Seismic techniques to delineate dissolution features in the upper 1000 ft at a power plant site

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Summary

Shallow seismic techniques (Steeples and Miller, 1990; Park et al., 1999; Xia et al., in press) were used to enhance the effectiveness of a drilling program designed to locate dissolution features large enough to put the integrity of equipment or environment at Alabama Electric Cooperative's proposed Damascus site at risk ("A" on Figure 1). Dissolution features will directly impact engineering design specifications and future plant safety. This applied research program identified acoustic characteristic unique to voids, subsurface subsidence, and/or karst features; evaluated the potential of acoustic methods to enhance drill-assisted mapping of major stratigraphic units and structural features; identified the maximum and minimum depths of seismic investigation; estimated resolution potential (vertical and horizontal features detectable and resolvable); defined optimum geometries and equipment; and incorporated production 2½-D reflection and shear wave profiles with exploratory drilling. The shear wave velocity field provided valuable information about areas that might be at risk of subsiding. From that feasibility survey, areas studied with "young" sinkholes, directly tied to karst features, produced pronounced velocity inversions in close proximity to large velocity gradients (generally forming a closure on contoured cross-sections). These anomalous areas were interpreted to indicate increased stress associated with roof rock loading over rubble zones or void areas. Data from both the reflection and shear wave profiles from the feasibility and 2½-D surveys possessed several unique features that are probably related to dissolution and subsidence.

Geology

Information about the local geologic setting, accompanied by physical examination of surface expressions and exposures of geologic features and anomalies similar to those targeted by this seismic imaging program, was the necessary background for evaluating the feasibility and optimizing these techniques. Dissolution caverns in the Glendon and Marianna limestones are postulated to be the origin of voids and collapse features within the Bucatunna Clay and river terrace deposits throughout this part of southern Alabama and nearby northern Florida. Incorporating seismic reflection and surface wave profiling allowed geologic features interpreted in boreholes to be extended. Coincident interpretations of these acoustic methods provided insight into the lateral coherency of geologic anomalies undetected by drilling alone. Present at depth (about 100 ft) is the Ocala Limestone, the geologic unit proposed to be responsible for many of the karst-related sinkholes in Florida. The Glendon, Marianna, and Ocala limestones, all present within the upper 150 ft at this site, have a history of dissolution. Critical to safe construction and operation of the proposed power station is the presence of an intact geologic section between the top of the river terrace deposits (ground surface) down to the base of the Ocala Limestone.

A swarm of sinkholes in Auburn University's Solon Dixon Forestry Research Center, less than 5 miles from the proposed site, provided an ideal setting to study the acoustic characteristics of pre-subsidence earth ("B" on Figure 1). Tests designed to identify acoustic signatures associated with developing sinkholes targeted areas near these sinkholes with no apparent surface expression. Since drilling in the national forest was not possible, survey lines were located in close proximity to sinkholes, with receiver stations adjacent to the sinkholes classified as subsidence prone areas. Results of seismic testing permitted estimation of the detectability of cavities, minimum resolvable dimensions of subsurface features, and depth ranges affected by dissolution.

Surface Wave Calibration

Surface waves, when used to image the earth, provide a rapid and relatively straightforward method of examining the shallow subsurface (Xia et al., 1998; Park et al., 1999; Xia et al., in press). Unfortunately, interpretations of the two-dimensional shear wave velocity field derived from the inversion of the surface wave dispersion curve are of much lower resolution than seismic reflection sections. However, the shear wave velocity field derived in this fashion is quite sensitive to abrupt changes in shear wave velocity. In this setting, it is reasonable to expect voids, caverns, or collapse features to be associated with an abrupt change in shear wave velocity.

Discerning the acoustic characteristics of subsurface voids on shear wave velocity profiles in this geologic setting required a surface wave profile in an area with known voids. A group of sinkholes in the Dixon Research Center that align generally along an east/west trend provided the appropriate density and distribution for the acquisition of a single profile traversing an area without sinkholes into an area with sinkholes. It must be kept in mind that without ground truth drilling it is not possible to unequivocally say dissolution voids similar to the ones responsible for the observable sinkholes are only present at stations adjacent to the observable sinkholes.

Correlation between the sinkholes identified near the survey line and the high velocity over low velocity closures on the shear wave velocity sections (Figure 2) is likely the unique acoustic characteristic necessary for this technique to guide an exploratory drilling program.

Acquisition

Data for the 2½-D survey were acquired with state-of-the-art near-surface imaging equipment. A Geometrics StrataView R60 sesimograph was used in a 240-channel configuration for the shallow reflection data and in a 48-channel configuration with a 240-channel roll-along switch to record the surface wave data. Receivers for the shallow reflection survey were a group of three Mark Products L28E 40 Hz geophones wired in series with 5-inch spikes (Figure 3). For the surface wave surveys, single Geospace GS-11D 4.5 Hz geophones with 3-inch spikes were deployed. Station spacing for both reflection surveying and surface wave profiles were the same, with a receiver station spacing of 4 ft and source station spacing of 8 ft. Three ground impacts from a rubberband accelerated weight drop (RAWD) were vertically stacked in the seismograph at each source location for the surface wave profiles, while a single shot from a 50 cal downhole rifle provided the energy for most of the shallow reflection data (Miller et al., 1986). The data were acquired with equipment and with parameters that optimized the available equipment for the site conditions and targets.

