

Detecting voids in a 0.6 m coal seam, 7 m deep, using seismic reflection

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ABSTRACT

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Surface collapse over abandoned subsurface coal mines is a problem in many parts of the world. High-resolution P-wave reflection seismology was successfully used to evaluate the risk of an active sinkhole to a main north–south railroad line in an undermined area of southeastern Kansas, USA. Water-filled cavities responsible for sinkholes in this area are in a 0.6 m thick coal seam, 7 m deep. Dominant reflection frequencies in excess of 200 Hz enabled reflections from the coal seam to be discerned from the direct wave, refractions, air wave, and ground roll on unprocessed field files. Repetitive void sequences within competent coal on three seismic profiles are consistent with the “room and pillar” mining technique practiced in this area near the turn of the century. The seismic survey showed that the apparent active sinkhole was not the result of reactivated subsidence but probably erosion.

INTRODUCTION

Detection of subsurface cavities by methods other than drilling is of interest to geologists and engineers in many parts of the world. Recent advances in high-resolution reflection seismology can be applicable to shallow cavity detection (Hunter et al., 1984; Branham and Steeples, 1988; Steeples and Miller, 1987, 1990). Recorded energy with a dominant frequency greater than 100 Hz is needed to detect targets shallower than 30 m using P-wave reflection seismology. High frequencies increase the resolution of the survey allowing shallower, smaller features to be detected and possibly delineated (Widess, 1973). These higher-than-normal frequencies have been attained in nonmarine environments using nonstandard seismic sources and severe low-cut analog filtering (Jongierius and Helbig, 1988; Birkelo et al., 1987; Miller et al., 1989; Pullan and Hunter, 1990). The extreme contrast of elastic properties between a void (water or air-filled) and the surrounding rocks provides an excellent reflecting interface.

Gradual earth subsidence forming shallow sinkholes is common in heavily undermined areas of southeast Kansas. The gradual collapse of near-surface material into voids commonly less than 5 m in diameter in the 7–10 m deep and 0.6–1.0 m thick Weir–Pittsburg coal generally results in sinkholes less than 3 m in diameter and 0.3 m deep. Most of these subsurface voids are remnants of the “room and pillar” mining method commonly used in this area.

The accelerated rate of subsidence of a previously dormant sinkhole within 20 m of a set of heavily used railroad tracks near Scammon, Kansas, USA, represented a potential risk to rail traffic. An approximately four-fold increase in the surface area of this sinkhole, predominantly toward the railroad tracks over a period of two months, suggested possible reactivation of subsid-

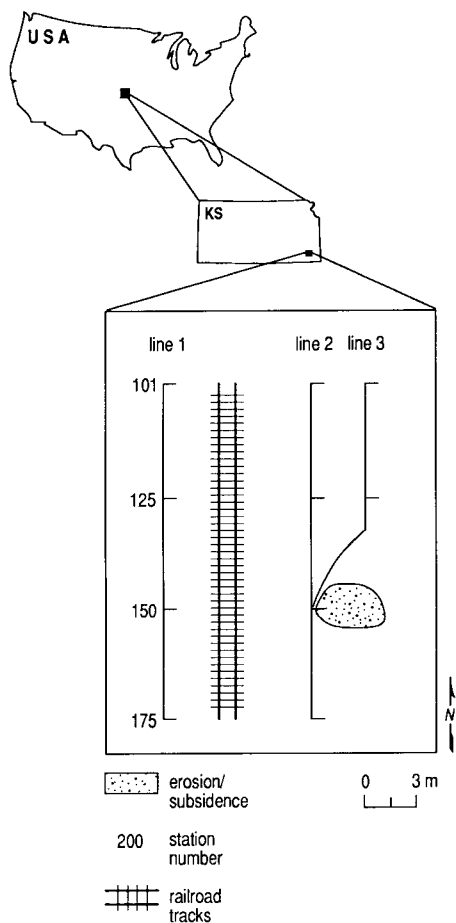


Fig. 1. Location map showing surface subsidence feature with respect to the seismic lines and railroad tracks.

ence. To determine appropriate remediation and ensure the structural integrity and safety of the tracks, it was necessary to locate precisely the mine shaft responsible for the sinkhole.

