a significant P-wave radiation (the green circle), but also can yield S-wave radiation in two parts --- the supercritical component (the red lobes) associated with surface wave and the subcritical component (the blue lobes) associated with downgoing S-wave. Such radiation patterns have also been modeled by Hardage and Wagner (2014). These radiation patterns, contrary to common understanding, demonstrate that a vertical-impact seismic source can generate both P and S waves, and that partitioning of the source energy depends on the *V*p/*V*s ratio. The fact that a vertical-impact source can generate significant S-wave energy has led to the idea of extracting SP reflections from conventional vertical-geophone data (Hardage, 2015).

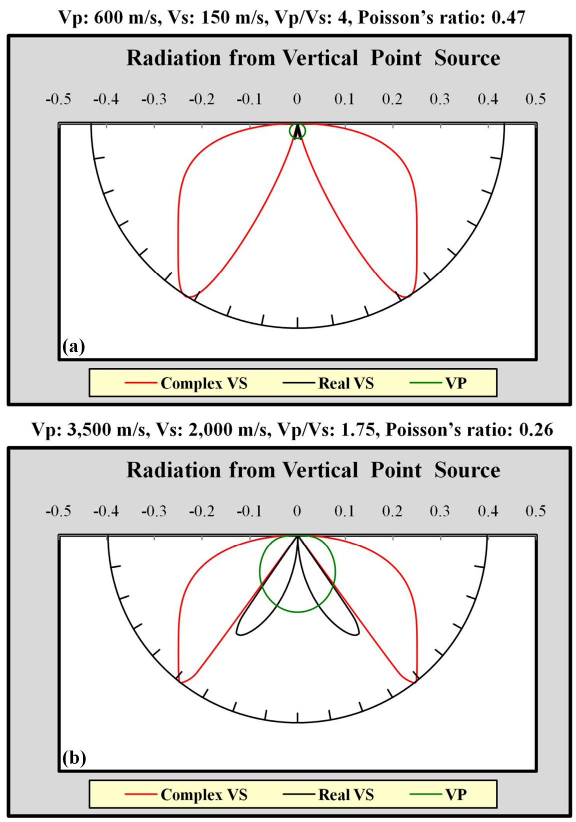

Figure 1. Radiation patterns from a vertical-impact source for two cases of *V*p/*V*s ratio: (a) 4, and (b) 1.75.

Field Experiment:

Inspired by the fact that a vertical-impact seismic source can generate both P- and S-waves, we conducted a field experiment at a soil site near Ottawa and recorded 9-C seismic data using a hand-held hammer and a receiver cable with 48 3-C 28-Hz geophones at 0.75-m intervals. The receiver spread length is 35.75 m and the near-offset is 0.75 m. We recorded three triplets of shot records with the impact source in vertical (V), inline horizontal (H1), and crossline horizontal (H2) orientations (Figure 2). Each triplet consists of shot records acquired by common source orientation and three geophone orientations (V: vertical, H1: inline horizontal, and H2: crossline horizontal). In Figure 2, each column represents a triplet acquired by common source, and each row represents a triplet acquired by common geophone orientation.

Data Analysis:

We performed vertical sum of the three records associated with each of the three different source orientations but with common geophone orientation, and computed the NMO semblance spectra of the composite records with common geophone orientation (Figure 3). Based on velocities, several modes (PP, PS, SP, and SS) can be labeled in the composite records.

The soil column at the test site is largely composed of interbeddings of marine clay deposited over a limestone-shale bedrock. Based on borehole information, the P-wave velocities vary from 930 m/s at the surface to 1,400 m/s at a depth of 22 m with bedrock velocity of 3,500 m/s. Whereas, the S-wave velocities are 270 m/s at the surface, decrease to nearly 100 m/s at a depth of 10 m, then increase to 200 m/s at a depth of 22 m with bedrock shear-wave velocity nearly 2,100 m/s. The Vp/Vs ratio varies from 9 to 1.7 within the soil column.
The highest amplitude reflection of the top bedrock interface present at a depth of 22 m is observed at 260 ms for the SS-wave; its amplitude is highest in the V-geophone gather; whereas in the H1-geophone gather, its peak amplitude decreases and merges with a high and broad peak which is likely associated with a mix of PS-SP and refraction energy. These two peaks also merge in the H2-geophone gather with little possibility to separate the SS mode from other modes. Even with the source orientation in H2, the highest energy comes back on the V geophone. The semblance analysis of the V-geophone gather exhibits detailed patterns of reflections from surface down to bedrock as these patterns are less obvious on the H1- and H2-geophone gathers.

