Near-Surface Seismic Reflection Applications

Don Steeples, The University of Kansas, Lawrence, KS USA

Abstract

Nonintrusive methods of gaining knowledge about the Earth's subsurface comprise several of the procedures used routinely in near-surface seismology, including reflection, refraction, and surface-wave analysis. During the early 1980s the advent of digital engineering seismographs designed for shallow, high-resolution surveys spurred significant improvements in engineering, mining, and environmental reflection seismology. Commonly, the reflection method is used in conjunction with other geophysical and geological tools and a well-planned drilling verification effort. To the extent that near-surface seismic methods can constrain shallow stratigraphy, geologic structure, engineering properties, and relative permeability, they are useful in groundwater, mining, environmental site characterization, and other civil engineering applications. Much of the improvement in shallow seismic surveys is related to advancements in instrumentation. Challenges remain, however, in developing ways to process near-surface seismic data sets that may contain attributes not seen in deeper petroleum surveys.

Introduction

In this paper, I provide one demonstration of the improvement in shallow reflection methods that has occurred over the past two decades. Two reflection data sets were collected above a known buried channel in the Blue River valley near Manhattan, Kansas, USA. The first data set was collected in the mid-1980s and the second data set was collected at the same site a decade later with more modern equipment.

For many reasons, knowledge concerning the Earth's shallow subsurface is of interest in groundwater, engineering, and environmental contexts. In recent years, shallow seismic reflection methods have been applied to near-surface geological problems including bedrock detection (Hunter et al., 1984; Miller et al., 1989), shallow fault detection (Treadway et al., 1988), shallow stratigraphy (Miller et al., 1995) and void detection (Branham and Steeples, 1988). Reflection methods have been employed for targets at depths of five meters or less (e.g., Birkelo et al., 1987; Bachrach and Nur, 1998; Baker et al., 1999). More recently, three-dimensional imaging of the shallow underground geology and stratigraphy has been successfully employed (Büker et al., 1998; House et al., 1996).

To a first approximation, the amount of energy reflected at a given boundary is dependent upon the contrast in the acoustic impedance of the two layers and the angle at which the wavefront meets the reflector. Acoustic impedance (Z) is defined as the product of the P-wave velocity (V) and the density (ρ) of each layer: $Z = (\rho V)$. The amount of energy reflected at normal incidence (where the wavefront is parallel to the reflector) is determined by the reflection coefficient (R).

$$R = (Z_2 - Z_1) / (Z_2 + Z_1)$$

where: Z_1 = Acoustic impedance of the upper layer and
Z_2 = Acoustic impedance of the lower layer

Therefore, if two consecutive layers show a contrast in acoustic impedance, reflections can result. In the case where the lower layer has a smaller acoustic impedance, the reflected wavelet will have reversed polarity in comparison to the incident wavelet.

Reflection surveys over a buried river channel

The buried river channel discussed below was known to be present on the basis of drilling performed in 1968 (Steeples, 1970). Typical depth to Permian-aged bedrock in the Blue River valley site located two km east of Manhattan, Kansas, USA, was about 15 to 18 meters. One test well out of more than 10 found bedrock at a depth of 35 meters. Seismic refraction methods fail at this site because of an intra-alluvial velocity inversion.

Two seismic reflection surveys were conducted at the same location along a country road and were intended to outline the buried river channel. The older survey was conducted in 1985 and the newer in 1995.

Figure 1 shows a field file from the older seismic survey. A reflection is very clearly present at a time of about 55 msec. The first arriving energy on this seismogram is the air blast, indicating that the near-surface P-wave velocity is less than 335 m/s. The 12-fold common midpoint processed seismic section (Figure 2) also shows the same 55 msec reflection. Near the Common Depth Points 250 and 300 on this seismic section a prominent diffraction-like pattern can be seen; it is caused by air-blast echoes from the recording truck.