A seismic survey was designed to maximize the potential for locating horizontal shafts associated with the observed subsidence that might cross beneath the north-south railroad tracks (Fig. 1). A preliminary seismic profile was collected to determine the optimum acquisition parameters for future production lines. Two production lines (lines 1 and 2) were then acquired parallel to and on opposite sides of the tracks, centered on the active sinkhole. The acquisition parameters used on the two production lines were designed to allow direct detection of any subsurface void present beneath the seismic lines. Confident correlation between the two production seismic lines is possible if the trend, size, and distance between horizontal shafts crossing beneath the tracks are relatively consistent.

GEOLOGICAL SETTING AND FIELD PROCEDURES

The Weir-Pittsburg coal bed has an average thickness of 1 m in southeastern Kansas. It is located within the lower portion of the Cabaniss Formation, which is part of the Pennsylvanian (Carboniferous) Cherokee Group. The various phases of the Cherokee cyclothems are best interpreted as facies of alluvial-deltaic complexes, the repetitive nature being due to delta shifting and distributary abandonment (Heckel et al., 1979). The Cherokee coals are the culmination of aggrading sedimentation of delta plains. The Weir-Pittsburg coal bed was extensively mined until about 1940 by both subsurface and strip-mining methods. As a result of the subsurface mining, large areas of southeastern Kansas are underlain by a maze of interconnected cavities.

The data were collected using a standard CDP acquisition method. The source-and-receiver spacings were 0.6 m. The source was a downhole .30-06 single-shot rifle with its barrel 0.1 m below the ground surface in a 3 cm diameter borehole about 0.2 m deep. The receivers were two 100 Hz geophones on 14 cm spikes, connected in series with a 0.3 m in-line spacing. The optimum recording window (Hunter et al., 1984) and acquisition parameters (Knapp and Steeples, 1986) were selected from walkaway tests with source-to-receiver spacing ranging from 0.3 m to 37 m on 0.3 m intervals and low-cut filters of 240 Hz, 340 Hz, and 480 Hz. Maximum recordable reflection frequencies were maintained partly as a result of careful attention to source-and-receiver ground coupling throughout the acquisition phase.

The data were recorded on an I/O DHR-2400 seismograph. The fixed-gain data were converted analog-to-digital (A/D) into an 11-bit plus sign value and then stored on magnetic tape in modified SEG-Y format. The recording system amplifiers have 72 dB of dynamic range with a 120 nV RMS noise level. The anti-alias filters used have a 60 dB/octave roll-off with a -60 dB

point of 2000 Hz. A pre-A/D low-cut filter with a 24 dB/octave roll-off and a -3 dB point of 340 Hz was used to maximize potential resolution and reduce the effects of ground roll. The selected low-cut filters were essential to the quality and success of this survey.

DATA PROCESSING

The data were processed on a Data General MV-20,000 computer (using basic CDP seismic-processing techniques). Special emphasis was placed on defining and applying a digital bandpass filter optimizing the spectral difference between voids and intact coal. A subtle difference can be observed on the CDP stacked sections between the dominant frequency of reflections from the coal seam and reflections, or a lack of them, from the interpreted void area. This observation is consistent with other documented studies in this area (Branham and Steeples, 1988). The primary processing procedures performed on the seismic data were focused on enhancing reflection information identified within the upper 40 ms on field files (common shot gathers).

Surgical muting of noise would have been detrimental to the reflection information, which was concentrated in time and offset windows rich in refraction, direct-wave, and air-wave energy. Changes in reflection wavelet characteristics between coal and void are difficult to identify and analyze on unprocessed field files. Reflection energy (or lack of it) from voids is not sufficiently distinctive to isolate it from random noise on field files. The lack of muting demands careful attention during each of the data processing phases to avoid misidentification and possible enhancement of non-reflection energy.

Digital bandpass filtering proved to be the key to enhancing reflection energy (or lack of it) from the coal seam and voids. The CDP stacking process alone did not enhance reflections from coal or void in the upper 40 ms. A digital low-cut filter with zero percent amplitude point in excess of 200 Hz was necessary to isolate reflections definitively from within the coal seam on the CDP stacked sections.

