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Special Issue

Shallow seismic reflection section—Introduction

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For those interested in shallow seismic reflection (SSR) techniques, this special issue of GEOPHYSICS is likely to serve as a useful reference for years to come. The idea for this issue grew out of discussions that took place at the Shallow Seismic Reflection Workshop at the Lawrence Berkeley Laboratory, California, in September 1996. The content of those discussions is the subject of a published report elsewhere (Steeples et al., 1997). Several workshop participants and their colleagues contributed to the papers in this issue as authors and as reviewers. The articles include case histories, novel uses of the SSR technique, state-of-the-art planning considerations for 3-D SSR surveys, and some examples of problems unique to SSR surveying.

With regard to SSR surveys as compared to those undertaken at greater depths, the physics of the earth remains constant; however, the relative importance of various aspects of the physics varies significantly between the two. For example, frequency filtering often can remove low-frequency surface waves from high-frequency SSR data, but this is not necessarily the case for reflection data gathered at greater depths. Conversely, removing shallow refractions from SSR data is a problem rarely encountered in deeper surveys.

The modern use of SSR methods can be said to have begun with Schepers (1975), who produced some excellent shallow P-wave reflection results in Germany that were not appreciated fully in North America until the 1980s. Even earlier, Evison (1952) had contemplated the problems and frustrations involved in detecting seismic reflections in the shallow zone.

Work by Pakiser and his colleagues at the U.S. Geological Survey appears to be the first published example of the successful use of seismic reflection at depths shallower than 50 m (Pakiser and Mabey, 1954; Pakiser et al., 1954; Pakiser and Warrick, 1956; Warrick and Winslow, 1960). This effort was abandoned because of the high cost of the surveys and because, in the absence of digital processing, the technique did not work well in many of the locations surveyed. In addition, Pakiser and his colleagues were called upon to implement a major program analyzing deep crustal structure to help detect underground nuclear explosions and to discriminate them from earthquakes, which diverted their efforts from shallow surveying. Indeed, little of significance concerning shallow seismic reflection appeared in the refereed literature between 1960 and 1975.

In the late 1970s and early 1980s, several groups made significant progress. For example, Hunter and Hobson (1977) noticed reflections on some shallow seismic refraction records. Following such observations, shallow seismic methods began to develop quickly, with the most rapid development occurring between 1975 and 1990. One of these developments, the optimum-window technique (OWT) of Hunter et al. (1984), is now used routinely in engineering, environmental, and groundwater applications, albeit with common-midpoint (CMP) processing rather than with their initial common-offset approach. The OWT specifically targeted the principal reflector of interest in terms of selecting appropriate geophone offsets, pre-A/D low-cut filters, geophones, and seismic sources. Also at about that time, Klaus Helbig and his students at the University of Utrecht in The Netherlands were making progress at a nearly ideal field-testing site in the Dutch tidal flats (Doornenbal and Helbig, 1983).

Surveying with shallow S-wave reflections has been done (e.g., Hasbrouck and Padget, 1982; Hasbrouck, 1991, Goforth and Hayward, 1992), but it has not been widespread. Separating S-wave reflections from the Love waves that usually arrive at the same time on seismograms has been and continues to be the major obstacle to progress in this area.

The limited number of channels (usually 24 or fewer) and the limited dynamic range (usually 60 dB or less) of engineering seismographs hindered SSR surveys throughout the 1980s. In addition, CMP data processing was prohibitively expensive until late in the decade, when personal computers began to be used for processing data (Somanas et al., 1987). The limitations of near-surface seismology in that era included imaging only one or two reflectors at the same time, recording with only a single component (usually vertical), and analyzing only a single phase or mode, usually P-waves.

Today, a growing number of universities, research laboratories, and contractors are using engineering seismographs possessing a dynamic range of more than 96 dB and 48 channels or

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more. Among the subsequent new opportunities are recording in three dimensions, employing three components, and examining more than one seismic mode at a time. The papers in this issue offer an overview of some of these developments along with the present state of the art.

HIGHLIGHTS OF THE SPECIAL ISSUE

"This Month in GEOPHYSICS" summarizes the papers contained in this issue, so I will not duplicate that effort. Although all of the papers contribute to the science of SSR, a few may be of special consequence to our readership and are thus singled out here.

Bachrach and Nur observed P-wave velocities in beach sands that are substantially less than half the P-wave velocity in air. Their work develops a firm theoretical foundation for the existence of these low P-wave velocities and, coupled with observations of P-wave reflections from a depth of about 2 m, provides an example of the detail attainable under favorable conditions using shallow seismic surveys.

Ghose and his colleagues present a number of successful shallow-reflection examples employing frequencies of several hundred Hz obtained by using a small, portable vibrator as a seismic source. They also report instances in which they were able to use diffractions to detect near-surface objects and voids.

Miller and Xia illustrate some of the problems unique to shallow reflection that are associated with normal moveout (NMO) correction of shallow reflections in the presence of extreme near-surface velocity gradients. Their solution to these problems is to process the data for each reflector separately and then to recombine the data sets following processing.

