Contrasting near-surface and classical seismology

By DON W. STEEPLES, BRIAN MACY,
CHRIS SCHMEISSNER, and RICK MILLER
University of Kansas
Lawrence, Kansas

A statement in the article “The velocity domain” by Dave Marsden (*TLE*, July 1993) motivated this paper. On page 747 he states, “From seismic wave tests, we see that air waves are the slowest of all, the direct wave and ground roll often have comparable speeds, and reflected *P*-waves are the fastest.” Those who have spent their careers in oil-exploration seismology probably would not question this assertion and would not necessarily be concerned by it. However, those experienced in near-surface seismology are aware of cases in which Marsden’s statement does not hold true. Thus, we present data from two seismograms to illustrate that near-surface seismology sometimes differs from that used to explore deeper targets.

Although the basic physics is the same for shallow- and deep-reflection work, the relative importance of certain aspects of the physics varies. In both cases seismologists deal with three principal types of waves: *P*-waves (essentially sound waves that travel fastest and arrive first on seismograms); *S*-waves (distortional waves that typically travel less than 60% as fast as *P*-waves); and surface waves (which move only along the earth’s surface and travel about 90% as fast as *S*-waves). The principal differences between shallow and deep surveys concern frequency and velocity which, in turn, translate to differences in wavelength. Some of the surface waves in our examples have wavelengths of less than 1 m.

For the most part, surface waves have been considered noise in prospecting for hydrocarbons. Nonetheless, surface waves have been used successfully in shallow engineering studies.

Historical perspective. Even though seismic refraction methods have been in use since the 1920s, shallow reflection techniques have been late in coming. Efforts by Evison in New Zealand in the early 1950s are documented, mostly as anecdotal reports explaining the problems and frustrations of working in the shallow environment. Research by Pakiser and colleagues at the US Geological Survey appears to be the first published indication of the successful use of shallow reflections, i.e., less than 30 m. (See “A preliminary evaluation of the shallow reflection seismograph,” GEOPHYSICS 1956).

Modern use of shallow seismic-reflection methods essentially began with Schepers who produced some excellent shallow *P*-wave reflection results that were not fully appreciated in North America until the 1980s. (See “A seismic reflection method for solving engineering problems,” *Journal of Geophysics* 1975). Hunter’s optimum-window shallow-reflection technique is now widely used in engineering, environmental, and groundwater applications. (See “Shallow seismic reflection mapping of the overburden-bedrock with the engineering seismograph—some simple techniques,” GEOPHYSICS 1984). At about that same time, Helbig and students at the University of Utrecht in The Netherlands were making progress at a nearly ideal field testing site in the Dutch tidal flats. Our own research during the 1980s focused on extending resolution limits and applying shallow-seismic reflection by means of CDP techniques as well as extensive routine digital processing.

The use of shallow *S*-wave reflections has not been widespread; only a few examples have appeared in the literature. The main problem has been separating *S*-wave reflections from the surface waves that usually arrive at the same time on a seismogram.

Regardless of which seismic technique is used, details of the near-surface seismogram often differ from those commonly seen in oil-exploration seismology.

Example 1. As Figure 1 shows, air waves are not always the slowest waves. In fact, they are the fastest (at 335 m/s) in Figure 1. The next coherent arrival is the direct *P*-wave (velocity of about 260 m/s). The most prominent arrival is the reflection at 26 ms, from the top of the water-saturated zone, at a depth of about 2.6 m (8 ft), with a best-fit hyperbolic velocity of about 260 m/s, which is identical to the velocity of the direct *P*-wave.

We used a geophone interval of 0.25 m (about 10 inches) and a minimum offset of 1.75 m (about 6 ft) for this extremely shallow seismic-reflection work. Our energy source was a 30.06 rifle bullet fired directly into the sandy surface. For recording, we used single 100-Hz geophones with 14-cm spikes.