Static anomalies associated with variable near-surface velocity can be observed on some field files (Fig. 2). A surface-consistent statics routine was used to minimize the effects of near-surface irregularities. Static problems on most field files were subtle and did not represent a significant obstacle in producing accurate CDP stacked sections.

Normal moveout (NMO) sample stretch was less than or equal to 15 percent. The NMO stretch mute was selected through iterative analysis. All samples were zeroed when relative stretch greater than 15 percent of the sample interval after NMO correction was encountered. Incorrect maximum sample stretch can decrease the dominant frequency as well as apparent amplitude and distort phase sufficiently to hamper the interpretation of the coal-seam reflection.

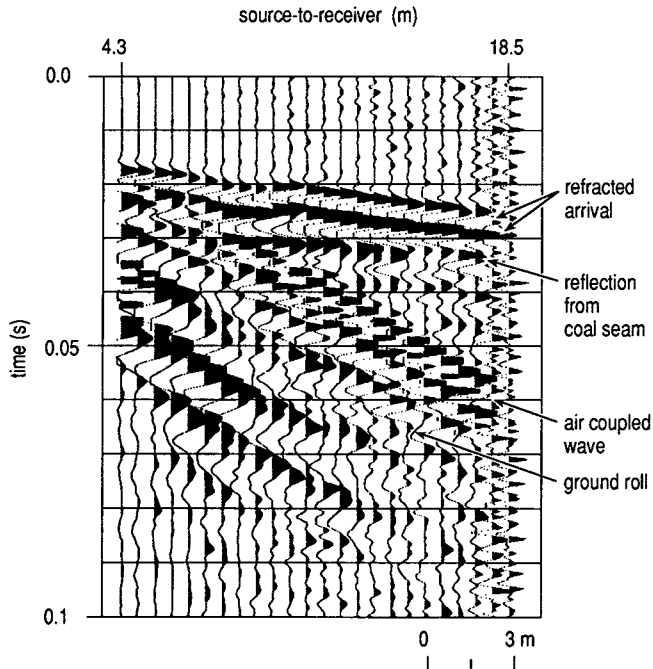


Fig. 2. Unprocessed field file with identified reflection, refraction, air wave, and surface wave. Confident identification is possible due to the unique characteristics and arrival pattern of the coal reflection.

RESULTS

Reflections from the coal seam can be interpreted from raw field-files (Fig. 2). The coal reflection has a unique frequency spectrum and hyperbolic arrival pattern that separates it from refracted-wave, direct-wave, and air-wave energy. The dominant reflection frequency is in excess of 200 Hz. Two-way arrival time of the coal reflection is consistent with the one-way travel time observed in an uphole survey. Reflection energy from voids lacks trace-to-trace consistency in frequency content.

The voids can be separated from competent coal according to frequency, amplitude, coherency, phase, and reflection-wave character on the 12-fold CDP, stack of line 2 (Fig. 4). The first three positive amplitude arrivals between 10 ms and about 22 ms on line 2 are refractions. As previously mentioned, refractions were not muted to avoid disturbing the reflecting arrivals that closely trail the refractions (Fig. 2). The difference in the seismic characteristics of voids and intact coal are obvious when the drill-confirmed voids on line 2 at station 123 and 144 are compared with the drill-confirmed coal at station 135 on line 2. The coal reflection at station 135 is higher in ampli-