As the theory would predict, the PS-SP bedrock reflection at 150 ms occurs with its highest amplitude on the H1-geophone gather with a velocity of 550 m/s. It is a total surprise to observe that the highest amplitude of the PP bedrock reflection is not on the V-geophone but on the H1-geophone gather at approximately 40 ms, this reflection is clearly visible on H1,H1 (Figure 2). As expected, the H2-geophone gather does not display coherent amplitude peaks for P-wave.

Conclusions:

This field test led to several important observations regarding characteristics of wave propagation in the near-surface.

(1) There is no pure P- or S-wave land seismic source --- any source type can generate any combination of wave modes.
(2) A wave mode may not be present in a record acquired with a given source-receiver orientation which theoretically should give rise to that mode, but can appear unexpectedly in a record acquired with a given source-receiver orientation which theoretically should not give rise to that mode.
(3) The combination of wave modes captured by a specific source-receiver orientation depends on the Vp/Vs ratio.
(4) These observations led to a realization that for a complete representation of the wavefield propagating within the near-surface, we need to record multicomponent data.

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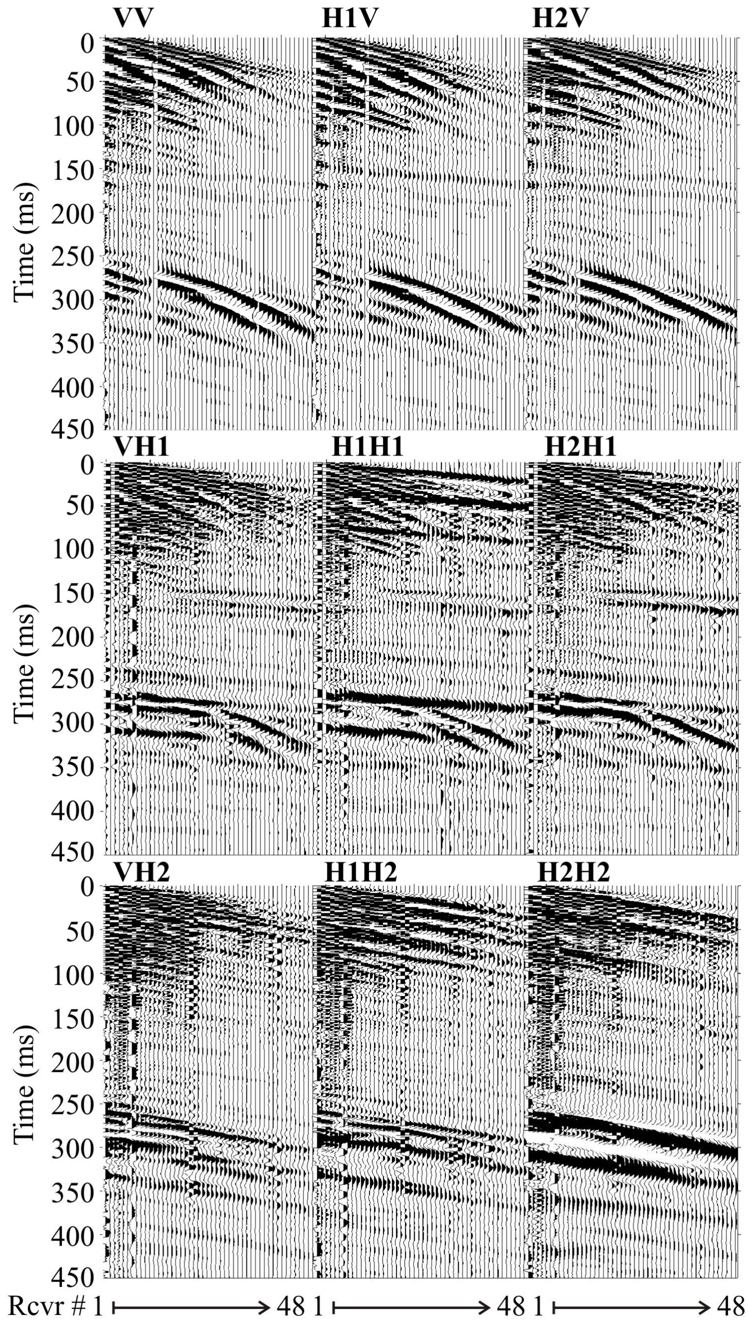

Figure 2. 9-C seismic data recorded using a hand-held hammer and a receiver cable with 48 3-C (V: vertical, H1: inline horizontal, and H2: crossline horizontal) 28-Hz geophones at 0.75-m intervals. We recorded three triplets of shot records (each represented by the columns) with the impact source in vertical (V), inline horizontal (H1), and crossline horizontal (H2) orientations. The receiver spread length is 35.75 m and the near-offset is 0.75 m. The labeling convention is as follows: the first index represents the source component and the second index represents the geophone component. As an example, record H1V was recorded using an inline horizontal source (H1) and a vertical source (V).

