A pitfall in shallow shear-wave refraction surveying

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Summary

The shallow shear-wave refraction method works successfully in an area with *a series of horizontal layers*. However, complex near-surface geology may not fit into the assumption of *a series of horizontal layers*. That a plane SH wave undergoes wave-type conversion along an interface in an area of non-horizontal layers is theoretically inevitable. One real example shows that the shallow shear-wave refraction method provides velocities of a converted wave rather than an SH wave. Moreover, it is impossible to identify the converted wave by refraction data itself. To verify if velocities calculated from a shear-wave refraction survey are velocities of converted waves, an additional P-wave refraction survey is necessary. The best alternative at this time is MASW, which can provide reliable S-wave velocities, even in an area of velocity inversion (a higher velocity layer underlain by a lower velocity layer).

Introduction

It is well known that for *a series of horizontal layers*, a pure, plane SH wave refracts and reflects only SH waves, and thus does not undergo wave-type conversion as does incident P- or SV- waves (Hasbrouck, 1986). If the assumption of *a series of horizontal layers* is valid at a study site, the shallow shear-wave refraction method provides a quick, low cost, and accurate tool to investigate near-surface S-wave velocities. This is why the shallow shear-wave refraction method is commonly used in groundwater, engineering, and environmental studies. However, complex near-surface geology may not fit into the assumption of *a series of horizontal layers*. That a plane SH wave undergoes wave-type conversion along an interface in an area of non-horizontal layers is theoretically inevitable. In this case, the shallow shear-wave refraction method provides velocities of a converted wave rather than an SH wave. Moreover, it is impossible to identify the converted wave by refraction data itself.

Two questions arise: Can we recognize converted waves? and How do we find true S-wave velocities if wave-type conversion really occurs? We will use a real example to demonstrate the wave-type conversion (SH wave to P wave) and provide an alternative technique to estimate near-surface shear-wave velocities.

A Real World Example of Conversion of SH- to P-wave

A shallow SH-wave refraction survey was conducted in Wyoming during last fall to determine shear-wave velocities in near-surface materials up to 7 m deep. SH-wave refraction data were acquired by forty-eight 28 Hz horizontal component geophones oriented in a N-S direction. Geophones were deployed on a 0.9 m (3 ft) interval along a W-E line. The source of seismic energy was a 6.3 kg (14 lb.) hammer. The long dimension of a fixture (S-wave source plate) was perpendicular to the geophone spread direction (W-E). N-S blows against both ends of the fixture generated two records with a phase difference of 180^o along the first arrivals (Figure 1). In subtraction of these two records, the P-wave component cancels and only the sum of the two SH-wave components remain (Helbig, 1986). The first arrivals of Figure 1a and 1b show a perfect shear pair—reversing the polarity between two records. It is easy to believe that the first arrivals in Figure 1 are SH-wave signals. A layer model with SH-wave velocities (Table 1) was generated based on the refraction travel time formula (Sheriff and Geldart, 1982). The SH-wave velocity of the first layer was determined by the direct wave. Velocities of the second and third layers were determined by the refracted waves. Compared with the SH-wave velocity of the first layer, the SH-wave velocity of the second layer is more than doubled. Are velocities of the second and third layers the true SH-wave velocities, or are they converted P-wave velocities? We cannot answer this question based only on SH-wave data.

Forty-eight-channel P-wave data were acquired along the same line at the same time for testing a new surface wave technique—MASW (Multi-channel Analysis of Surface Waves [Park et al., 1999; Xia et al., in press]). Forty-eight 8 Hz vertical-component geophones were used on the same geophone interval. The source of seismic energy was a 6.3 kg (14 lb.) hammer. The hammer was vertically impacted on a metal plate. Figure 2 shows acquired P-wave data. A layer model with P-wave velocities (Table 2) was generated based on the refraction travel time formula (Sheriff and Geldart, 1982). It is interesting to see that P-wave velocities of the second and third layers (Table 2) are almost the same as the relevant velocities shown in Table 1.

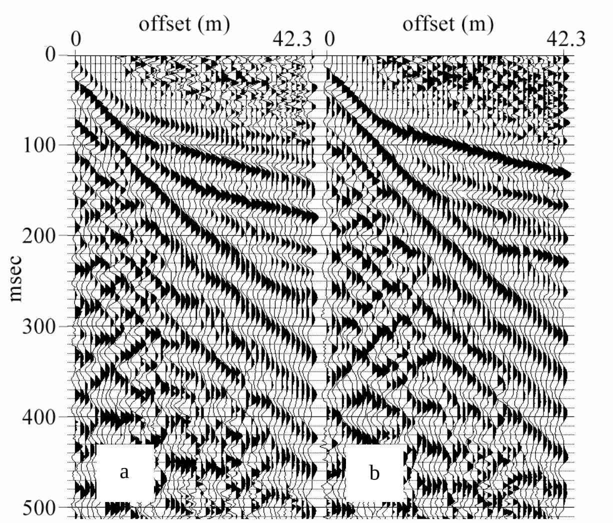

Fig. 1. SH-wave refraction data along a W-E line. N-S blows against both ends of the fixture generated data with the polarity revision of the first arrivals.