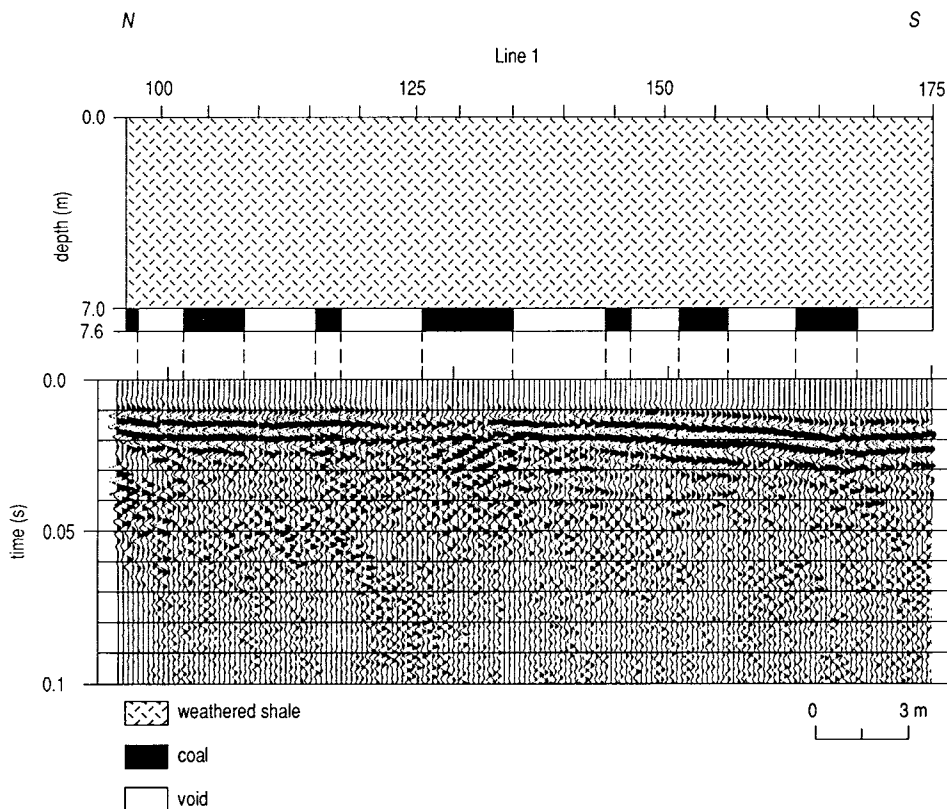


Fig. 3. Twelve-fold CDP stack and geologic interpretation of line 1. The first two dominant cycles after first breaks are stacked refraction energy not muted to avoid adversely affecting the reflection arrivals. Rooms and pillars, as indicated on the geologic cross-section, are remnants of a coal-mining technique commonly practiced in this area around 1900.

tude, more coherent, and lower in frequency than the reflection energy of the bounding voids.

The drill-confirmed criteria for identifying voids in the coal from line 2 were used to interpret lines 1 and 3 (Figs. 3, 4, and 5). Consistent emphasis was placed on each of the various seismic characteristics in defining location and extent of void areas in the subsurface. Voids are seismically represented on stacked sections as either an increase in the dominant frequency (location 125 on line 3; Fig. 5) or a loss of coherency resulting in a chaotic zone (location 125 on line 1; Fig. 3). The repetitive nature of the void/coal patterns on all three lines is consistent with the "room and pillar" mining technique as shown on old mine maps from this area.

Reflection events can appear continuous across abrupt discontinuities when subsurface sample points are closer together than the diameter of the first