Note that we employed a pre-A/D, 600 Hz low-cut filter with rolloff of 24 dB per octave. Dominant frequency is about 350 Hz, almost a factor of two below the -3 dB point of our low-cut filter. Contrary to what would be expected in classical reflection seismology, we did not find ringing in the data, and the reflected wavelets are nicely defined. The purpose of using low-cut filtering was to decrease the amount of surface-wave information that enters the A/D converter and to allow high-frequency

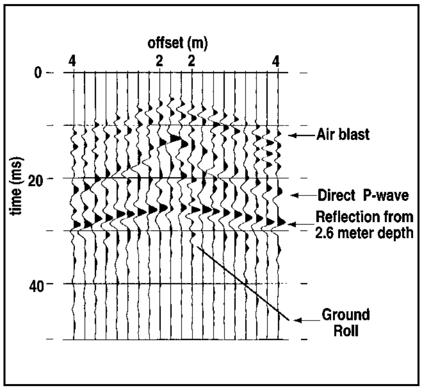

Figure 1. Unprocessed seismogram from test site near Great Bend, Kansas, showing reflection from top of saturated zone at a depth of 2.6 m in the alluvium of the Arkansas River. Dominant frequency of the reflection is about 350 Hz. Near-surface direct *P*-wave velocity at this site is about 260 m/s. High frequency ground roll on some records at this site has wavelengths of approximately 1/2 m. Shot was acquired with a 30.06 rifle, pre-A/D low-cut filter: 600 Hz, and a 100 Hz Mark L-40 A geophone.

reflections to fill a significant number of bits in the digital words.

Small vestiges of surface waves appear on the seismogram in Figure 1, but they are quite subtle. Although ground roll is not obvious in Figure 1, other seismograms from the same data set indicate velocities of 30-75 m/s for surface waves, depending on which phase of the ground roll is measured.

One important consequence of high frequencies and low velocities is wavelengths that are a couple of orders of magnitude shorter than those with which oil company seismologists are familiar. The ground roll mentioned in the previous paragraph has a dominant frequency of about 150-200 Hz. Given that frequency range and the above noted velocity range, we calculate a wavelength range of 0.15-0.5 m. Even with a geophone interval of only 0.25 m, we have the possibility of spatial aliasing of ground roll. Indeed, spatial aliasing of ground roll is one of the more serious pitfalls of near-surface seismology, even with geophone group intervals of less than 1 m.

Hasbrouck has indicated (see "Use of shear wave seismics in evaluation of strippable coal resources," in *Utah Geological and Mineral Survey Bulletin* 118, 1982) that near-surface *P*-waves typically travel 2-7 times faster than *S*-waves, which is consistent with all of our experiments. Consequently, the 30-75 m/s velocity we see for the ground roll at this site is not unreasonable, given that the *P*-wave velocity averages about 260 m/s to a depth of 2.6 m.