Processing

Processing of these data was consistent with all current methodologies and flows using software specially designed and written for shallow seismic surveys. Shallow reflection data were processed into CMP stacked section using WinSeis, a commercially available software package. The shallow reflection data were nominal 120-fold with the actual fold ranging from 2 to over 240. This level of redundancy provided ample traces within the optimum window for reflection from depths as shallow as 40 ft extending to depths in excess of 1000 ft. Shallow seismic reflection processing flows must be optimized/customized for each data set and target objective. Processing the reflection data for this survey required extreme detail and attention to statics. Variability on the order of several milliseconds was observed between adjacent traces. Since these data possess dominant frequencies as high as 200 Hz in some locations, less than 3 ms of mismatch between stacked traces would result in cancellation of reflected wavelets.

Surface wave data processing required fewer individual steps and involved about one-fifth as many traces as the reflection data; therefore, it was completed in a much shorter time frame. Surface wave data were processed into shear wave velocity field cross-sections with SurfSeis, a proprietary set of algorithms developed by the Kansas Geological Survey. Processing of surface wave data involves the transformation of the time-distance shot gathers into a frequency-phase velocity domain curve (dispersion curve). Once displayed as a dispersion curve, the appropriate frequency band can be selected and the dispersion curve is inverted into a shear wave velocity trace (shear wave velocity as a function of depth). With a shear wave velocity trace for each source station a 2-D contour map of the velocity field as a function of station location and depth could be generated for each profile line.

Interpretation

Reflection data from this survey possess excellent resolution potential down to depths in excess of 1000 ft. Several high quality reflection events can be interpreted in the upper 250 ft. Time to depth conversions are based on stacking velocities that average around 4000 ft/sec at around 25 msec, 5000 ft/sec at 100 msec, 6000 ft/sec at 200 msec, and 7000 ft/sec at 300 msec. These velocities provide gross estimations of interpreted reflector depths. Reflection events as shallow as 25 msec (~40 ft) are interpretable on both the eastern and western portions of the line. The 100 msec reflector (~250 ft) will provide the reference for structures interpreted in the shallow portion of the sections. This high amplitude, continuous (at least within the survey area) reflection allows shallower structures to be distinguished from static resulting from ultra-shallow variations in stratigraphy or structure. Interpretation of these data will be broken up according to each individual line, with coincident interpretations of the reflection and shear wave data made when possible.

Reflection Data

Several features significant to this study are evident on the CMP stacked section of line 1 (Figure 4). Probably the most striking is the paleo-sinkhole center around station 1390. This bowl shaped depression in the reflectors shallower than 250 ft is striking evidence that supports this area being an active subsidence area at some point in the past. The lack of flat-laying reflection events above this feature prohibits estimations of subsidence rates, length of activity, or even when subsidence ended. Careful analysis of the relative location of the various coherent reflection events that are present within the depression suggests this sinkhole to have been active at several different times. Subsidence rates cannot be estimated with these data. It is, however, possible to estimate the dimensions of this depression prior to notable periods of sedimentation that appear to have infilled the depression. The fact that no surface expression exists today is strong evidence to suggest the dissolution process that resulted in the sinkhole is currently experiencing an extended period of inactivity.

Based on seismic stacking velocities and keeping in mind that these data have not been migrated, it is reasonable to suggest this sinkhole can account for 60 to 70 ft of subsidence. It appears to have been active at least twice prior to its current state of inactivity. Interpretations of this feature from this line alone suggest it is about 200 ft across (this takes into consideration that this section has not been migrated and other horizontal sampling issues). It is reasonable to assume this sinkhole was around 200 ft across and 50 ft deep prior to infill of sediments. The empirically derived ½-wavelength criterion for vertical resolution (Miller et al., 1995) suggests 8 ft of vertical resolution is reasonable for the shallow part of the section (35 ft to 100 ft) and 15 ft of vertical resolution for the deeper part of the section (250 ft to 650 ft).

Other noteworthy features include the disturbed reflection between stations 1115 and 1190 between 40 and 80 msec (80 and 200 ft) of depth. These chaotic-looking reflection events are within the same depth interval where the sinkhole at the east end of the line has its origin. It is reasonable to suggest that the dissolution responsible for the paleo-sinkhole is or has been active within this portion of the profile. Between stations 1130 and about 1240 the shallowest reflector (30 to 40 ft) appears to be either missing or extremely disturbed. This could be related to dissolution, bedrock erosion prior to burial by the overlying unconsolidated sediments, or this could be simply a portion of the bedrock lacking sufficient lateral coherence to be mapped with this resolution seismic data.