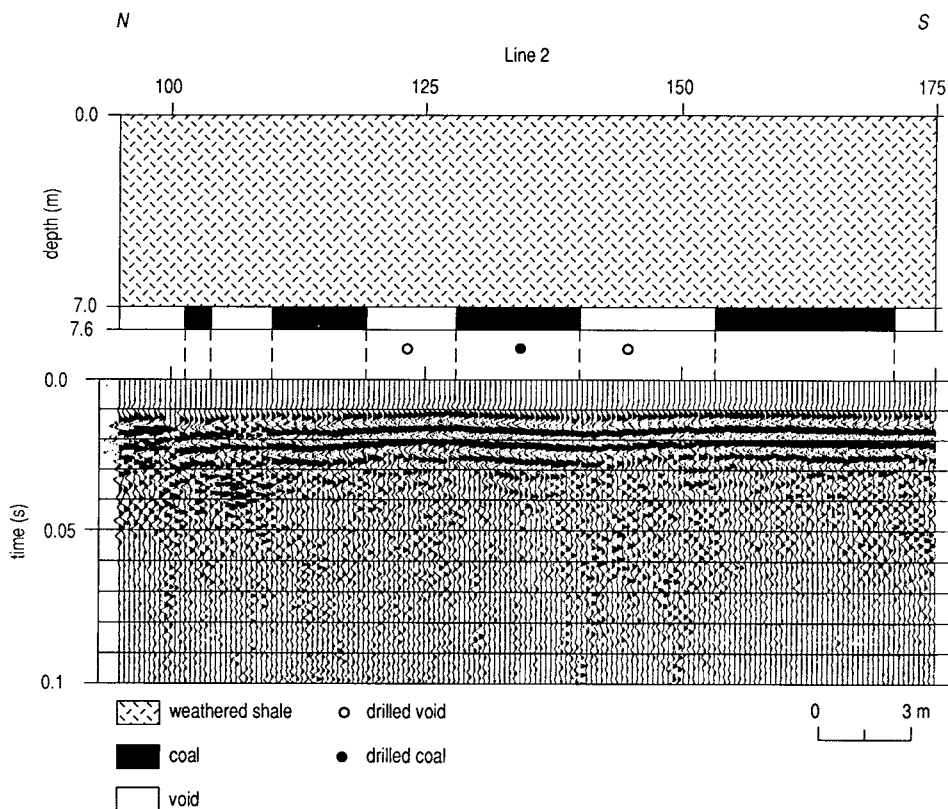


Fig. 4. Twelve-fold CDP stack and geologic interpretation of line 2. Drilling on line 2 confirmed the presence of the interpreted voids in the competent coal. The first two dominant cycles after first breaks are stacked refraction energy not muted to avoid adversely affecting the reflection arrivals.

Fresnel zone (Waters, 1987; Miller et al., 1990). Oversampling of the first Fresnel zone resulted in diffused boundaries between voids and competent coal on all three CDP stacked sections. The boundaries between coal and void identified on the geologic cross-sections are subjective and were selected based on localized relative amplitude and frequency changes. Horizontal focusing of subsurface features occurs as the spatial sampling interval approaches the radius of the first Fresnel zone. The oversampling on this data set was necessary to maintain good coherency on the coal seam reflection.

The sinkhole's migration path toward the railroad tracks does not appear to directly correlate to interpreted voids having sufficient volume to yield over 3 m of surface subsidence (Fig. 6). Voids interpreted on lines 1, 2, and 3 all possess consistent seismic character, approximate void size, and "room and pillar" grid patterns. It would be speculative, due to the isolated and

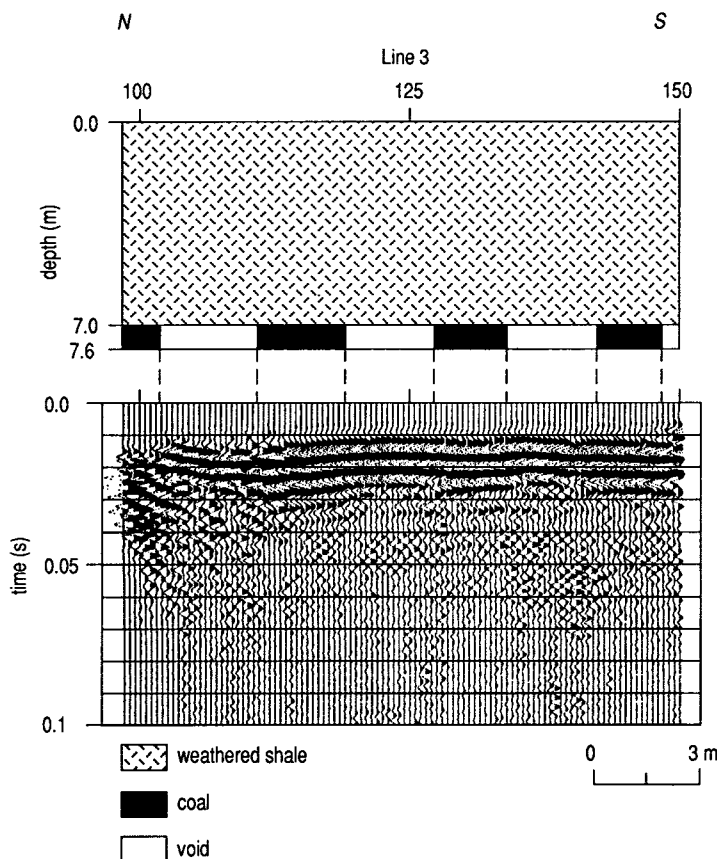


Fig. 5. Twelve-fold CDP stack and geologic interpretation of line 3. Line 3 was a preliminary test line intended to determine the feasibility of the CDP reflection technique at this location. The first two dominant cycles after first breaks are stacked refraction energy not muted to avoid adversely affecting the reflection arrivals.

