Seismic physical modeling measurements on solid surfaces

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ABSTRACT

Using the University of Calgary Seismic Physical Modeling facility, we recorded common source on phenolic and acrylic solid slabs in order to characterize their velocity properties. P and S seismograms were recorded by placing piezoelectric transducers to the solid surfaces using different coupling techniques with various high-viscosity compounds. Analysis of various seismic gathers confirmed that the velocities of the acrylic plastic slab are isotropic. The P- and S-wave velocities of the phenolic slab are clearly orthorhombic. We observed how velocity anisotropy affected NMO stacking in different azimuthal directions, and determined the form of the non-hyperbolic stacking trajectories that must be applied in order to optimize the stack quality.

INTRODUCTION

The fidelity of seismic reflection images in anisotropic velocity environments depends on recognizing the presence of anisotropy in the field data and accounting for it in the processing. The most obvious adjustment that needs to be made is in the step that determines the NMO stacking velocity. In the presence of significant velocity anisotropy, reflections from flat subsurface boundaries no longer have normal moveouts that follow hyperbolic trajectories. Byun et al. (1989) and Kumar et al. (2004) have devised a simple but effective formula for determining moveout corrections for P-wave reflections as a function of source-receiver offset in the presence of VTI anisotropy.

The analysis of scale model measurements on anisotropic materials with simple geometry and known anisotropic behavior can help quantify adjustments in reflection processing that must be made to improve pre-stack or post stack migrated images in geological media with anisotropy. In particular, with the increased emphasis on applying reflection seismics for characterizing reservoirs in geological environments with extensive vertical fracturing, we need to study these adjustments for HTI velocity media. We constructed a solid slab with characteristics that approximated an HTI medium by cutting sections of phenolic LE material, and gluing the sections together with the appropriate orientation. Ultrasonic measurements using piezoelectric transducers were made on the slab at the University of Calgary Seismic Physical Modeling Facility described by Wong et al. (2009). An important reason for doing these measurements was to evaluate different ways of coupling transducers to the solid surfaces.

The main problem of using such transducers on solid surfaces arises from the need to establish firm and consistent contact between the transducer active face and the surface of the solid medium. This is particularly difficult for transducers used to produce or detect horizontal particle motion. Producing and detecting S-waves with sufficiently repeatable amplitude is strongly dependent on using a suitable high viscosity coupling compound in the proper way. Some of the commonly used compounds are petroleum jelly, vacuum grease, molasses, honey, and Olympus shear coupling compound. The trade-off in using these different coupling compounds is between their effectiveness and their convenience and ease of use in physically modeling of land seismic surveys. In this report, we present data that compares the effectiveness of some of these compounds used to couple the transducers to the solid medium.

ANISOTROPIC MEDIA: PHENOLIC AND ACRYLIC SLABS

Figure 1 is a photograph showing two slabs on which scale-model seismograms were recorded. The slabs consist of phenolic laminate and acrylic plastic, two materials with very different velocity properties (Cooper et al., 2007; Cheadle et al., 1991). The acrylic slab is a single solid piece, with dimensions of 610 mm by 610 mm by 50 mm thick. Acrylic has P-and S-wave velocities that are very close to being isotropic.

The phenolic slab was constructed by cutting sections of orthorhombic phenolic LE material and gluing them together (seams between sections can be seen on the photograph). The slab was coated with water-proof epoxy paint so that it could be immersed in water (the resin in uncoated phenolic and the glue between seams dissolve would be dissolved by water). Dimensions of the slab are 575 mm by 575 mm by 70 mm thick.