Büker et al. discuss shallow seismic-reflection data collected using a land streamer and gimbal-mounted geophones. A similar approach has been used for several years by Charles Reynolds, of C. B. Reynolds Associates in the southwestern USA, but Reynolds has not obtained the resolution shown by Büker and his group. The approach of Büker et al. to data collection is significant because it could lead to the efficient and cost-effective use of shallow-reflection surveys in terrains in which dragging a land streamer is viable.

Cardimona et al. show a comparison of shallow seismic reflection data and ground-penetrating-radar (GPR) data from the same depth along the same line. This may be the first paper in the refereed literature to display data generating credible images from both data types from within the same volume of earth material.

In concluding this section, I would like to highlight the paper on shallow 3-D reflection surveys prepared by Büker et al. This paper is significant because it shows that collecting a shallow 3-D data set properly requires substantial thought during the planning stage. The authors determined that large numbers of traces recorded at small shot-to-geophone offsets are required to obtain good images of the shallowest layers. Because of its inherently high cost, this requirement may be the single most significant deterrent to the widespread and cost-effective use of shallow 3-D reflection surveys.

THE LIMITS OF SHALLOW SEISMIC REFLECTION

Early in the history of seismic exploration, Clewell and Simon (1950) recognized the importance of high frequencies in high-resolution surveys by noting that "It is concluded that the more profitable advances in the improvement of the resolving power of the reflection seismograph will result from techniques that shorten and simplify the input signal, rather than from efforts to widen the band of usable frequencies. The elimination of the nonlinear displacements in the vicinity of the shot point appears to be an obvious approach." Currently, we understand that the information-carrying capacity of all seismic reflection data is directly proportional to reflection-frequency bandwidth, but we also know that the use of high frequencies is necessary to resolve shallow reflections (Widess, 1973).

High frequencies are also necessary to detect shallow reflections. The present, practical limits pertaining to resolution as well as to the minimum depth to which seismic reflection methods can be applied are demonstrated to some extent by the figure. This field file, which was subjected to low-cut frequency filtering only, displays a dominant reflection frequency of about 600 Hz. At the SSR workshop mentioned previously, none of the participants were aware of any seismic reflection data exhibiting dominant frequencies higher than 600 Hz when both the source and the receivers were placed at the surface. This frequency limit appears to constitute a research threshold that may not be surpassed easily.

The data in the figure display two reflections: a "deep" reflection representing the top of the saturated zone at 2.6 m below the surface, which was examined in detail by Birkelo et al. (1987), and a newly detected (1997) shallow reflection at a depth of slightly more than 1 m. These data were collected in the Arkansas River valley near Great Bend, Kansas, where more than a score of test wells have been drilled in one small area over the past 15 years, providing excellent geologic and hydrologic "ground truth."

The seismic P-wave velocity required to fit the reflection hyperbolas is about 250 m/s for both of the reflections. With a dominant frequency of 600 Hz, for example, the wavelength of these two reflections is about 0.4 m. Using the commonly applied 1/4-λ vertical-resolution criterion of Widess (1973), the vertical resolution attainable with the reflections in the figure is about 10 cm.

Two recording-parameter changes were critical in shifting the shallow-reflection threshold limit at Great Bend from 2.6 m to 1 m: moving the geophone interval from 25 cm to 10 cm and changing to a much smaller source. Even with the geophone interval at 10 cm, only about 40 of the 96 recording channels provided useful information about the hyperbolic curvature of the shallower reflection. Hence, moving the geophone interval to 5 cm would improve the imaging at 1 m.

The data from Birkelo et al. (1987) were collected with a 30.06-rifle source fired directly into the earth's surface through an air-blast containment device. The data in the figure were obtained with a .22-caliber rifle source using subsonic, .22-caliber, short ammunition. The end of the rifle barrel was placed about 15 cm below the surface, into a hole prepared by punching an iron bar into the ground. The difference in muzzle energy between the 30.06 rifle and the smaller .22-caliber rifle is more than an order of magnitude. In each case, nonlinear deformation results from the ground penetration of the bullet, but the .22 clearly disturbs a smaller volume of earth. This seems to support the approach to high-resolution sources suggested by Clewell and Simon in 1950.