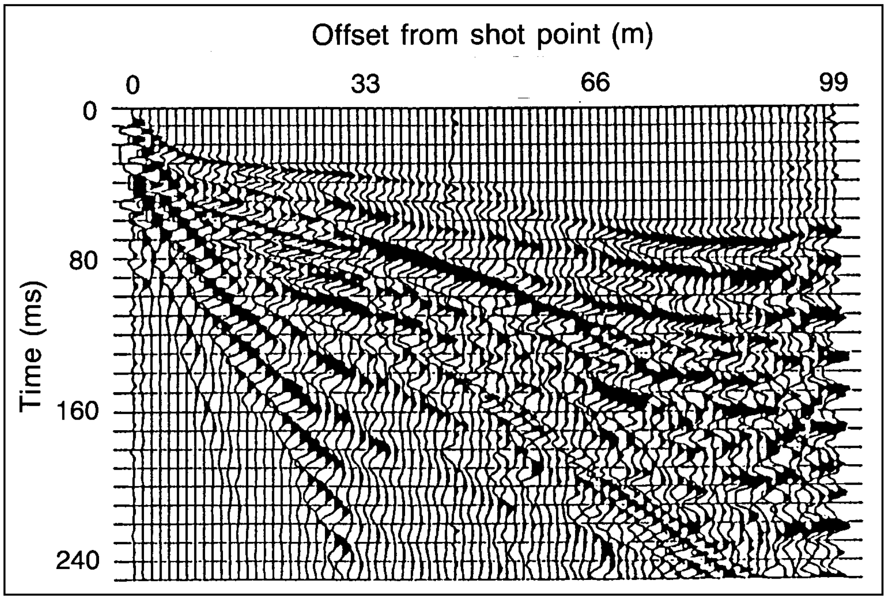

Figure 2. Field record taken from tests at the Bala kimberlite in Riley County, Kansas. The longest offset on the seismogram is at the center of the kimberlite. Shot was acquired with a vertically oriented Betsy eight-gauge shotgun, low-cut filters open, and a geophone interval of 1.2 m. A low filter of 200 Hz and an amplification factor of 4 have been applied to the trace normalized record.

Example 2. Figure 2 is an example of refracted first arrivals that have an apparent velocity greater than infinity. At this particular site, we first noted this phenomenon with an eight-channel seismograph in the late 1970s. The data were shown to a prominent seismologist for comment; however, his analysis was that we did not know where our geophones were during recording.

We returned to the site in the summer of 1994, equipped with a 96-channel seismograph, with the intent of documenting the phenomenon. A single shot from an eight-gauge Betsy Seisgun served as the energy source. Single 100-Hz Mark Products geophones were placed at intervals of 1.2 m, with a 0.5-ms sampling interval. No pre- A/D low-cut filters were used during recording.

At offsets of about 80-99 m, there is a zone on the ground where the first arrivals come in at the same time or earlier with increasing distance from the source. We have seen this phenomenon at other sites, and we have talked with other investigators who have also seen it occasionally. Generally, the phenomenon has occurred over a limited distance, and geophone group intervals as short as 1 m are required to see it distinctly. This phenomenon would not likely be seen with the much larger geophone intervals commonly employed in deeper seismological surveys unless the scale of the necessary geology were increased proportionately to the geophone interval.

At other sites, we have only seen this phenomenon when a rapidly varying thickness of low-velocity material overlies material having *P*-wave velocity 5-10 times faster. Manual calculations show that this can occur when extreme velocity discontinuities and rapid changes in the thickness of the low-velocity layer are present.

In the case of the data shown in Figure 2, a kimberlite has intruded into a thick Pennsylvanian section of alternating shales and limestones where individual beds range from 1 m or less to several meters in thickness. The high velocity comes from the limestone, which has been tilted and may be on edge beneath the kimberlite. The low velocity comes from the soil and weathered shale that overlie the limestone. The kimberlite (approximately 9000 ft/s) is of intermediate velocity relative to the weathered shale (4-5000 ft/s) and limestone(13 000+ ft/s). Hence, it is faster for the *P*-wave energy to travel down into the limestone, propagate along it, and then propagate back toward the source than it is for it to travel along the surface as a direct *P*-wave or as a refraction in the weathered shale.

As in Example 1, the ground-roll velocity is slower than the air-wave velocity — in this case by about 50%. The wavelength of the ground roll for offsets of 8-15 m is about 5 m. Again, geophone intervals of the order of 1-2 m are required to prevent spatial aliasing of the ground roll.

Discussion. The physical principles upon which near-surface and deep-reflection seismology are based are identical, but the relative importance of those principles varies. We have commonly seen near-surface *P*-wave velocities that are lower than the velocity of sound in air. At the other end of the apparent velocity spectrum, we have noted phase velocities that are larger than infinity. We have also seen ground-roll wavelengths with length on the order of 1 m, suggesting that one way of examining the causes of such anomalies is to use a shovel. LE