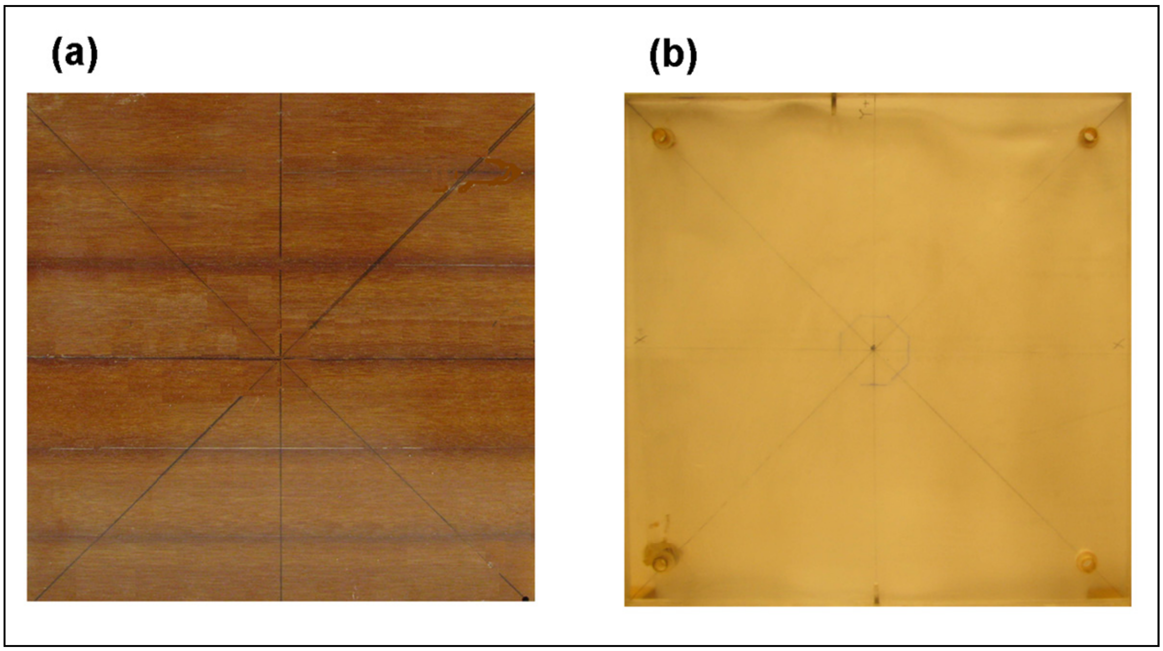

FIG. 1. Solid slabs on which seismic modeling measurements are made. (a) Phenolic slab with dimensions of 575 mm x 575 mm x 70 mm thick. (b) Acrylic slab with dimensions of 610 mm x 610 mm x 50 mm thick.

In the following sections of this report, the x-axis is defined to be along the direction of the seams on the phenolic slab, i.e., horizontal across the photographs. The z-axis is along the thickness direction.

METHOD

Ultrasonic seismograms were recorded with piezoelectric transducers on the surfaces of these slabs using the University of Calgary Seismic Physical Modeling Facility.

Positioning on the slabs was in units of millimeters, and dominant recording frequencies were on the order of 0.1 to 0.5 MHz. A standard scaling factor of 10,000 was applied, so that a model unit of 1 mm becomes a world unit of 10 m, and a model frequency of 0.1 MHz becomes a world frequency of 10 Hz. The mode1 sample time of 0.1 μs is equivalent to a world value of 1 ms.

Panametric transducers V103 (P-type) and V153 (S-type) were used on the surfaces of phenolic and acrylic slabs to record seismograms. Different high viscosity substances (petroleum jelly, molasses, honey, and Olympus shear couplant) were used to couple the transducers to the solid surfaces. Gathers of seismograms were recorded with P- and S-type transducers as both sources and receivers. We judged the effectiveness of the coupling method on the clarity of the direct P and S arrivals and of the primary reflections from the tops and bottoms of the slabs.

Figure 1 schematically shows two configurations of source and receiver placements on the surfaces of a solid slab. One transducer (Tx) acts as a source that generates ultrasonic vibrations in the solid medium. The second transducer (Rx) acts as a receiver that detects the vibrations. Provided there is sufficient physical coupling, V103 transducers will produce and detect particle motion primarily in the vertical direction. V153 transducers, on the other hand, will produce and detect vibrations primarily with particle motion in the horizontal direction. The V153 transducer can be rotated in the horizontal plane to produce or detect particle motion in two orthogonal directions.