Based on an uphole check-shot survey, the 55 msec reflection is an intra-alluvial reflection from a depth of only about 14 meters. We know from the uphole survey that the bedrock reflection from 35 meters depth should arrive at 86 msec. The acoustic impedance contrast at the bedrock interface is known to be quite large because the Permian-aged bedrock has a P-wave velocity of 3000 m/s or more, while the saturated alluvium has a P-wave velocity of less than 2000 m/s. Furthermore, the density of the consolidated sedimentary bedrock is about 2.4 g/cc whereas the density of the unconsolidated alluvium is probably less than 2.0 g/cc, which increases the acoustic impedance contrast even more. Why, then, do we not see a bedrock reflection, even with this large acoustic impedance contrast?

The answer lies in the dynamic range of the seismograph, which is no better than 66 dB with the 12-bit, fixed gain (i.e., not floating point) seismograph that was used in the 1985 survey. The data collected in figures 1 and 2 were collected with a 24 channel seismograph with 12-bit analog to digital (A/D) conversion. The seismic source was a 30.06 caliber rifle. The rifle provided a good signal to noise ratio of the 55 ms reflector, but did not have enough energy to penetrate to the bedrock reflector at 86 msec. Walkaway tests run with an 8-gauge Betsy seisgun could image the reflection at 86 msec, but only when the intra-alluvial reflection at 55 msec was clipped on the field records. Consequently, in this situation, the seismologist must choose which of the two reflections to use and cannot use both. Also, with only 24 channels available, the geophone intervals and shot-to-geophone offsets that were available did not allow maintaining good visual coherency on the field files for both reflectors.

Figure 3 is a field file recorded 10 years later with a 96-channel seismograph with 24-bit A/D conversion. In this field file we can see both the 55 msec reflection and the 86 msec reflection, as well as deeper reflections from limestone-shale interfaces at greater depths. In this case the dynamic range of the seismic system is limited by the noise in the cables and geophones, rather than by the A/D conversion. The potential dynamic range based only on A/D conversion is 138 dB, but sensor and connector noise limit the dynamic range to somewhere around 100 dB (Owen et al., 1988).

One problem with the reflection data in Figure 3 is that the two reflectors cross at trace numbers 33 and 75 on opposite sides of the shotpoint. Consequently, even though the system has sufficient dynamic range to see both the 55 ms and the 86 ms reflections, it is not possible to process the data in a single-pass fashion to optimally image both reflections because of normal moveout (NMO) stretch. If one concentrates the NMO and the resultant stacking on the shallow reflection, the deeper reflection disappears because of NMO stretch. If one concentrates on enhancing the deeper reflection, the NMO applied for the shallow reflection is far too little. This is the shallow reflection processor’s dilemma: which one to optimize.

One approach to solving the shallow reflection processing dilemma is to process the data twice to enhance the two reflections separately, optimizing each one with its own NMO. This results in two seismic sections, and then the two are added together as the last processing step (Rick Miller, Kansas Geological Survey, personal communication).

Figure 4a is a processed section in which the processor concentrated on the deeper reflection in order to see the buried alluvial valley. Figure 4b is an interpreted version of Figure 4a, showing the location of the buried channel. Access to land at the left end of the survey line was not available, so the left side of the buried valley is not defined in this figure. The right side and the floor of the buried valley, however, are well constrained by the data. The bottom of the valley is visible at reflection times of 85 to 90 msec. One additional confirmation well was drilled near CMP location 90 in which bedrock was encountered at 36 meters.

Conclusions

Increased dynamic range of seismographs has allowed near-surface seismologists to see more reflections on field files than could be seen in the early 1980s. However, the large velocity contrasts in the shallow subsurface provide processing challenges not seen on deeper seismic-reflection data sets. In the example shown here, a processor must focus either on the 55 msec intra-alluvial reflection or on the 86 msec bedrock reflection, but not on both simultaneously.