Table 1. A layer model calculated from the first arrivals of SH-wave data (Figure 1).

Layer number	t (ms)	offset (m)	v (m/s)	t_0 (ms)	Δ z (m)
1	6.00	0.9	150	0	1.68
	24.00	3.6			
2	47.50	9.0	330	20	3.18
	58.25	12.6			
3	71.50	18.9	525		
	81.75	24.3			

A non-horizontally layered model shown in Figure 3 explains why the same velocities appear on both SH-wave data and P-wave data. SH-wave energy splits on the non-horizontal layer. Part of SH-wave energy is converted into P-wave energy that travels along the interface. At a point *P*, part of the converted P-wave energy is converted back to SH-wave energy that is observed from the first and the second refracted events at a certain offset (> 8.1 m) on seismic records (Figure 1). Seismic energy along the first refraction path *OMPR* is converted from SH to P, then P to SH. This is why the seismic records show perfect shear pair—reversing the polarity between two records (Figure 1). Because the velocity of the first layer was determined by the direct wave, it was SH-wave velocity. However, velocities of the second and third layers in Table 1 are converted P-wave velocities due to dipping layers.

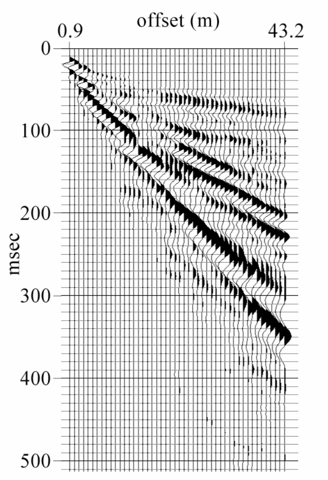

Fig. 2. P-wave data along the same line as Fig. 1.

Table 2. A layer model calculated from the first arrivals of P-wave data (Figure 2).

Layer number	t (ms)	offset (m)	v (m/s)	t_0 (ms)	Δ z (m)
1	3.50	0.9	270	0	0.9
	6.75	1.8			
2	11.75	2.7	340	4	1.38
	17.00	4.5			
3	20.50	5.4	510	10	2.17
	25.75	8.1			
4	27.00	9.0	900		
	30.00	11.7			

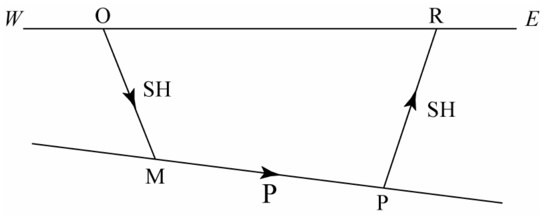

Fig. 3. A possible model to explain the SH-P-SH conversion. This is a cross section from an interface that is assumed dipping towards the NE direction.

MASW—An Alternative for Determining Near-surface S-wave Velocity

The Kansas Geological Survey has conducted a three-phase research project since 1995 to estimate near-surface S-wave velocity from ground roll:

1) acquisition of high frequency (≥5 Hz) broadband ground roll (Park et al., 1999),
2) creation of efficient and accurate algorithms organized in a basic data processing sequence designed to extract Rayleigh wave dispersion curves from ground roll (Park et al., 1998a), and
3) development of stable and efficient inversion algorithms to obtain near-surface S-wave velocity profiles (Xia et al., in press; Xia et al., 1997).

This new technique is at a stage of reliability testing (Xia et al., 1998a) and is being used to map bedrock and detect voids (Xia et al., 1998b, 1999; Park et al., 1998b, 1999a and 1999b). Real examples demonstrated that in certain geological sites 85% accuracy in S-wave velocity compared with borehole measurements and 90% accuracy when mapping bedrock can be achieved (Xia et al., 1998a and 1999).

Surface wave data were acquired along the same W-E line where the shallow SH-wave refraction data were acquired and along an N-S line perpendicular to the W-E line. Surface wave data were acquired at both ends of the lines. Figure 4 shows shot gathers on both ends of the W-E line and Figure 5 shows dispersion curves and inverted S-wave velocities of the two shots. The inverted S-wave velocities in the top 3 meters are approximately the same as the SH-wave velocity determined by the direct wave of the SH-wave refraction data (Figure 1). The difference between inverted S-wave velocities from both the W-E line and the N-S line is 18%. The inverted S-wave velocity linearly increases with depth in the range of depth that is larger than 7 meters.

To confirm the inverted S-wave velocity, a borehole was drilled on the site and suspension logging was conducted (Figure 6). We believe that the zigzag pattern of suspension log results is caused by errors of measurements. If average values of the suspension log results are calculated, the inverted S-wave velocities will be very close to the average values of the suspension log velocities and the general trend of both results are approximately the same.