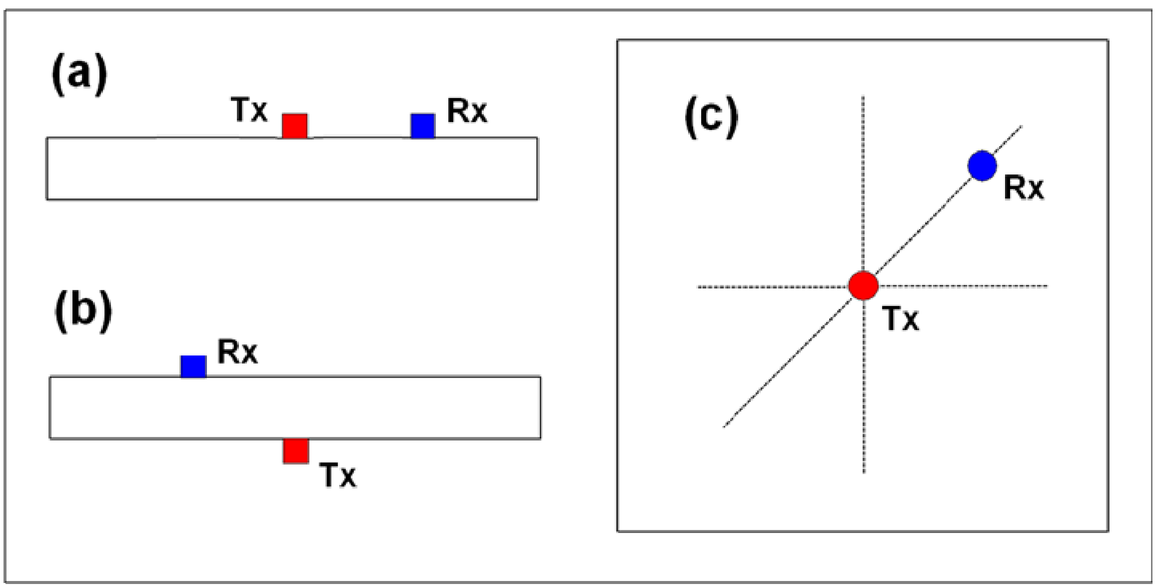

FIG. 2. Placement of source (Tx) and receiver (Rx) transducers on the solid slabs. (a) Surface configuration: Tx fixed on top surface and Rx moving on top surface. (b) Through configuration: Tx fixed on bottom surface and Rx moving on top surface. (c) Plan view of top surface with lines along which Rx moves for both configurations.

If both the source and detector transducers are the V103 type, measurements will simulate P-P land surveys. If the source is a V103 transducer and the detector is a V153 transducer, measurements will simulate P-S land surveys. By using the appropriate combinations and orientations of transducers, scale model measurements can simulate three-component seismic surveys on land.

RESULTS AND ANALYSIS

Many common source gathers were recorded during the course of this investigation. For the surface configuration, the gathers were end-on fixed source profiles with the receiver moving in straight lines at different azimuths with respect to the x-axis. For the through configuration, fixed source split-spread gathers were recorded with the receiver again moving in straight lines at different azimuth (generally at 0º, 45º, and 90º with respect to the x-axis). P and S arrivals were identified, and apparent group velocities were determined from the arrival times.

Acrylic results

Fixed source gathers recorded with the surface and through configurations on the acrylic slab are displayed on Figure 3. The first P arrivals as well as the slow surface waves can be seen with linear moveout on Figure 3(a). On the through gather of 3(b), the hyperbolic moveouts of the first P and S arrivals are clearly discernible. The codas following the first reflected P event on all three figures are dominated by multiple reflections between the top and bottom surfaces of the slab.

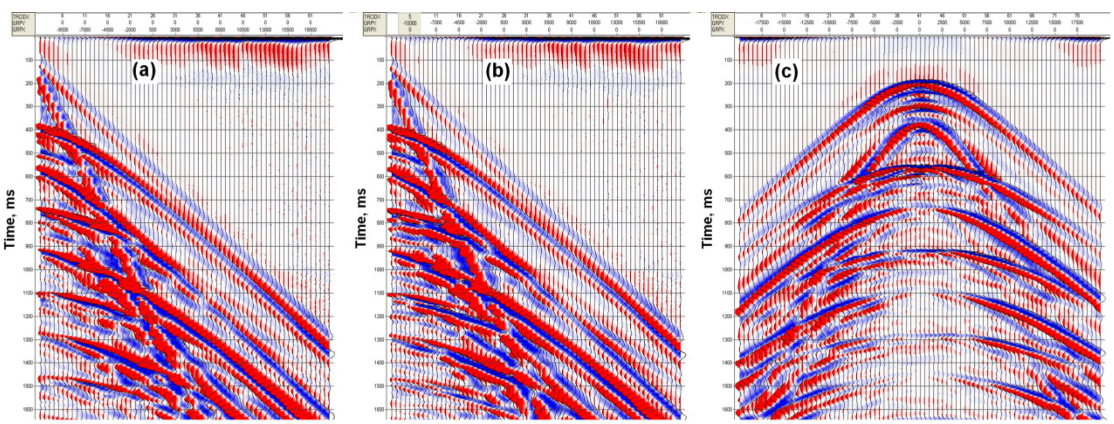

FIG. 3. P-P gathers recorded on the acrylic slab. (a) Surface configuration end-on profile in the x-direction; (b), surface configuration end-on profile in the y-direction; (c) Through configuration split-spread profile along the x-direction. Timing lines are 100 ms apart; trace spacing is 50 m.

Analysis of the first arrivals on the gathers on Figure 3 gives an isotropic P-wave velocity of 2740 ±40 m/s for acrylic. Analysis of the surface wave arrivals gives the surface velocity as 1220 ± 20 m/s. On the through gather of Figure 3(c), the S-wave arrival times in the thickness direction gives a shear-wave velocity V_s of 1440 ± 20 m/s. As expected the V_{surf} to V_s ratio is about 0.85.