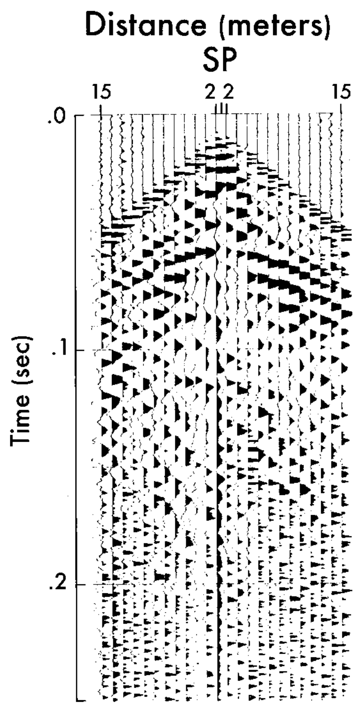

Figure 1. Field file from older survey using 24-channel seismograph with 12-bit A/D conversion. Note prominent intra-alluvial reflection at 55 msec. First-arrival energy is from air blast.

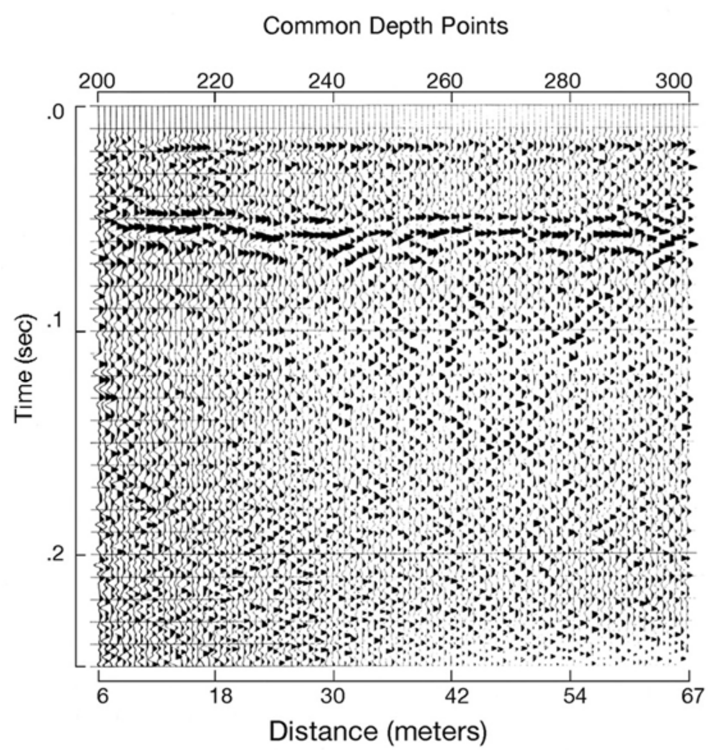

Figure 2. Intra-alluvial reflection at 55 msec in Blue River valley, Kansas, USA. Example of air-blast echo from recording truck at common depth points 246 and 298. The air-blast echo could be mistaken for a diffraction; in reality, the truck was moved from one location to another as the survey progressed. The line location corresponds to CMP locations 50 to 150 on Figures 4a and 4b. From Steeples & Miller, 1990.

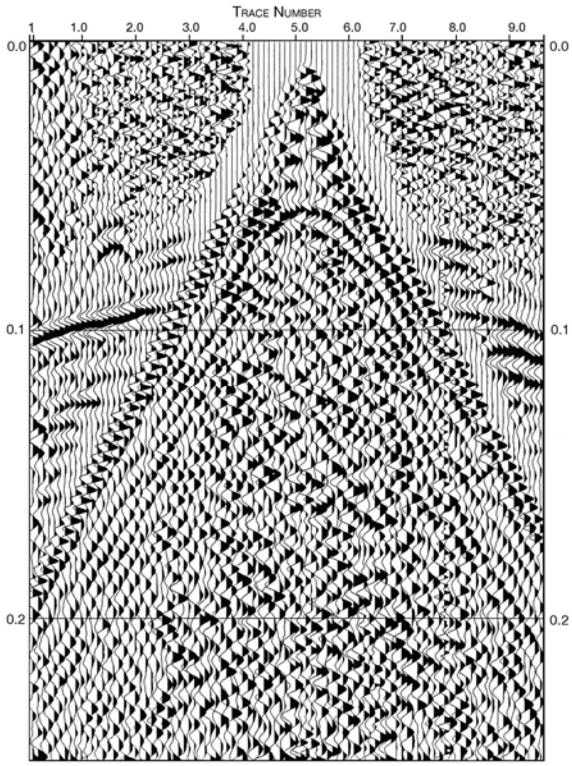

Figure 3. Field file from Blue River valley near Manhattan, Kansas, USA. Geophone interval was 1.2 meters. Note prominent reflections at about 60 msec and about 85 msec. The two reflections arrive at the same time at about trace 33 and trace 75, which makes processing to enhance both reflections difficult. Source: Surface Betsy Seisgun, single 3 oz. lead slug. Seismograph: Bison 24096, A/D 24 bits, 96 channels.

