Shallow seismic reflection does not always work

Richard D. Miller, Jianghai Xia, Kansas Geological Survey*
Don W. Steeples, Department of Geology, University of Kansas

Summary

Shallow seismic reflection has seen widespread use in a variety of environmental, groundwater, and engineering applications over the last 15 years. Seismic reflection, like any other geophysical technique, has reasonably well defined limitations. Besides the well-published resolution limitation, the effectiveness of the technique is strongly dependent, and in many cases controlled, by near-surface conditions. Moisture content, sorting, grain size, organic matter, and consolidation are just a few of the key properties of the near-surface that can dramatically affect the quality of seismic reflection data. In some difficult data areas thoughtful parameter design, high-quality equipment (large dynamic range and small electronic noise), and careful processing can overcome adverse near-surface conditions. Tendencies to suggest that data processing is the key to bringing out reflections on CMP stacks that are not identifiable on shot or CMP gathers leads to overselling the technique and inevitable skepticism by clients and potential clients as to the reliability of shallow seismic reflection. As difficult as it may be for shallow seismic reflection practitioners to admit, shallow seismic reflection simply will not work in some settings and for some targets.

Introduction

Abundant examples exist in the literature demonstrating successful application of seismic reflection to environmental, groundwater, and engineering problems. For every successful application presented in the published literature or by a practitioner touting highly favorable results there are surveys that end unsatisfactorily. Shallow seismic reflection, like all geophysical techniques, does not always work. In some cases the success or lack thereof is related to the unfavorable nature of the near surface. There are, however, many times when survey design, equipment, processing techniques, or overselling cause failure. Concern that the technique was being misrepresented and inappropriately used prompted a DOE workshop which culminated in suggested feasible applications and unrealistic targets based on the current state-of-the-art (Steeples et al., 1997). Effective use of the technique, even for applications that classically have met with success, strongly depends on the properties of the very near surface and how they influence the acoustic wave.

Identifying and describing the pitfalls of shallow seismic surveying have been the topic of previous publications (e.g., Steeples and Miller, 1998). Due to the complex nature of the wavefield at close source offsets, distinguishing reflections from coherent source noise is neither an easy task nor one that can be done with confidence in all cases. Inappropriate identification or misindentification of recorded coherent arrivals is the most common source of artifacts on shallow CMP stacked sections. In areas with near-surface conditions conducive to shallow seismic reflection, identification of shallow reflections is a straightforward process. However, in areas where the “optimum window” is either very small or does not exist, shallow reflections cannot be identified on unstacked gathers and processing to extract hidden reflections generally results in artifacts on CMP stacked sections. Geologic settings do exist where seismic reflection surveying should not be considered.

Several physical characteristics of the near-surface play critical roles in how effectively broad band, high frequency, seismic waves propagate through the shallow subsurface. Saturation of the near-surface, or more practically the depth to the water table, has probably the biggest influence on the wave characteristics and arrival pattern of coherent source-generated energy (Knight and Nolen-Hoeksema, 1990; Jefferson and Steeples, 1995). The significance of moisture content is somewhat decreased by consolidation. However, at the extreme the presence of high-velocity consolidated material very close to the surface can dramatically reduce data quality (Kalik, 1988). Since most shallow reflection surveys focus on the unconsolidated portion of the geologic section, probably the second most significant set of factors influencing the acoustic wave properties are lithology, grain size, porosity, and sorting (Marion et al., 1992). Fine grained, well-sorted near-surface materials are generally conducive to the propagation of high-frequency, low-amplitude acoustic energy (Pullan and Hunter, 1990b).

Identification of reflection events on unstacked gathers is absolutely essential to the confident, appropriate, and ethical use of shallow seismic reflection profiling. The specialized nature of event identification and optimized parameter selection necessary for the recording and processing of shallow seismic data can easily be taken for granted. Shallow seismic reflection surveying is unlike some geophysical techniques that require little more than a basic understanding of theory, instruction on instrument use, and appropriate software. The ability to recognize the limitations of the technique and adjust parameters and/or modify equipment or even terminate the survey is important. Sufficient experience to appreciate the fact that all methods do not always work and the integrity to respond appropriately is critical to the efficient and effective use of geophysical tools for site characterization.