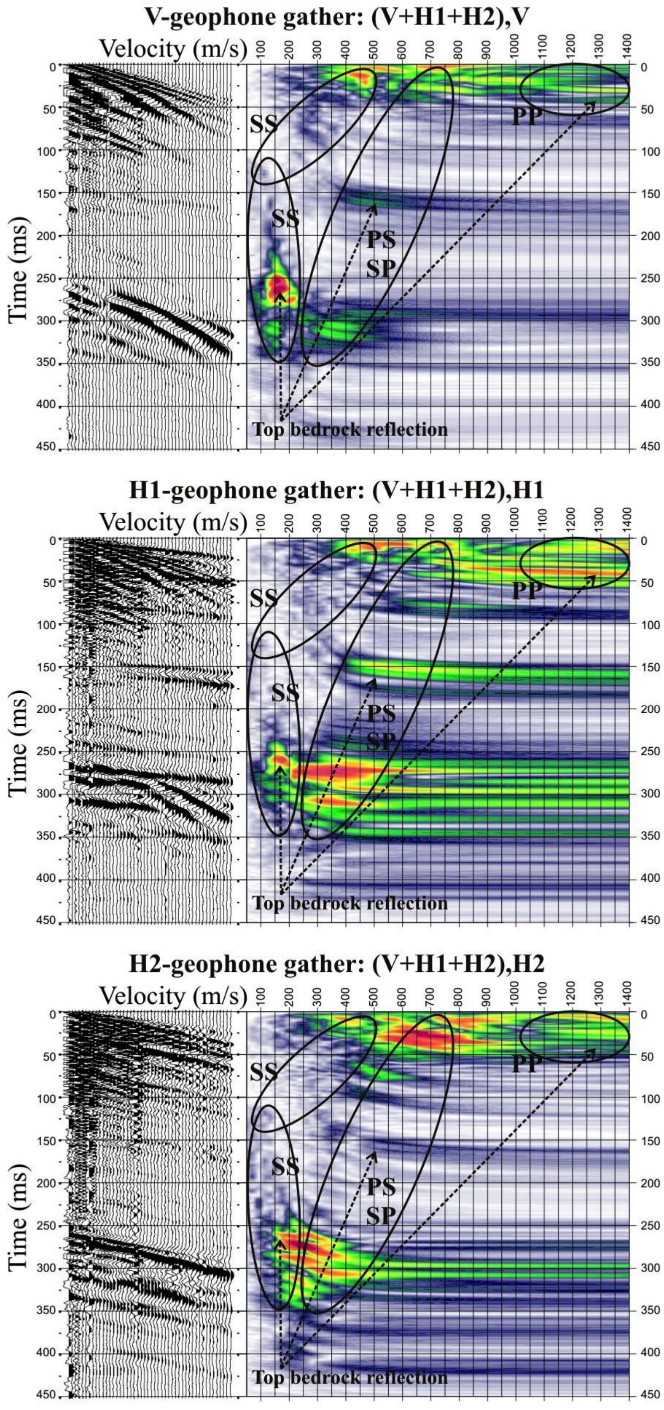

Figure 3. Left column: Composite records constructed by vertically summing the records shown in each row of Figure 2 with three different source orientations (V, H1, H2), but with one geophone orientation. Center column: the semblance spectra of the records shown in the left column. Based on velocities, several modes (PP, PS, SP, and SS) can be labeled in these records.

EDITED REFERENCES
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REFERENCES
Hardage, R., 2015, Simplifying and lowering the cost of S-wave reflection seismology through use of P-wave sources: SEG-GSH Webinar.
Hardage, R. and D. Wagner, 2014, 2-D modeling of direct-S and direct-P wavefields - part1 - modeling principles and examples: EGL Sponsor Report, available at the private Members Area of the EGL Website.
Miller, G. F., and H. Pursey, 1953, The field and radiation impedance of mechanical radiators on the free surface of a semi-infinite isotropic solid: Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, **223**, 521–541, https://doi.org/10.1098/rspa.1954.0134.
Pugin, J.-M. A., S. E. Pullan, and J. A. Hunter, 2009, Multicomponent high-resolution seismic reflection profiling: The Leading Edge, **28**, 1248–1261, https://doi.org/10.1190/1.3249782.