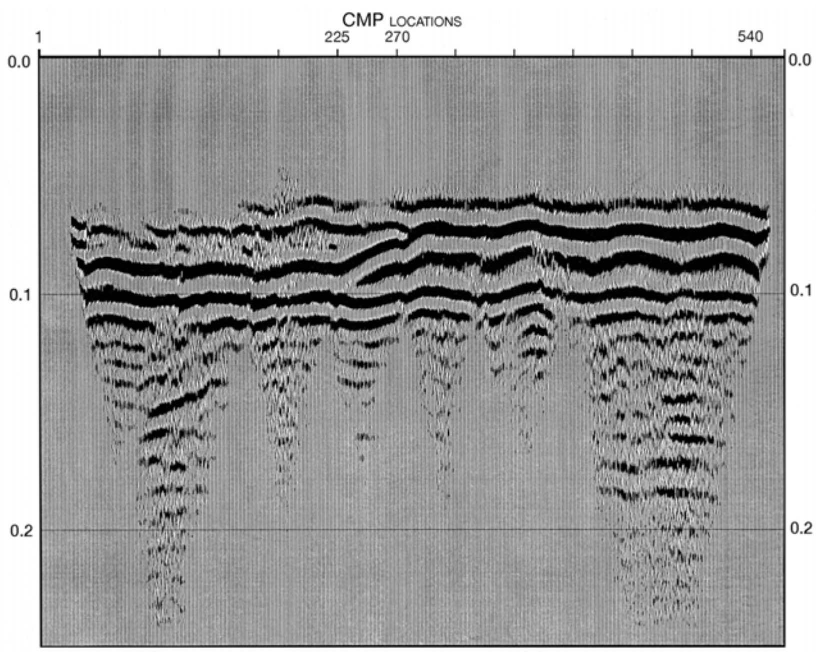

Figure 4a. Processed section from same location as data in Figure 1. A buried river channel is present between CMP locations 1 and 225 where depth to bedrock is about 35 meters. In contrast, bedrock between CMPs 270 and 540 is about 17 meters. (Processing courtesy of Greg Baker.)

