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Effects of soil-moisture content on shallow-seismic data

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ABSTRACT

Repeated shallow-seismic experiments were conducted at a site on days with different near-surface moisture conditions in unconsolidated material. Experimental field parameters remained constant to ensure comparability of results. Variations in the seismic data are attributed to the changes in soil-moisture content of the unconsolidated material. Higher amplitudes of reflections and refractions were obtained under wetter near-surface conditions. An increase in amplitude of 21 dB in the 100–300 Hz frequency range was observed when the moisture content increased from 18% to 36% in the upper 0.15 m (0.5 ft) of the subsurface. In the time-domain records, highly saturated soil conditions caused large-amplitude ringy wavelets that interfered with and degraded the appearance of some of the reflection information in the raw field data. This may indicate that an intermediate near-surface moisture content is most conducive to the recording of high-quality shallow-seismic reflection data at this site. This study illustrates the drastic changes that can occur in shallow-seismic data due to variations in near-surface moisture conditions. These conditions may need to be considered to optimize the acquisition timing and parameters prior to collection of data.

INTRODUCTION

The objective of this study was to examine variations induced in shallow-seismic data by changes in the moisture content of near-surface material. Grantham (1990) observed significant variations in seismic data quality that appeared to correspond to short-term changes in moisture conditions. Recent work has found significant moisture-driven variations to be both site and source dependent (Jefferson, 1995). This paper presents results from one of three sites examined by Jefferson.

Source-earth and geophone-earth coupling are known to affect the signal characteristics of recorded seismic waves generated by a seismic source. Source coupling has been found to vary due to factors such as soil compaction and source relocation (Pujol and Smithson, 1991; Miller et al., 1992). Factors affecting geophone coupling include geophone mass, geophone size, soil density, sound-wave velocities (Wolf, 1944; Miller and Pursey, 1954; Bycroft, 1957, 1978; Lamar, 1970; Hoover and O'Brien, 1980), and soil firmness (Krohn, 1984). Changes in the moisture content of the near-surface material may also affect some of these factors. The effect of changing surface-moisture content has been noted in passing (Goforth and Hayward, 1992) for shallow-seismic work, but there appears to be a great deal of uncertainty as to the significance of such variation.

Other seismic work on seemingly unrelated topics has been affected by variations in near-surface water content. A study by Karageorgi et al. (1992) noted seasonal changes in seismic data while the investigators were searching for temporal variations in wave propagation related to earthquake prediction near Parkfield, California. They found seasonal fluctuations in traveltimes on the order of 15 to 20 ms for raypaths of about 6.5 km and 14.3 km (Karageorgi et al., 1992). Placement of sensors at the bottom of 25-m boreholes (below the zone of effective water-content variation) below the source locations showed that virtually all of the traveltime changes seen at distant receivers could be accounted for in the 25-m path though the near-surface material between the surface and the downhole sensors (Karageorgi et al., 1992). Whereas the zone of effective water-content variation and thickness of unconsolidated material in their study is much thicker than that expected in ours, the results presented here show clear traveltime effects caused by the same types of variations.

A verification and closer examination of shallow-seismic reflection data quality versus moisture content may aid in the understanding of the nature of the possible changes. Significant changes in data quality with moisture content may introduce a new factor in the planning of shallow-seismic surveys that may

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be helpful in dealing with some of the problems encountered in certain locales. Indeed, differences found to occur under certain moisture conditions may prove to be significant enough in some instances to warrant planning survey operations around local soil-moisture conditions.

SITE CHARACTERISTICS

Data were collected from a site in Lawrence, Kansas, on the campus of the University of Kansas (Figure 1) at a culturally quiet location. Near-surface material at this site consists of a 0.35-m-thick (14-inch-thick) surface zone consisting of a silty-clay loam underlain by a more clay-rich soil unit to a depth of 1.8 m (6 ft) (Dickey et al., 1977). The soil cover is directly underlain by sandy-shale sediments of the Lawrence Shale (Keiswetter and Steeples, 1995). Deeper bedrock lithologies consist of relatively flat-lying Pennsylvanian shale, limestone, and sandstone.