Phenolic results

Figure 4 shows raw data collected with S-type transducers as both source and receiver in the through configuration. The average spectrum of the unfiltered traces indicates signal energy residing below 100 Hz. On the traces, the dominant frequencies of the strongest events (the shear arrivals), based on peak-peak times, are about 12 Hz. The P arrivals at 200 ms have dominant frequencies of about 50 Hz. There is considerable noise at both high and low frequencies.

We can improve the visual appearance of the gather by applying a zero-phase bandpass filter to the raw traces. The filter and the average spectrum after filtering are shown on Figure 5(a) as the red and blue curves, respectively. Figure 5(b) shows the traces after filtering; we see enhancement of the first S arrivals with apex at about 480 ms, and the S_3 reflection with apex at about 1440 ms.

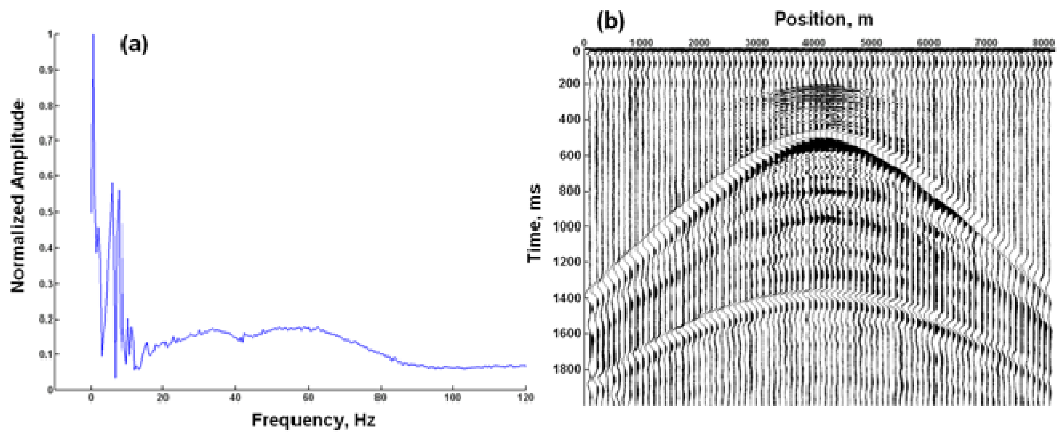

FIG. 4. (a) Average spectrum of the raw traces as on Figure 4(b). (b) Raw, unfiltered traces displayed in wiggle format.

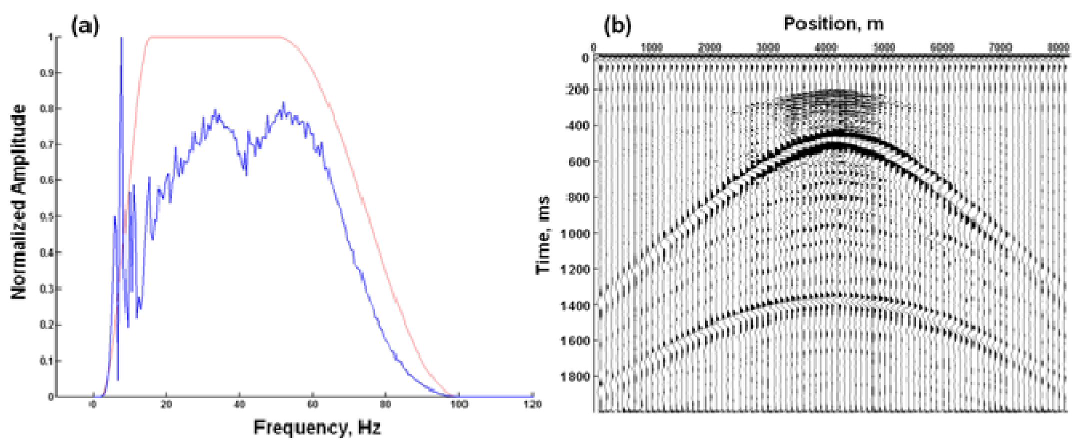

FIG. 5. (a) Average spectrum of traces on Figure 4(b) after they were filtered with the filter plotted in red. (b) The gather of Figure 4(b) after filtering.

ANISOTROPIC VELOCITIES IN THE PHENOLIC SLAB

Velocities determined from arrival times of seismic events are group velocities. The group velocities observed through the phenolic slab data has been analyzed in terms of orthorhombic anisotropy (Mahmoudian et al., 2010). For this report, we will present a simplified analysis, making the assumption that the phenolic slab has (different) VTI velocities in the XZ and YZ planes.