Shallow seismic reflection has proven instrumental in mapping structure at sites where knowledge of lateral heterogeneities have added to and improved the overall design and implementation of techniques and facilities used for remediation. Mapping changes in the bedrock topography under several meters of unconsolidated sediments is an application where shallow seismic reflection has consistently demonstrated success (Miller et al., 1989; Goforth and Hayward, 1992). Faults, fractures, and bed terminations can dramatically alter fluid flow and transport. Delineating discontinuities in otherwise coherent layers is probably one of the more common applications of shallow seismic reflection and focuses on the strength of this technique (Pugin et al., 1995; Miller et al., 1992; Gochioco, 1991; Pullan and Hunter, 1990a). Paleochannels represent lateral heterogenic features that consistently plague hydrodynamic models and that have become a routinely imageable shallow target (Miller and Xia, 1997). Correlating stratigraphy with boreholes in variable unconsolidated settings has provided a challenge to investigators on many surveys (Miller et al., 1996; Schieck and Pullan, 1995). In all the previously noted applications, if the conditions are not adequate for the propagation and recording of high frequency, broad band, reflected waves from shallow interfaces, seismic reflection will not work.

Bad Data Examples

Any geologic setting can produce bad data if the acquisition parameters and target are not properly matched. When properly deployed, the primary factor influencing the outcome of a shallow seismic reflection survey is the near-surface velocity structure. Recording and identifying reflection arrivals among all the coherent source noise at very close offsets and shallow times relies on good time separation between reflections and source noise as well as distinct differences between hyperbolic reflections and linear source noise. Arrival patterns of the various acoustic waves are dictated by velocity and depth.

Probably the most common type of interference comes from refractions, which can take the form of guided waves (Robertsson et al., 1996), wide angle interference (Pullan and Hunter, 1985), and low dominant-frequency refraction waveforms. These situations occur as a result of the velocity structure, layer depths, and attenuative properties of the near surface, none of which can be modified or ignored. In a few rare situations narrow bandwidth refraction ring can be minimized with spectral enhancement techniques. Second to refraction interference is the case when prominent direct wave and ground roll arrive minimally separated from refraction energy, which reduces or even eliminates the optimum window (Hunter et al., 1985). In some settings the air-coupled wave arrives before or within the time and offset portion of the seismogram in which reflections are expected to arrive. This air-wave contamination can eliminate any opportunity to interpret reflections.

This California example data shows where the refraction ring or guided waves are a detriment to the recording of shallow reflections (Figure 1). The target here was volcanic bedrock overlain by siltstone and unconsolidated sediments. The cyclic nature of the near-offset direct wave and refractions is evident and clearly obscures the recording of reflections with a vertically incident arrival time less than 100 msec. The only event with apparent curvature on this seismogram does not even come close to fitting a model hyperbola with its apex at zero offset. This data set would produce coherent events if pushed through a CMP processing flow. None, however, would be reflections.

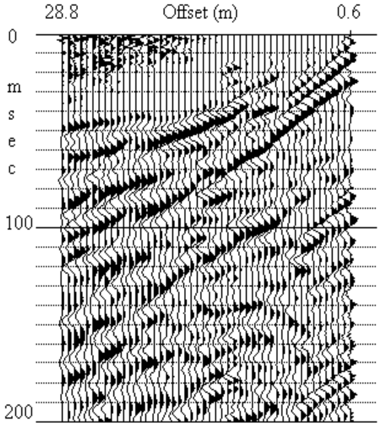

Figure 1. This four-shot stack of from a 7.3-kg sledge hammer with a 0.6 m trace spacing is saturated with direct and refracted energy. No arrivals possess a geometry appropriate for shallow reflections at this site.

Another situation where direct wave and refraction interference rules out the use of shallow seismic reflection is a case in Tennessee where the target was a 7 to 10 m deep bedrock surface with karst features (Figure 2). The bedrock was overlain by weathered, unconsolidated materials. With the velocity structure at this site the reflection from bedrock should arrive at times less than 40 msec. It is evident from inspection that no reflection is present at or near that time. A curved event with vertical incident time of around 20 msec could be fit to a hyperbola. However, this event is not a reflection; it generally mimics the direct wave, which also has a curved nature. This event could easily be called a reflection and would stack in on a CMP section. However, a combination of apparent NMO velocity, lack of unique geometry (in comparison to the direct wave), narrow bandwidth, and inconsistency with surrounding shots eliminates this event from being classified as a reflection.

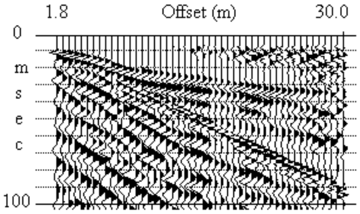

Figure 2. The obvious curvature of the direct wave is related to near-surface velocity and geometry. It is possible to NMO correct the waveforms in the 10 to 20 msec that precede the onset of the direct wave. The 0.6 m trace spacing provides abundant horizontal sampling.

Direct wave and refraction arrivals eliminate shallow seismic reflection as a tool to image the bedrock surface overlain by variable sand and clay layers at this California site (Figure 3). The cyclic nature of the refractions and lack of high frequency waveforms provide no optimum window for reflected arrivals. The shallower events, if present, are completely obscured by the direct wave, ground roll, and air-coupled wave which is dominant on the near-offset traces. This site can produce coherent events on CMP stacked sections but they will not be reflections. An interesting fact about this site is that the coherent events on a CMP stack (refractions) would mimic the very shallow geology.