PROCEDURES

A Bison model 24096 seismograph, which is a fixed-gain system with 24-bit analog-to-digital (A/D) conversion, was used to record all of the seismic data in this study. Consistent recording parameters were maintained during all data acquisition. A 0.25-ms sample interval was used and a 192-Hz, low-cut, pre-A/D frequency filter was employed.

The receivers used were groups of three undamped 40-Hz natural-frequency Mark Products geophones on 14-cm (5.5-inch) spikes, wired in series, and spaced 7.6 cm (3 inches) apart. A consistent geophone group spacing of 1.22 m (4 ft) was maintained during each individual test.

A Betsy seisgun (Miller et al., 1986) firing 8-gauge lead slugs was used as the seismic source. A consistent minimum source-to-receiver offset of 1.8 m (6 ft) was maintained during each test.

A series of five seismic experiments was performed between May and September 1995 using these consistent parameters. Each experiment consisted of acquiring data from a 2-D seismic line. Each line was arranged parallel to, but perpendicularly offset from, the others. This was done to avoid source effects that may have been imparted by the previous experiment. The average distance between subsequent lines was about 0.6–0.9 m (2–3 ft).

A series of soil samples was collected during each experiment using a simple, manual soil corer. Samples were recovered from shallow depths including 0.025 m (1 inch), 0.13 m (5 inches), 0.30 m (1 ft), 0.46 m (1.5 ft), 0.61 m (2 ft), 0.76 m (2.5 ft), and 0.91 m (3 ft). The samples were taken at multiple locations along the seismic lines during each experiment to produce an average overall sample for each experimental day and for each depth. Sample locations remained fixed relative to the location of the specific seismic line being studied during each individual period of data acquisition. That is, when a seismic line was moved 0.6 m (2 ft) from the previous seismic line, the soil-sample locations were also moved the same distance in the same direction.

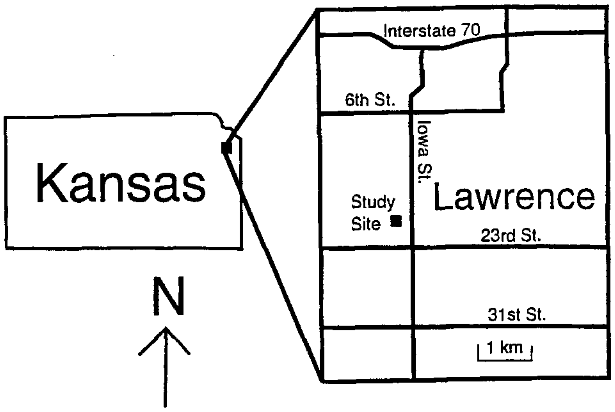

FIG. 1. Location of the study site.

When the soil samples had been collected, the average moisture content of each sample depth was determined using standard gravimetry with oven drying, as discussed by Gardner (1986). The level of precision obtainable using this routine procedure is around ±0.5% water content (Gardner, 1986).

The series of experiments was planned to address some key questions: (1) are the results repeatable, and (2) how much soil moisture is needed to produce a variation in the quality of seismic data?

RESULTS

Repeatability of Results

Before valid inferences could be made concerning the variations in seismic data quality that were produced by changes in soil moisture, variations related to experimental error under the same conditions had to be determined. To examine this variability, two seismic experiments were conducted on the same day at the study site. These experiments were conducted using the same equipment and parameters, with the geophones and the source simply moved laterally by 3 m (10 ft). This produced data from two parallel seismic lines that could then be examined and compared.