Surface configuration results

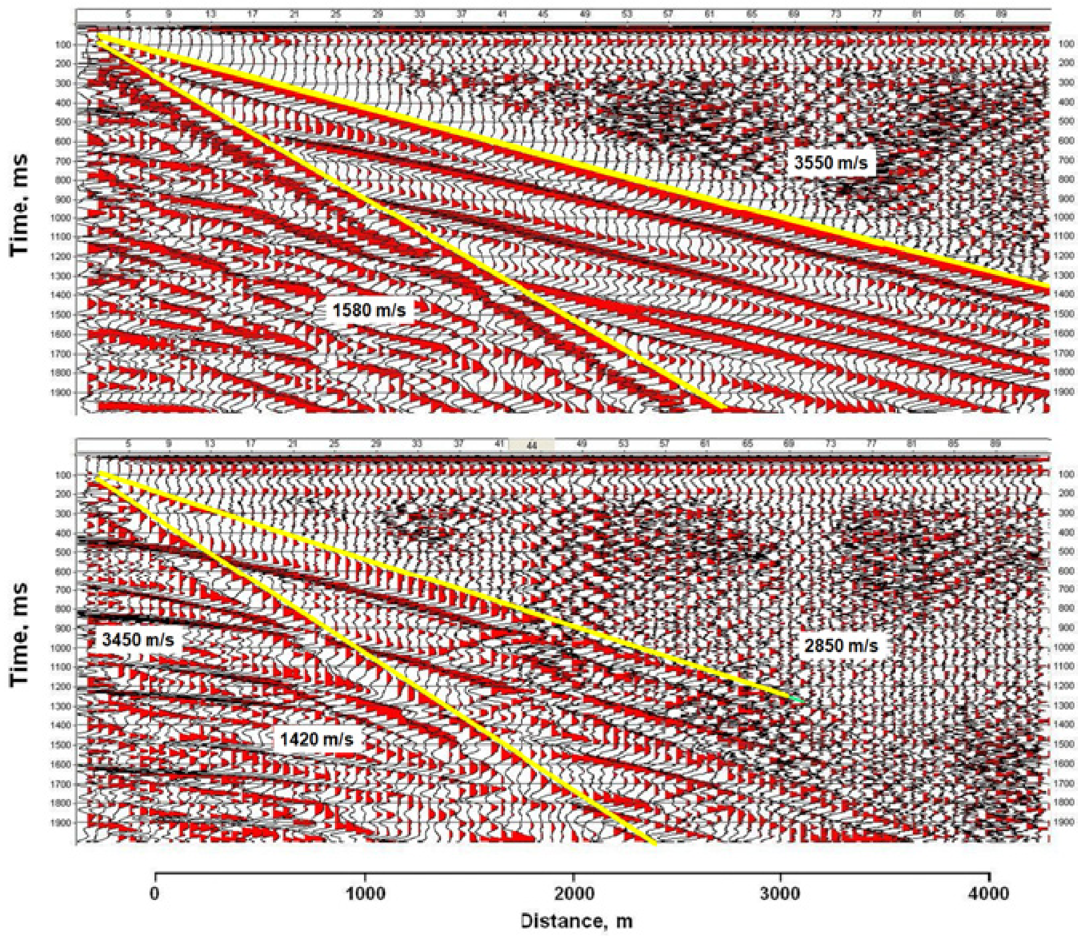

FIG. 6. Two fixed source, end-on gathers of seismograms on the anisotropic phenolic slab. Top gather is in the x direction, bottom gather is in the y direction. P-wave velocities are 3550 m/s, 2850 m/s, and 3450 m/s in the x, y, and z directions. Surface wave velocities are 1580 m/s and 1420 m/s in the x and y directions.

Two surface end-on gathers are displayed on Figure 6, one parallel to the seams (x direction), and the other perpendicular to them (y direction). These gathers were recorded with P-type transducers acting as both the source and receiver. From the first-arriving linear events, we can calculate the P-wave velocities of the phenolic slab in the x and y directions to be 3550 m/s and 2850 m/s, respectively. From the time difference between the first and second multiples at near-zero offset, we can estimate the P-wave velocity in the z direction to be about 3450 m/s.

Using P transducers for the source and receiver on the surface, we cannot obtain the S-wave velocities. To record data that enables us to determine the anisotropic S-wave velocities, we must use S-type transducers as both source and receiver in the through configuration.

Through configuration results

Byun et al. (1989) and Kumar et al. (2004) have devised a simple but accurate approximation for describing qP group velocities in VTI anisotropic media. In this report, we used the Byun/Kumar formulation to analyze both the qP and qS observed arrival times, even though the formulation strictly speaking is applicable only to qP arrivals. The Byun/Kumar approximation for quasi-P wave group velocities is given by:

$$V_p^{-2}(\emptyset) = a_0 + a_1 \cos^2\emptyset - a_2 \cos^4\emptyset \ , \qquad (1)$$

$$a_0 = V_h^{-2} \ , \qquad (2)$$

$$a_1 = 4V_{45}^{-2} - 3V_h^{-2} - V_v^{-2} \ , \qquad (3)$$

$$a_2 = 4V_{45}^{-2} - 2V_h^{-2} - 2V_v^{-2} \ , \qquad (4)$$

where $\emptyset$ is the dip angle measured from the VTI symmetry axis, V_v, V_h, and V_{45} are the group velocities in the vertical ($\emptyset$=0°), horizontal ($\emptyset$=90°), and 45° directions. For the isotropic case, a_1 and a_1 are identically zero.