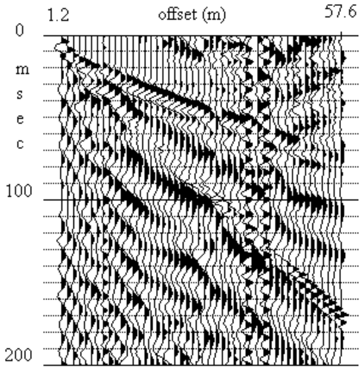

Figure 3. The 1.2 m trace spacing should allow identification of any coherent reflections arriving at this site with the upper 100 msec. The apparent curvature in the arrival that precedes the direct wave is related to near-surface velocity and line geometry not indicative of a reflection.

No optimum window exists on this shot gather from Nevada (Figure 4). The bedrock surface (0-65 m) and top of water table (10 to 20 m) are the targets of this survey. The near surface is extremely dry and consists of relatively unsorted colluvial materials. From borehole data in this area there appears to be little in the way of correlatable interfaces across distances as small as several hundred meters. Based on the arrival patterns, the NMO velocity model suggests all the reflections of interest should arrive in the upper 150 msec. It is not possible to distinguish any reflection arrivals from refractions or direct wave. All the energy recorded at this site appears to come from direct wave, refractions, and ground roll.

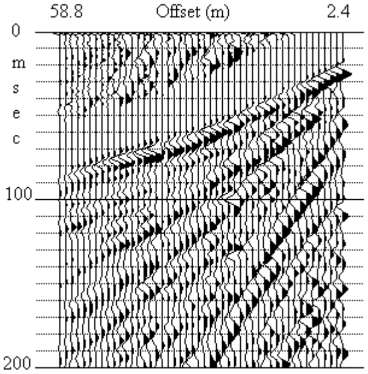

Figure 4. There are not even any candidates for a reflection on this four-shot stack with a 7.3-kg sledge hammer. The 1.2 m trace spacing allows confident identification of direct wave, ground roll, and refractions.

The velocity of the very near surface is extremely slow at this Nebraska site (Figure 5). The air-coupled wave clearly is the first arrival on this shot gather from the source location out to at least 12 m from the source. Refractions at this site could easily be mistaken for reflections if the air-coupled wave was incorrectly identified as a refraction or direct wave. The real refraction is accompanied by several linear arrivals with varying slope. The direct wave is quite prominent and possesses a velocity of around 200 to 250 m/sec. Also noteworthy on this gather are the high frequency wavelets evident at offsets less than 2 m and depths less than 40 msec. These high frequency waveforms are a result of energy saturation and will stack coherently on a CMP section. There are no reflection events interpretable on this shot gather, but processed CMP data at this site could easily produce coherent events on a CMP stacked section.

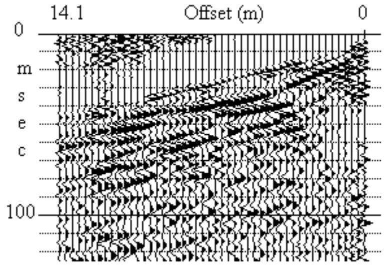

Figure 5. Air-coupled wave is the first coherent arrival from 0 m to more than 12 m source offset on this 30.06 shot gather. Data were acquired with 100 Hz geophones on 0.3 m spacing and a 220 Hz low cut (12-bit fixed-gain system).

The key reflection event should have a zero offset time of around 80 msec on this shot gather from Tennessee (Figure 6). The target at this site was a clay layer at about 30 m below ground surface. The materials between the clay and the surface are alternating sands and clay stringers. The upper 2 m at this site was covered with a clay cap and gravel layer. It is evident on the shot gather that the only arrival above the air-coupled wave is a short refraction segment that is likely from the clay fill material beneath a meter or so of surface gravel. No energy is apparent within the window for reflections at or around 80 msec. The source energy was an eight-shot stack from a sledge hammer and dug-in steel plate. Near-offset traces, which are preferred for reflection imaging, possess high amplitude surface wave energy without any indication that hyperbolic reflection arrivals are present. Some potential exists to record longer offset reflections if energy penetration was improved. No reflector with an arrival time less than 50 msec could be recorded at this site without dramatic increases in the data frequency.