Figure 2 shows the two trace-normalized records that were recorded from the repeated experiments with the Betsy seisgun as a seismic source. The overall similarity of the records is apparent. The seismic characteristics from one record can be seen in the other, although there are some variations. Figure 3 shows the averaged amplitude-frequency spectra associated with identical parts of the two time-domain records. The time interval investigated in this figure lies above any air-blast contamination and is dominated by refraction and reflection information. The two spectra share similar characteristics. The average amplitude difference between the two in the 100–300-Hz frequency range is 6 dB, which we believe is our level of experimental error. This error is undoubtably due to factors such as differences in geophone plants, shot placement, variations in shell loads, slight variations in moisture content associated with the two lines (due to factors such as microdrainage patterns), etc.

Effects of Varying Soil-Moisture

Table 1 shows the moisture contents for each sample depth from all of the experiments. The water content associated with experiment A was significantly higher than that from any other experiment, especially within the upper 0.15 m (0.50 ft) of the subsurface. This upper 0.15 m (0.50 ft) is especially important for the Betsy seisgun. It is assumed that coupling efficiency of the Betsy seisgun is most affected by the water content in this region because this is the depth of greatest plastic deformation.

This depth range also is important to the average geophone coupling efficiencies. Table 2 shows the average water content of each of the experiments in this crucial upper 0.15 m (0.50 ft) of depth [average of measurements made at 0.025 m (1 inch) and 0.13 m (5 inches)]. Figure 4 shows the precipitation that was measured approximately 1.5 km from the study site over the period during which the experiments were conducted.

Figure 5 shows seismic-records that were acquired during each of the five (5) individual seismic experiments. Identical scaling has been applied to all traces within this figure. The identical scaling allows true-amplitude comparisons among the various signals. The water content in the upper 0.15 m (0.50 ft) of the subsurface associated with each record is also noted in the figure. The amplitudes of the wettest-soil record (water content of 36.6%) and the damp-soil record (water content of 26.3%) are larger than those for the other, drier-soil records (water contents of 18.8%, 21.5%, and 21.9%). The record acquired under the wettest condition (water content of 36.6%) displays a large-amplitude, ringy character that dominates the upper portion of the record. This is markedly different from what appears in any of the other records and is likely to result from source and/or receiver effects influenced by a change in the soil moisture.

Figure 6 shows the amplitude spectra of identical portions of the time-domain records. Care has been taken to ensure that identical-offset traces were examined. Because a single bad trace existed in one of the records (obtained under conditions of 21.9% water content within the upper 0.15 m of the subsurface), the trace corresponding to this offset was removed from all records. In general, a trend of higher amplitudes with higher water content is evident.

The overall average increase in amplitude in the 100–300-Hz frequency range between the records with the highest and lowest water contents is approximately 21 dB. Although the

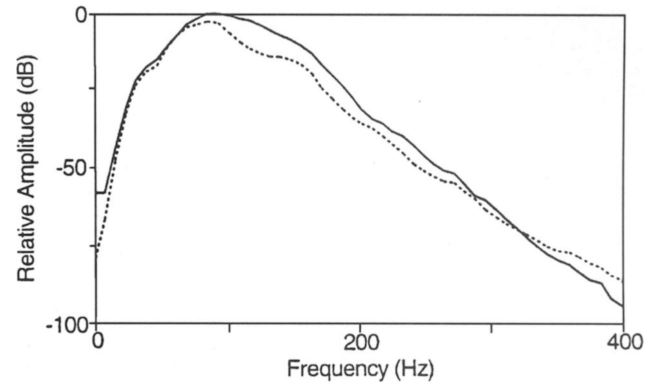

FIG. 3. Amplitude-frequency spectra from same-day seismic experiments shown in Figure 2. The examined signal includes everything arriving before possible air-blast contamination (everything above an approximate line extending from 0 ms at the near offsets to about 200 ms at the farthest offset). These spectra have been smoothed with a 25-point averaging function.

Table 1. Average water content of collected samples.