Figure 7 displays split-spread gathers with P-type transducers as source and receiver in the through configuration. The split-spread lines run parallel and perpendicular to the seams on the phenolic slab. Coupling of the P-type transducers to the solid surface achieved was through petroleum jelly aided by a thin layer of water.

High-quality first arrivals can be seen on both gathers, and their different moveouts indicate P-wave velocity anisotropy. Complex coda follows the first arrivals on both profiles, and they are quite different for the two directions. On both gathers there is evidence of the direct S wave, but it is much clearer on Figure 7(b). There appears to be complicated mode conversion at the tops and bottoms of the anisotropic slab and at the seams. On Figure 7(b), we see obvious disruptions in the continuity of the first arrivals at positions near -600 m and +400 m. as seams are crossed.

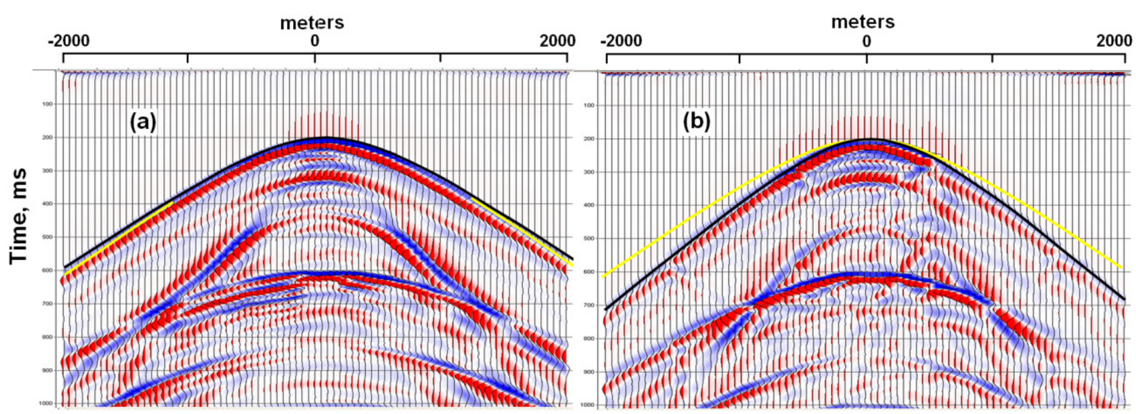

FIG. 7. Through configuration seismograms recorded with P-type transducers, with velocity analysis of the P arrival times; (a) x-direction profile; (b) y-direction profile.

The yellow lines on Figure 7 are hyperbolic moveout curves for a constant velocity of 3500 m/s. They are close to but not equal to the observed moveouts on the separate profiles.

The black lines are the moveouts obtained by adjusting angle between the source and receiver positions, adjusting the parameters V_v, V_h, and V_{45} in Equations 1 to 4 to get group velocity, and calculating the arrival time. The fitting of the observed first arrival times is achieved as follows:

For the x-profile of Figure 7(a), V_h= 3650, V_v = 3500, V_{45} =3550.

For the y-profile of Figure 7(b), V_h = 2950, V_v = 3500, V_{45} = 3250.

We conclude that the qP group velocities are 3650 m/s, 2950 m/s, and 3500 m/s in the x, y and z directions, respectively. These values are consistent with the values determined from the linear and reflection events on Figure 6.