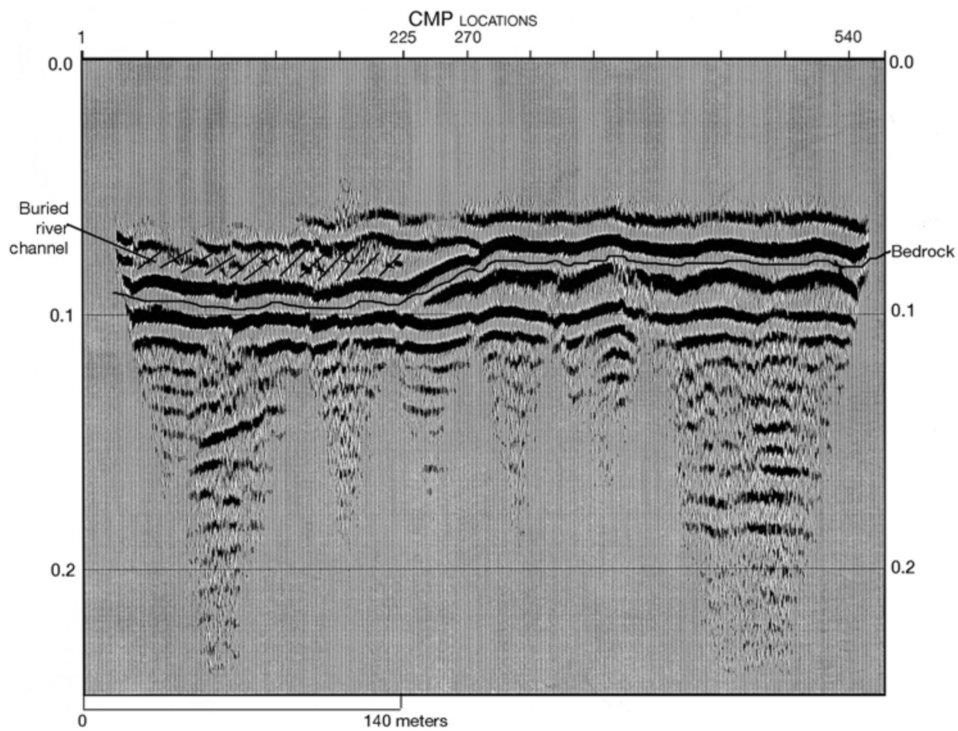

Figure 4b. Interpreted seismic section showing location of buried channel and of bedrock. The stacked data in Figure 2 were recorded between CMP locations 50 and 150 on this line.

References

Bachrach, R. and A. Nur, 1998. High-resolution shallow-seismic experiments in sand, Part I: Water table, fluid flow, and saturation. Geophysics, 63: 1225–1233.

Baker, G. S., C. Schmeissner, D. W. Steeples, and R. G. Plumb, 1999. Seismic reflections from depths of less than two meters. Geophys. Res. Letter, 26: 2, 279–282.

Birkelo, B. A., D. W. Steeples, R. D. Miller, and M. A. Sophocleous, 1987. Seismic reflection study of a shallow aquifer during a pumping test. Ground Water, 25: 703–709.

Branham, K. L. and D. W. Steeples, 1988. Cavity detection using high-resolution seismic reflection methods. Mining Engineering, 40: 115–119.

Büker, F., A. G. Green, and H. Horstmeyer, 1998. Shallow 3-D seismic reflection surveying: Data acquisition and preliminary processing strategies: Geophysics, 63: 1434–1450.

House, J.R., T. M. Boyd and F.P. Haeni, 1996. A case study for the acquisition, processing, and relevance of 3-D seismic data as applied to the remediation of DNAPL contamination. In Applications of 3-D seismic data to

exploration and production, Weimer, P. and Davis, T. L., eds. AAPG Studies in Geology No. 42, SEG Geophysical Developments Series No. 5, 257–265.
Hunter, J.A., Pullan S.E., Burns, R.A., Gagne, R.M., and Good, R.L., 1984. Shallow seismic reflection mapping of the overburden-bedrock interface with the engineering seismograph--some simple techniques. Geophysics 49: 1381–1385.
Miller, R. D., D. W. Steeples, and M. Brannan, 1989. Mapping a bedrock surface under dry alluvium with shallow seismic reflections, Geophysics, 54: 1528–1534.
Miller, R.D., N.L. Anderson, H.R. Feldman, and E.K. Franseen, 1995. Vertical resolution of a seismic survey in stratigraphic sequences less than 100 m deep in southeastern Kansas. Geophysics, 60: 423–430.
Owen, T. E., Parra, J. O., and O'Brien, J. T., 1988. Shear wave seismic reflection system for detection of cavities and tunnels (Exp. Abstr). Technical Program of SEG 58th annual meeting, 294–297.
Steeples, D. W., 1970. Resistivity methods in prospecting for groundwater. M.S. thesis, Department of Geology, Kansas State University, Manhattan, Kansas, USA.
Steeples, D. W. and R. D. Miller, 1990. Seismic-reflection methods applied to engineering, environmental, and ground-water problems. Soc. Explor. Geophys. volumes on Geotechnical and Environmental Geophysics, Stan Ward, ed., Volume 1: Review and Tutorial, 1–30.
Treadway, J. A., D. W. Steeples and R. D. Miller, 1988. Shallow seismic study of a fault scarp near Borah Peak, Idaho. Journal of Geophysical Research, 93,B6: 6325–6337.