Experiment	Water contents (%) measured at various depths of the subsurface						
	0.025 m	0.13 m	0.30 m	0.46 m	0.61 m	0.76 m	0.91 m
A	41.5	31.8	31.3	27.9	26.7	22.8	23.6
B	25.7	26.9	30.9	27.9	26.1	25.0	24.2
C	17.1	20.4	24.0	21.8	21.1	21.4	22.5
D	20.8	22.2	22.2	21.9	20.2	19.9	22.0
E	21.8	21.9	23.5	20.1	19.3	19.5	20.7

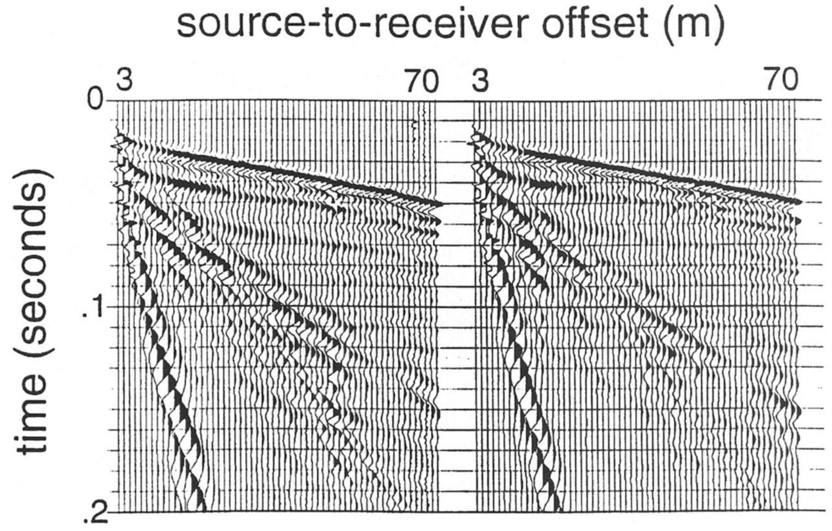

FIG. 2. Repeated records obtained on the same day after moving the seismic line 3 m (10 ft). All other recording parameters remained fixed.

time-domain record (see Figure 5) acquired under the conditions of the highest water content contains the greatest amplitudes, it also contains large-amplitude ringy wavelets. The record associated with a water content of 26.3% within the upper 0.15 m (0.50 ft) of the subsurface is probably the best data acquired at this site.

An explanation for the severe ringing seen in the record associated with a moisture-content of 36.6% within the upper 0.15 m (0.50 ft) of the subsurface may be related to the liquid or Atterberg limit of the soil at the site. The liquid limit refers to the moisture content at which soil passes into a liquid state (Dickey et al., 1977) in which the soil becomes predominantly supported by the liquid and the grains are not in direct contact with each other. The upper 0.25 m (10 inches) of soil at this site was found to have a liquid limit of about 35% (Dickey et al., 1977). Thus, during the acquisition of the record obtained

Table 2. Average water contents of samples from the upper 0.15 m (0.50 ft) of the subsurface.

Experiment	Water Content (%)
A	36.6
B	26.3
C	18.8
D	21.5
E	21.9

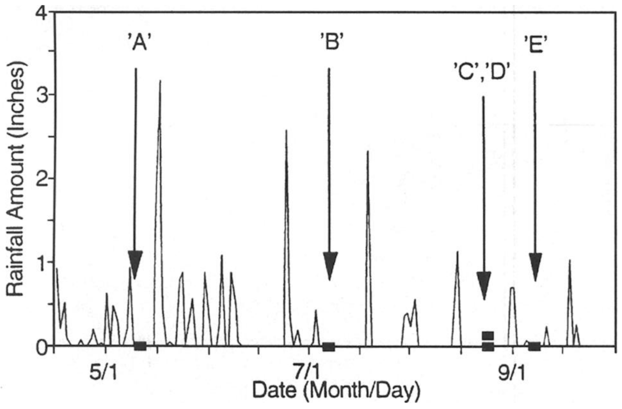

FIG. 4. Precipitation measured approximately 1.5 km (1 mile) from the study site over the period during which experiments were conducted. Arrows and letters indicate the experiment dates (all during 1995). Precipitation measurements were obtained from the University of Kansas Weather Service.