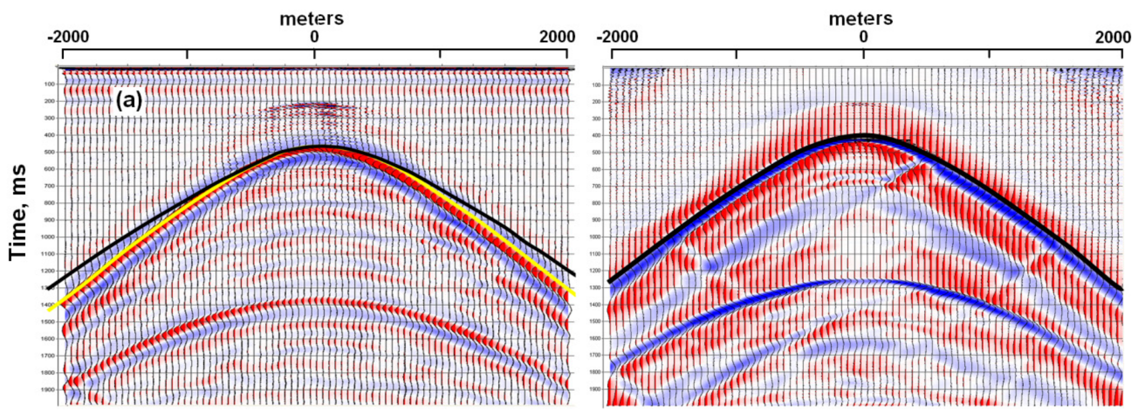

FIG. 8. Through configuration seismograms recorded with S-type transducers, with velocity analysis of the S arrival times; (a) x-direction profile; (b) y-direction profile.

S-wave arrival time fits

The same analysis was applied to the profiles of Figure 8. These are split-spread gathers with S-type transducers as source and receiver in the through configuration. Coupling of the S-type transducers to the solid surface achieved was with petroleum jelly and a thin, soft layer of paper. The role of the paper is to attenuate P-wave motion produced and detected by the S-type transducers (they are by no means purely S-type; see below in the section on coupling methods). If these were not attenuated, multiples of the faster P modes severely degrade the clarity of the S mode. On both Figures 8(a) and 8(b), high-frequency P arrivals can be seen at 200 ms, despite the attenuating effect of the paper layer.

On Figure 8(a), the yellow line is the hyperbolic moveouts based on an isotropic velocity of 1560 m/s. The black lines are the moveouts obtained by adjusting angle between the source and receiver positions, adjusting the parameters V_v, V_h, and V_{45} in

Equations 1 to 4 to get group velocity, and calculating the arrival time. For the x-profile of Figure 8(a):

V_h= 1730 m/s V_v = 1560 m/s, V_{45} =1550 m/s (XZ plane).

For the XZ plane, the yellow line (moveout due to an isotropic velocity) and the black line (moveout due to VTI velocity) clearly are not identical.

For the y-profile of Figure 8(b),

V_h= 1700 m/s, V_v = 1680 m/s, V_{45} = 1690 m/s (YZ plane).

In this case, the moveouts due to an isotropic velocity and the moveouts due to the very slightly VTI velocities are practically identical, so the yellow line is covered by the black line. In the YZ plane, the qS velocity is, for practical purposes, isotropic.

We note that the VTI parameters V_v, V_h, and V_{45} are different for the XZ and YZ planes. The qS particle motions for the seismograms are (nearly) transverse to the profiling direction. This means that the velocity parameters determined for the XZ plane are for particle motion in the y-direction. On the other hand, the velocity parameters determined for the YZ plane are for particle motion in the x-direction. The fact that the velocity parameters are not identical in the XZ and YZ planes is a direct indication that the phenolic slab has orthorhombic anisotropy.

EFFECT OF DIFFERENT COUPLING METHODS

The quality of acquired seismograms is critically dependent on how the transducers couple to the solid surface. For P-P transducers, effective coupling can be achieved simply by using modest pressure on the transducers with a thin layer of water or grease between the transducer face and the solid.

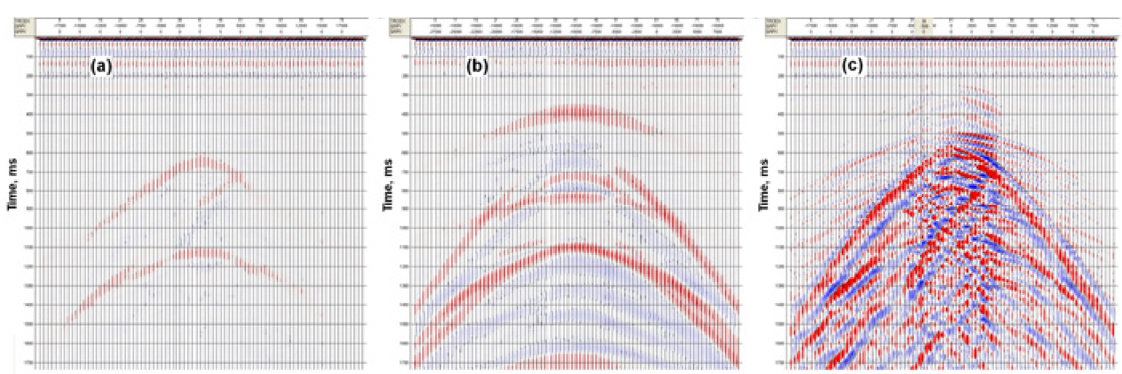

FIG. 9. Surface configuration raw S-S gathers recorded on the phenolic slab. (a) Coupling with petroleum jelly and paper; (b) coupling with petroleum jelly; (c) coupling with high-viscosity Olympus shear couplant. Timing lines are 100 ms apart; trace spacing is 50 m.