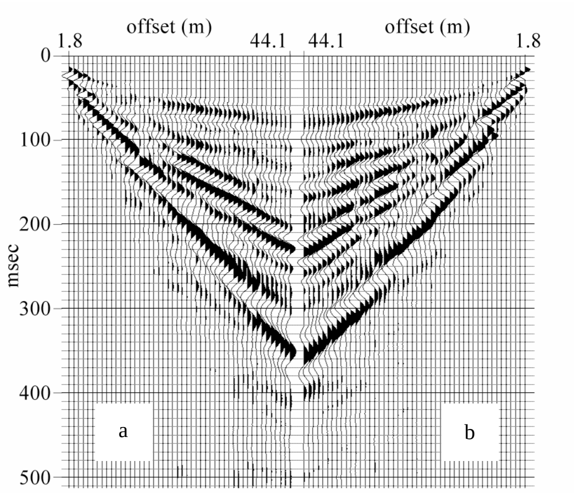

Fig. 4. Surface wave data acquired at both ends of the W-E line. Shot (a) was at the east end of line and shot (b) was at the west end of line.

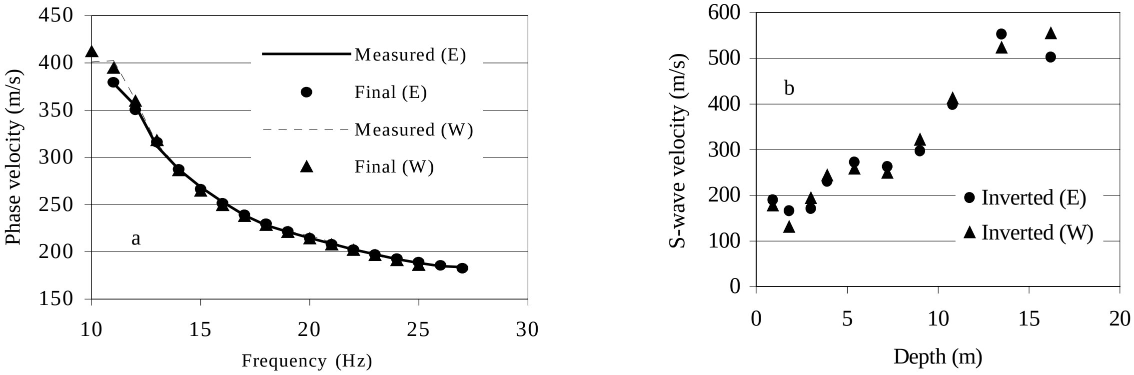

Fig. 5. Dispersion curves and inverted S-wave velocities from data of Figure 4. Values label (E) or (W) are those associated with shot gathers at the east end or the west end of the line (Figure 4). For example, Measured (E) and Final (E) in (a) are the dispersion curve extracted from data of Figure 4a and the calculated dispersion curve based on inverted S-wave velocity model labeled Inverted (E) (b), respectively.

Conclusions

Shallow shear-wave refraction survey may not provide the true S-wave velocity because of wave-type conversion in an area of non-horizontal layers. To verify if velocities based on shear-wave refraction surveys are velocities of converted waves, an additional P-wave refraction survey is necessary. The best alternative at this time is MASW, which can provide reliable S-wave velocities, even in an area of velocity inversion (a higher velocity layer underlain by a lower velocity layer).

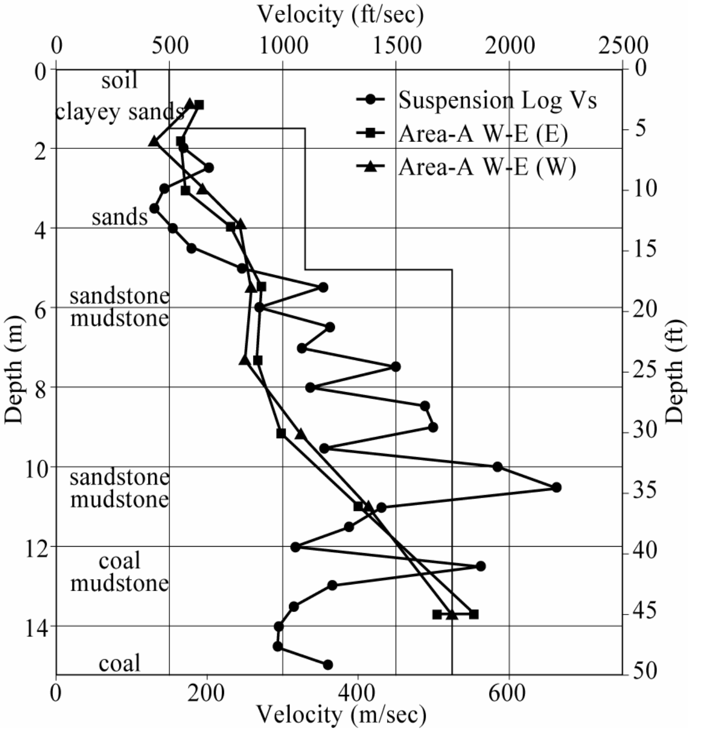

Fig. 6.
S-wave velocities from a suspension log, inverted S-wave velocities labeled as Area-A W-E (E) and Area-A W-E (W), and the drilling log. Labels (E) and (W) have the same meaning as labels of Figure 5. The three-layer velocity model from Table 1 is also presented by a solid line.

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