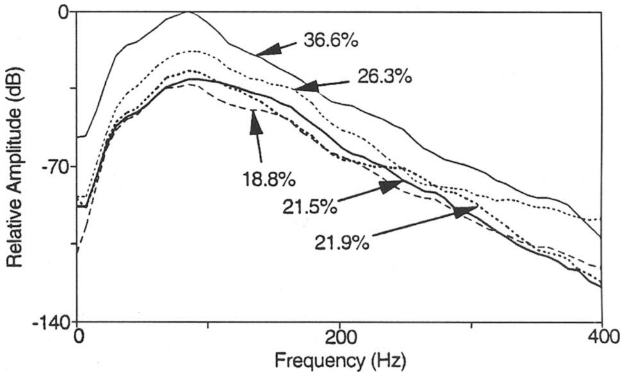

FIG. 6. Amplitude-frequency spectra from identical portions of all the seismic experiments (records shown in Figure 5). The examined signal includes everything arriving before possible air-blast contamination (everything above an approximate line extending from 0 ms at the near offsets to about 200 ms at the farthest offset). These spectra have been smoothed with a 25-point averaging function. Average water contents within the upper 0.15 m (0.5 ft) of the subsurface are indicated.

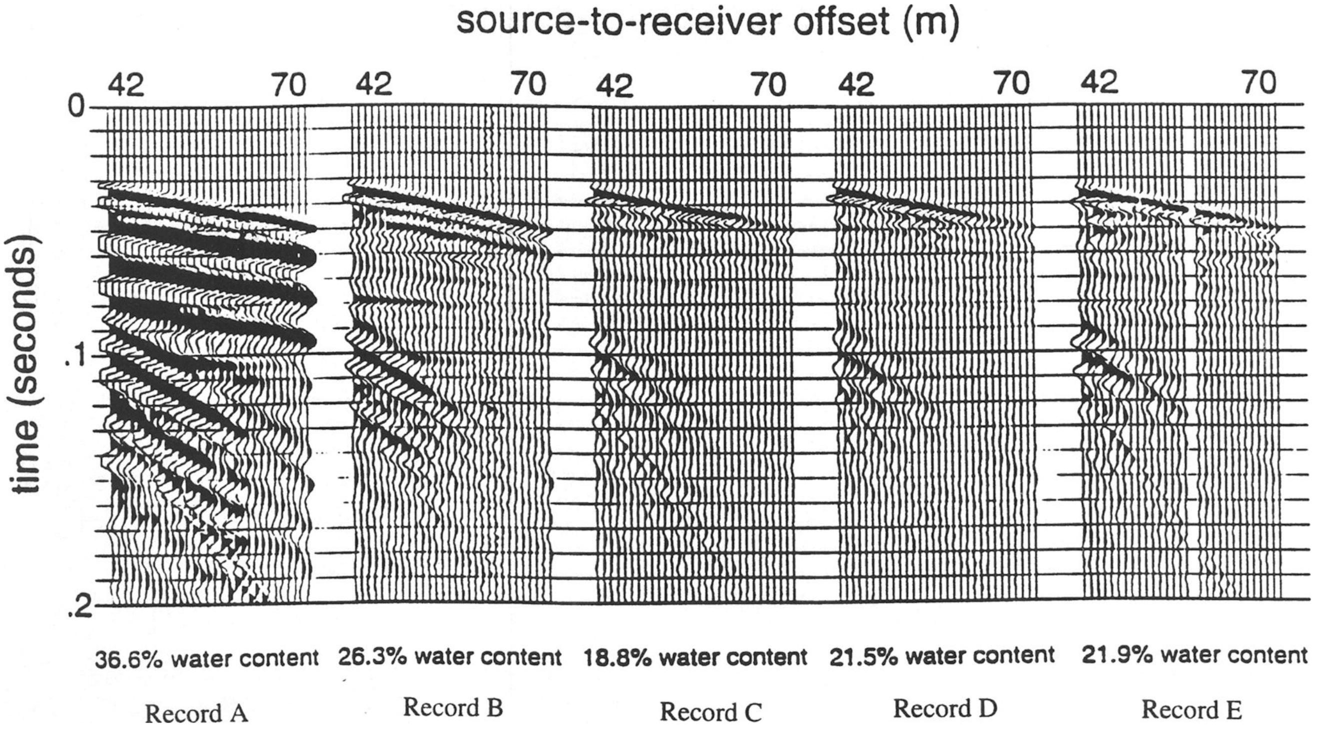

FIG. 5. Identically scaled records obtained under varying soil-moisture conditions. The indicated water contents are the average values found from samples within the upper 0.15 m (0.5 ft) of the subsurface.

when soil moisture was 36.6%, the shot-impulse–stressed soil would have behaved as a liquid or semiliquid. A shot within such material could result in oscillations within the zone of nonlinear deformation near the moving projectile. This may partially explain the ringing seen in the wettest-soil record.

Figure 7 shows the record from Figure 5 after application of digital frequency filtering and first-arrival muting. The relatively gentle bandpass filter contained a lower shoulder frequency of 225 Hz with a 9.4-dB/octave rolloff, and an upper shoulder frequency of 230 Hz with an 11.5-dB/octave rolloff. It was specifically designed to emphasize the reflection event at 80 ms. The first-arrival mute has been applied to remove most of the refraction energy from the top of the records so that the deeper reflections can more easily be viewed.

The frequency filter improved the appearance of the targeted reflection, especially in the wettest soil record (compare with Figure 5). The amplitudes of this reflection are visibly greater in this wettest-soil record than in any other record. This may be expected given the amplitude-frequency spectra in Figure 6, which showed that the wettest-soil record contained consistently higher amplitudes across the examined frequency range. These filtered time-domain records show that the wettest soil record contains the largest amplitude signal from the 80-ms reflection; but that it may be obscured on the raw data unless specifically designed filters (analog or digital) are applied. We also note that a reflection at 105 ms is most easily seen on the wettest soil record in Figure 7.