sometimes chaotic nature of mine works in this area, to extrapolate the voids interpreted on this data set beneath the tracks without more supporting evidence. The surface location and migration path of the sinkhole suggests a room at least 3 m in height, and approximately 3 m in diameter beneath stations 145–155 on lines 2 and 3. The seismic sections show no voids meeting these criteria at that location. The mechanism responsible for the accelerated growth rate of the sinkhole, both horizontal and vertical, is apparently not related to subsidence.

Subsequent surface investigation revealed a correlation between the migration path of the sinkhole walls and the local drainage pattern of surface water (Fig. 6). The original formation of the sinkhole was probably from surface collapse of material surrounding a vertical shaft. The recent reactivation and

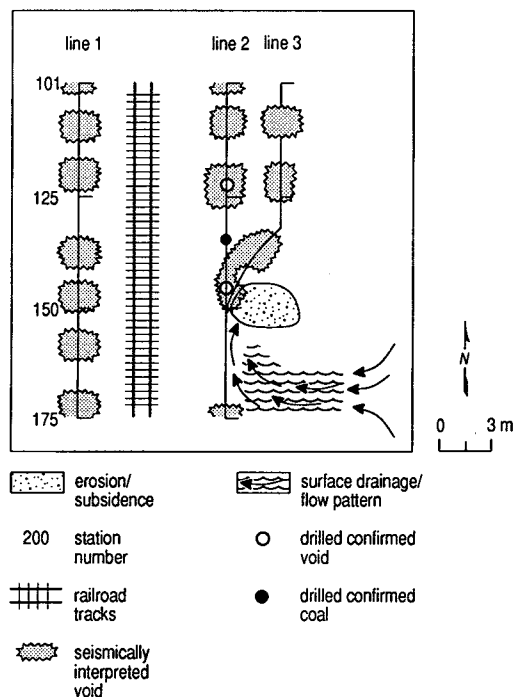


Fig. 6. Map view interpretation of the voids (rooms) and competent coal (pillars) interpreted on each of the three lines. Confident correlation of this grid-mining technique (as interpreted on the CDP stacked section) between lines would be speculative. The erratic nature of the orientation of the "rooms and pillars" as indicated by many mine maps from this area discourages line-to-line ties (with the exception of lines 2 and 3 near CDP 150). Surface drainage, as indicated, is responsible for the drop in the ground surface previously attributed to subsidence.

resulting expansion of the sinkhole perimeter is focused predominantly along a topographic low that is acting as a channel for surface-water runoff. The erosion associated with the water flow has lengthened the sinkhole along the drainage channel. Absence of water in the sinkhole indicates that surface water is probably escaping through the reopened vertical shaft. The accelerated rate of subsidence and growth direction of the sinkhole should remain consistent with the amount and drainage pattern of surface-water runoff in the immediate area.

CONCLUSION

High-resolution seismic-reflection methods were successfully used to evaluate the risk to rail traffic of an active sinkhole within 20 m of the tracks. Voids were interpreted on the seismic sections. The remnants of "room-and-pillar" mining can be clearly interpreted on stack seismic sections. Drill data

and an uphole survey agreed with the seismic-reflection data on depth-to-coal, location of intact coal, location of voids in the coal seam, and two-way travel time from the surface to the coal and back to the surface. The geologic interpretation is based on information acquired through confirmation drilling along the seismic-reflection profile and on uphole travel times. The correlation of the drill information and the seismically derived interpretation of line 2 justifies confidence in the overall interpretation (Fig. 6). The areal expansion of the sinkhole was determined from seismic data not to be related to the collapse of a horizontal mine shaft. The accelerated growth is probably a result of erosion.

As a result of the seismic survey and interpretive geologic cross-section, the recommendation was made to fill the active sinkhole with impermeable material and reroute surface drainage away from the hole. These recommendations were accepted and completed by the railroad, ending the apparent sinking and the immediate danger to the railroad tracks.

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