In summary, shallow seismic reflection has come a long way over the past two decades, and the future looks bright. As the

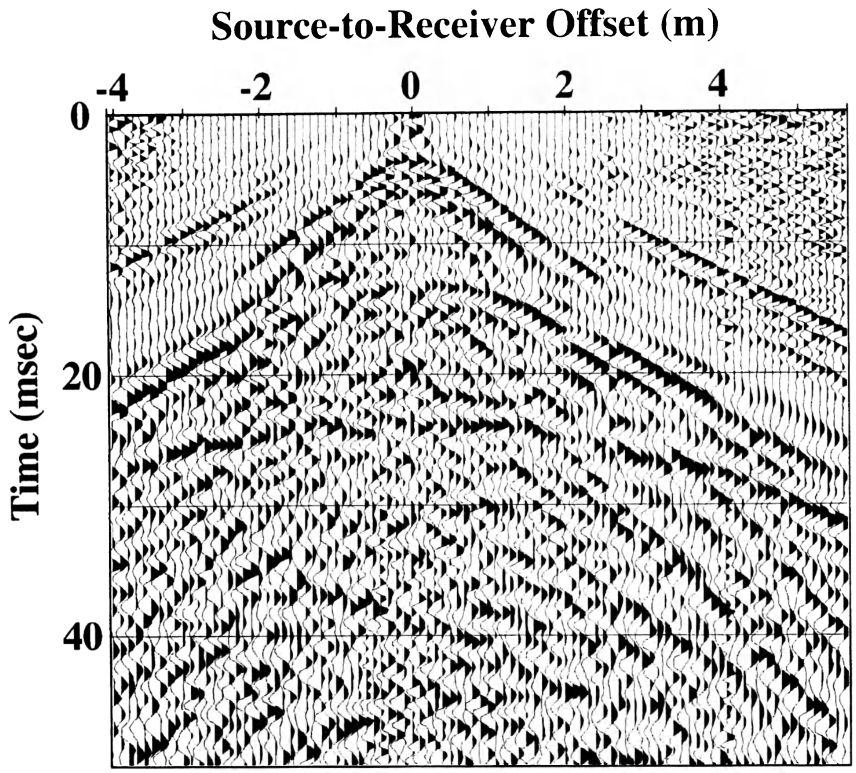

FIG. 1. Example of very shallow seismic reflection data collected 10/17/97 near Great Bend, Kansas. The source was a .22-caliber rifle fired downhole at a depth of about 15 cm, with a nominal off-line perpendicular distance of 8 cm. The geophone interval was 10 cm. Two prominent reflection events with zero-offset times of 14 ms (shallow) and 24 ms (deep) can be seen. The apparent hyperbolic event with a zero-offset time of 4 ms is direct P-wave energy. The event appears to be hyperbolic because of the offset between the geophone line and the tip of the rifle barrel (both vertically and horizontally). The shallow event is calculated to have been generated by a horizon at a depth of 1.5 m, and the deep event at a depth of 2.7 m. The deep event has been confirmed to be the water table by available well information. The dominant frequency of the reflected events is nominally 600 Hz. The first arrival is the air wave. Coherent noise prior to the air wave is from movement by the gun operator.

capabilities of electronic equipment continue to expand at relatively stable prices, new applications will evolve. In addition, data processing is likely to continue to become relatively less expensive for the foreseeable future. These factors, coupled with a growing cadre of experienced users and experimenters in many countries will lead to the development of new applications and improved techniques.

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REFERENCES

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

Clewell, D. H., and Simon, R. F., 1950, Seismic wave propagation: Geophysics: **15**, 50–60.

Doornenbal, J. C., and Helbig, K., 1983, High-resolution reflection seismics on a tidal flat in the Dutch Delta—Acquisition, processing and interpretation: First Break, **1**, No. 5, 9–20.

Evison, F. F., 1952, The inadequacy of the standard seismic techniques for shallow surveying: Geophysics, **17**, 867–875.

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

Hasbrouck, W. P., 1991, Four shallow-depth, shear-wave feasibility studies: Geophysics, **56**, 1875–1885.

Hasbrouck, W. P., and Padget, N., 1982, Use of shear-wave seismics in evaluation of strippable coal resources: Utah Geol. and Min. Surv. Bull., **118**, 203–210.

Hunter, J. A., and Hobson, G. D., 1977, Reflections on shallow seismic refraction records: Geoexpl. **15**, 183–193.

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

Pakiser, L. C., and Mabey, D. R., 1954, Mapping shallow horizons with reflection seismograph: Science, **119**, 740.

Pakiser, L. C., Mabey, D. R., and Warrick, R. E., 1954, Mapping shallow horizons with reflection seismograph, AAPG Bull., **38**, 2382–2394.

Pakiser, L. C., and Warrick, R. E., 1956, A preliminary evaluation of the shallow reflection seismograph: Geophysics, **21**, 388–405.

Schepers, R., 1975, A seismic reflection method for solving engineering problems: J. Geophys., **41**, 367–384.

Somanas, D., Bennett, B., and Chung, Y., 1987, Infield seismic CDP processing with a microcomputer. The Leading Edge, **6**, 24–26.

Steeples, D. W., Green, A. G., McEvilly, T. V., Miller, R. D., Doll, W. E., and Rector, J. W., 1997, A workshop examination of shallow seismic reflection surveying, The Leading Edge, **16**, No. 11, 1641–1647.

Warrick, R. E., and Winslow, J. D., 1960, Application of seismic methods to a groundwater problem in northeastern Ohio: Geophysics, **25**, 505–519.

Widess, M. B., 1973, How thin is a thin bed? Geophysics, **38**, 1176–1180.