For some targets (such as the 80-ms reflection), the larger reflection amplitudes that can be obtained by further processing may make data acquisition during the wettest possible period desirable. In some cases, however, the large-amplitude ringing may interfere with specific targets and may reduce the quality of the appearance of raw field data. For studies targeting these specific events or a wider range of events, an intermediate soil-moisture content may be the most conductive for seismic data acquisition.

DISCUSSION AND CONCLUSIONS

A pattern of behavior between seismic data and the moisture content of the near-surface material during data acquisition was observed at this site using the Betsy seisgun as a seismic source. For this source at this site, it was found that the water content within the upper 0.15 m (0.50 ft) of the subsurface appears to exert considerable control over absolute amplitudes of seismic P-waves.

In the seismic data collected under different soil-moisture conditions, an increase of about 21 dB was observed in the 100–300-Hz frequency range for a water-content increase of about 17% within the upper 0.15 m (0.50 ft) of the subsurface. This amplitude variation is significantly greater than the experimental error level, which is about 6 dB. Therefore, much of the change is inferred to result from the variations in near-surface moisture content.

The increase in amplitude did not, however, necessarily translate into better appearing data with the general recording parameters used at this site. The record that displayed the largest amplitudes contained the large-amplitude ringy wavelets that resulted in a poor overall appearance for the raw data. This large-amplitude ringing may result from the transition of the shot-stressed soil to a liquid or semiliquid state in the vicinity of the moving source projectile at moisture contents comparable to those measured during the acquisition of the wettest soil data. The wettest soil record shows that, for certain sources at certain sites, too much moisture can result in a degraded appearance of the raw data. However, these data may contain higher quality information for specific targets upon further processing (Figure 7).