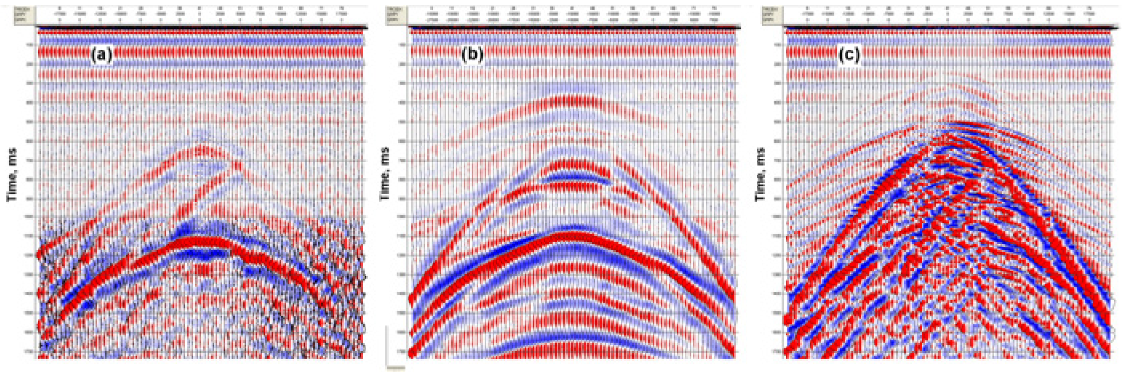

FIG. 10. Same surface configuration S-S gathers as on Figure 5, but with AGC. Timing lines are 100 ms apart; trace spacing is 50 m.

In the through configuration with S-type transducers, we have found that having petroleum jelly and a thin paper layer between the transducers and the solid surface gave good quality S-wave arrivals. It is more difficult to obtain repeatable, good-quality shear wave data when the source and receiver transducers are both on the top surface. This configuration is the one that must be used to model seismic surveys on land. Figures 9 and 10 show the results of three different methods of coupling S-type transducers in the surface configuration.

Although the V153 S-transducers are nominally producers and detectors only of particle motion parallel to the flat surface on which they sit, they are not perfect in this regard. They actually also produce and detect vertical motion to some degree. We expended a great deal of effort in trying to find the optimum combination to minimize the ratio of P to S responses of these transducers, because the P multiples can be strong enough to totally obscure the S arrivals.

One can use high-viscosity shear-wave couplant sold by Olympus NDT to maximize the shear wave response. This is an expense organic paste (basically a supersaturated sugar solution) that works well for static measurements where the transducers do not move. Figure 9 shows that the Olympus couplant is extremely effective in maximizing the shear response. Figure 9(a), (b) and (c) all have the same display gain, but the data on Figures 9(a) and 9(b) were recorded after the received signal were passed through a 40db preamplifier. The data on Figure on Figure 9(c), where the Olympus compound was used for coupling, was not amplified at all before recording. The shear arrivals on Figure 9(c) are much stronger than the P arrivals (which, nevertheless, are still present).

There are two problems in using this shear couplant. It so viscous and binds so well that it is difficult to lift a transducer off the surface that it is bonded to. Forcibly doing so in order to move the transducer has pulled apart the thin piezoelectric wafer on the transducer and destroyed it. The second problem is that the couplant dries fairly quickly, so that it forms a crust in about 20 minutes that renders its coupling properties useless if a transducer needs to be lifted and lowered repeatedly over an extended period of time in order to complete a multifold seismic line.

Other coupling compounds that may be suitable are molasses, honey, leg wax, and vacuum grease. We have tried some of these alternatives, but the results are inconclusive at this time. The relative advantages and disadvantages of using them as couplants need to be further studied. Resolving the problem of coupling S-type transducers in the surface configuration is critical for undertaking scale model seismic studies of shear arrival amplitudes.

SUMMARY

Seismic physical modeling using piezoelectric transducers on solid surfaces depend on making good contact between the transducer active surfaces and the surface of the solid medium. We have recorded seismograms using several different coupling techniques and different coupling compounds. So far, we have found that no one method is completely satisfactory for all of the different types of transducers.

We made measurements on simple slabs of acrylic and phenolic materials preliminary to making future measurements on more complicated model composed of both materials. For example, we will try to study the amplitudes of reflections from an acrylic-to-phenolic interface, so as to gain data on reflection coefficients associated with isotropic to HTI transitions. Measurements on models of composite materials should give insight to how reflection AVAZ behaves with different combinations of isotropic/VTI/HTI transitions.

ACKNOWLEDGEMENT

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