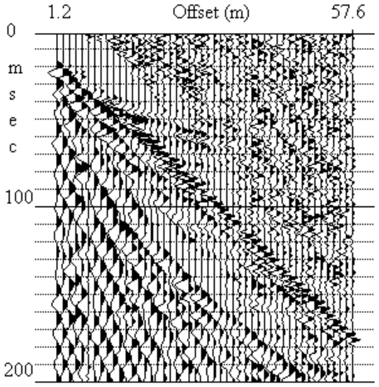

Figure 6. A pronounced air-coupled wave is evident on this scaled four-impact vertically-stacked sledge hammer shot gather. Close-offset traces (trace separation is 1.2 m) are saturated with direct wave, air-coupled wave and ground roll.

Conclusions

Shallow seismic reflection is a power tool that, with proper care and feeding, can dramatically enhance the subsurface understanding at certain sites. Like all geophysical techniques, there are near-surface settings that are not conducive to the near-vertical propagation of high frequency seismic waves and targets that are outside the abilities of seismic reflections at some sites and not at others. Careful evaluation of the site characteristics and targets of interest provide valuable insight into the feasibility of shallow reflection, but nothing can substitute for a careful and informed evaluation of field test data.

References

Gochioco, L.M. 1991, Tuning effect and interference reflections from thin beds and coal seams: *Geophysics*, 56, 1288-1295.

Goforth, T., and C. Hayward, 1992, Seismic reflection investigations of a bedrock surface buried under alluvium: *Geophysics*, 57, 1217-1227.

Hunter, J.A., S.E. Pullan, R.A. Burns, R.M. Gagne, and R.S. Good, 1984, Shallow seismic-reflection mapping of the overburden-bedrock interface with the engineering seismograph–Some simple techniques: *Geophysics*, 49, 1381-1385.

Jefferson, R.D., and D.W. Steeples, 1995, Effects of short-term variations in near-surface moisture content on shallow seismic data: Soc. Expl. Geoph., 419-421.

Kalik, A.J., 1988, The effects of near-surface geology on shallow high resolution seismic data quality in northeastern Kansas: Masters thesis, University of Kansas.

Knight, R., and R. Nolen-Hoeksema, 1990, A laboratory study of the dependence of elastic wave velocities on pore scale fluid distribution: *Geophysical Research Letters*, 17, 1529-1532.

Marion, D., A. Nur, H. Yin, and D. Han, 1992, Compressional velocity and prosity in sand-clay mixtures: *Geophysics*, 57, 554-563.

Miller, R.D., V. Saenz, and R. Huggins, 1992, Feasibility of CDP seismic reflection to image structures in a 220-m deep, 3-m thick coal seam near Palau, Coahuila, Mexico: *Geophysics*, 57, 1373-1380.

Miller, R.D., D.W. Steeples, and M. Brannan, 1989, Mapping a bedrock surface under dry alluvium with shallow seismic reflection: *Geophysics*, 54, 1528-1534.

Miller, R.D., and J. Xia, 1997, Delineating paleochannels using shallow seismic reflection: *Leading Edge*, 16, 1671-1674.

Miller, R.D., J. Xia, J.M. Anderson, and D.R. Laflen, 1996, High resolution seismic surveys at Cherry Point Marine Air Base, Cherry Point, North Carolina: Kansas Geological Survey Open-file Report 96-4.

Pugin, A., H. Horstmeyer, and A. Green. 1995, High-resolution seismic mapping of glacial and proglacial sediments in the Swiss Molasse Basin: *In* Proceedings, 1st Meeting on Environmental and Engineering Geophysics, EEGS Suropean Section.

Pullan, S.E., and J.A. Hunter, 1985, Seismic model studies of the overburden-bedrock reflection: *Geophysics*, 50, 1684-1688.

Pullan, S.E., and J.A. Hunter, 1990a, Delineation of buried bedrock valleys using the optimum offset shallow seismic reflection technique: Soc. Expl. Geoph. Investigations in Geophysics no. 5, S.H. Ward, ed., *Vol. 3: Geotechnical*, 75-87.

Pullan, S.E. and J.A. Hunter, 1990b, Shallow shear-wave reflection tests: Soc. Expl. Geoph., 1, 380-382.

Robertsson, J.O.A., K. Holliger, A. Green, A. Pugin, and R. De Iaco, 1996, Effects of near-surface waveguides on shallow high-resolution seismic refraction and reflection data: *Geophysical Research Letters*, 23(5), 495.

Schieck, D.G., and S.E. Pullan, 1995, Processing a shallow seismic CDP survey: An example from the Oak Ridges Moraine, Ontario, Canada: *In* SAGEEP 95 Proceedings, Orlando, Florida.

Steeples, D.W., A.G. Green, T.V. McEvilly, R.D. Miller, W.E. Doll, and J.W. Rector, 1997, A workshop examination of shallow seismic reflection surveying: *Leading Edge*, 16, 1641-1647.

Steeples, D.W., and R.D. Miller, 1998, Avoiding pitfalls in shallow seismic reflection surveys: *Geophysics*, July/Aug., in press.