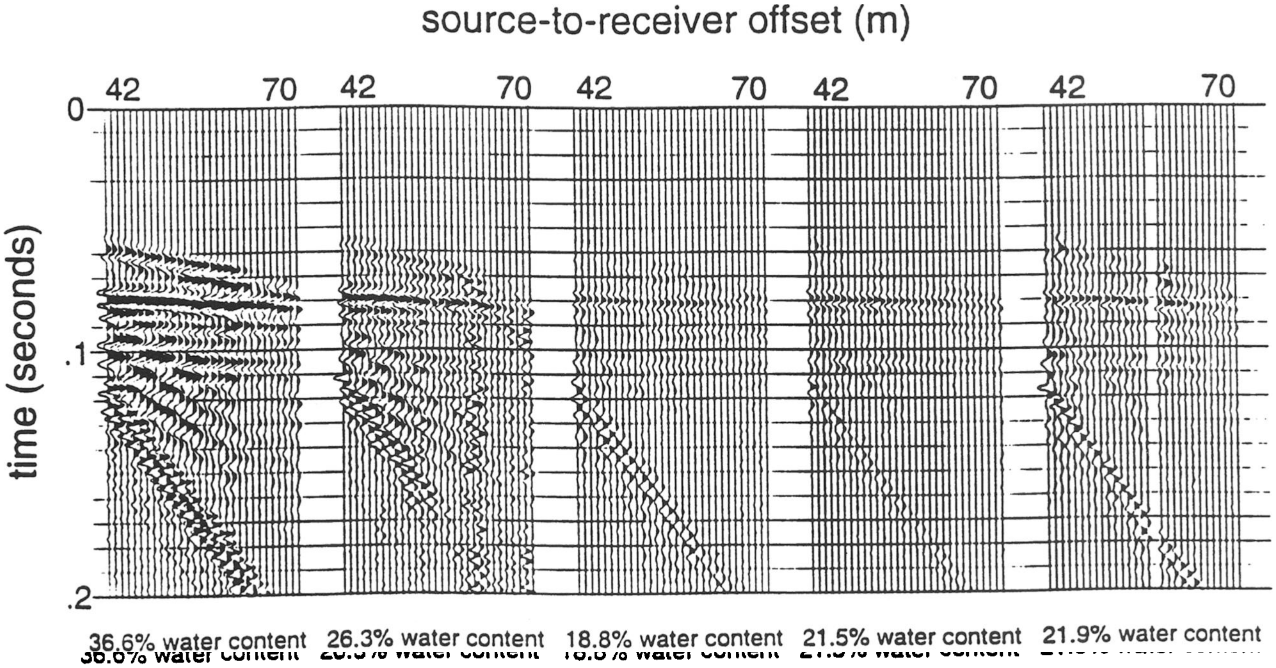

FIG. 7. Identically scaled records obtained under varying soil-moisture conditions. First-arrival muting and frequency filtering has been applied. The indicated water contents are the average values found from samples within the upper 0.15 m (0.5 ft) of the subsurface.

The water content of the upper 0.15 m (0.50 ft) can be greatly affected by single rainfall events. Therefore, the appearance of data collected after rainfall events may be drastically different from data collected after prolonged dry periods. In general, the amplitude of reflection signals was observed to increase with increasing surface soil-moisture content careful thought should be given to overall planning and to selecting the recording parameters and processing steps used for data collected under different moisture conditions. In some cases, the wettest soil conditions may produce interference of reflected and refracted seismic signals, and the desired data may be unobtainable due to limitations of the system's dynamic range. Under these circumstances, an intermediate soil-moisture level may provide the most favorable conditions for the acquisition of seismic data.

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