Surface Wave

Shear wave velocity profiles provided valuable information about the uniformity of the upper 100 ft or so. Line 1 possesses several features correlatable to the reflection data and consistent with the geology based on drilling (Figure 4). The bedrock surface, interpreted as a shallow, relatively competent limestone, increases in depth below ground surface from east to west. A large area of low shear wave velocity is interpreted as a zone of erosion/dissolution with infill of lower velocity unconsolidated materials. This zone could easily appear laterally consistent on boring logs, with apparent increase in porous size of the rock matrix filled with either clay type materials or fluid. Considering this geologic setting, the average shear wave velocity drop through the zone between stations 1210 and 1330 is likely related to dissolution of the limestones in the upper 100+ feet. Of interest in terms of anomaly detection is the higher velocity closure observed beneath station 1070 at about 10 ft. This feature represents a drainage culvert passing under the road along which this line was collected. A curious feature, however, that is the result of real geology is the higher velocity zone beneath station 1080 or so. This feature is too far east to be related to the culvert.

Conclusions

Shallow seismic reflection and surface wave profiling in conjunction with a focused drilling program dramatically reduced the size of a subsurface feature potentially undetectable by pattern drilling alone. A unique acoustic signature interpreted on shear wave velocity field data can be indirectly (in proximity of recently developed sinkholes) correlated to sinkhole development. Reflection imaging successfully detected reflectors from 35 ft to over 630 ft while surface wave imaging provided a reasonable representation of the first 100 ft of the earth. Both data sets can be correlated to borehole geology.

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References

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.

Miller, R.D., S.E. Pullan, J.S. Waldner, and F.P. Haeni, 1986, Field comparison of shallow seismic sources: Geophysics, 51, 2067-2092.

Park, C.B., R.D. Miller, and J. Xia, 1999, Multi-channel analysis of surface waves (MASW): Geophysics, May-June.

Rand McNally Road Atlas, 1995 edition: Rand McNally & Company.

Steeples, D.W., and R.D. Miller, 1990, Seismic-reflection methods applied to engineering, environmental, and groundwater problems: Soc. Explor. Geophys. Investigations in Geophysics, Investigations in Geophysics no. 5, Stan H. Ward, ed., Volume 1: Review and Tutorial, p. 1-30.

Xia, J., R.D. Miller, and C.B. Park, 1998, Construction of vertical seismic section of near-surface shear-wave velocity from ground roll [Exp. Abs.]: Soc. Explor. Geophys./AEGE/CPS, Beijing, p. 29-33.

Xia, J., R.D. Miller, and C.B. Park, in press, Estimation of near-surface shear-wave velocity by inversion of Rayleigh waves: Geophysics.

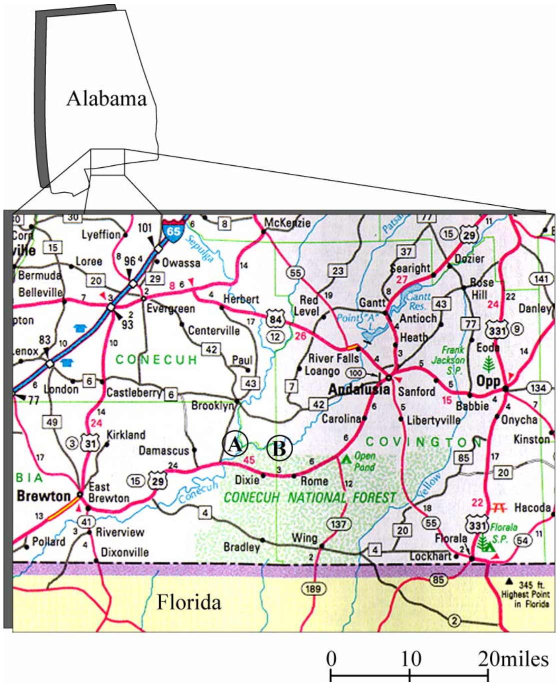
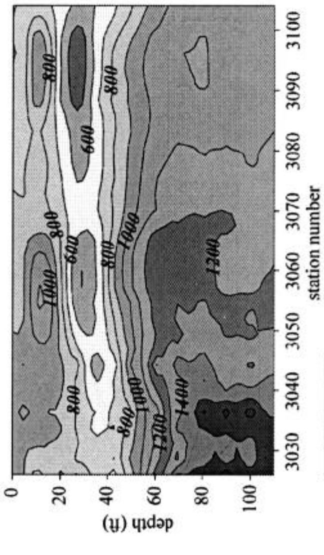


Figure 1. Site map (from Rand McNally Road Atlas, 1995).



Contour interval is 100 ft/s.

Figure 2. Shear-wave velocity profile of the testing site.

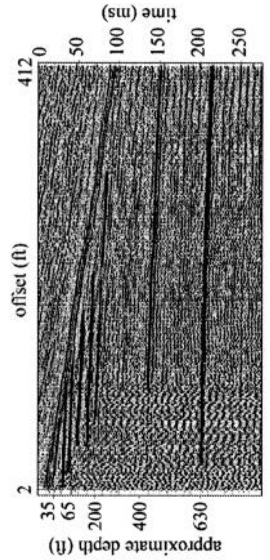
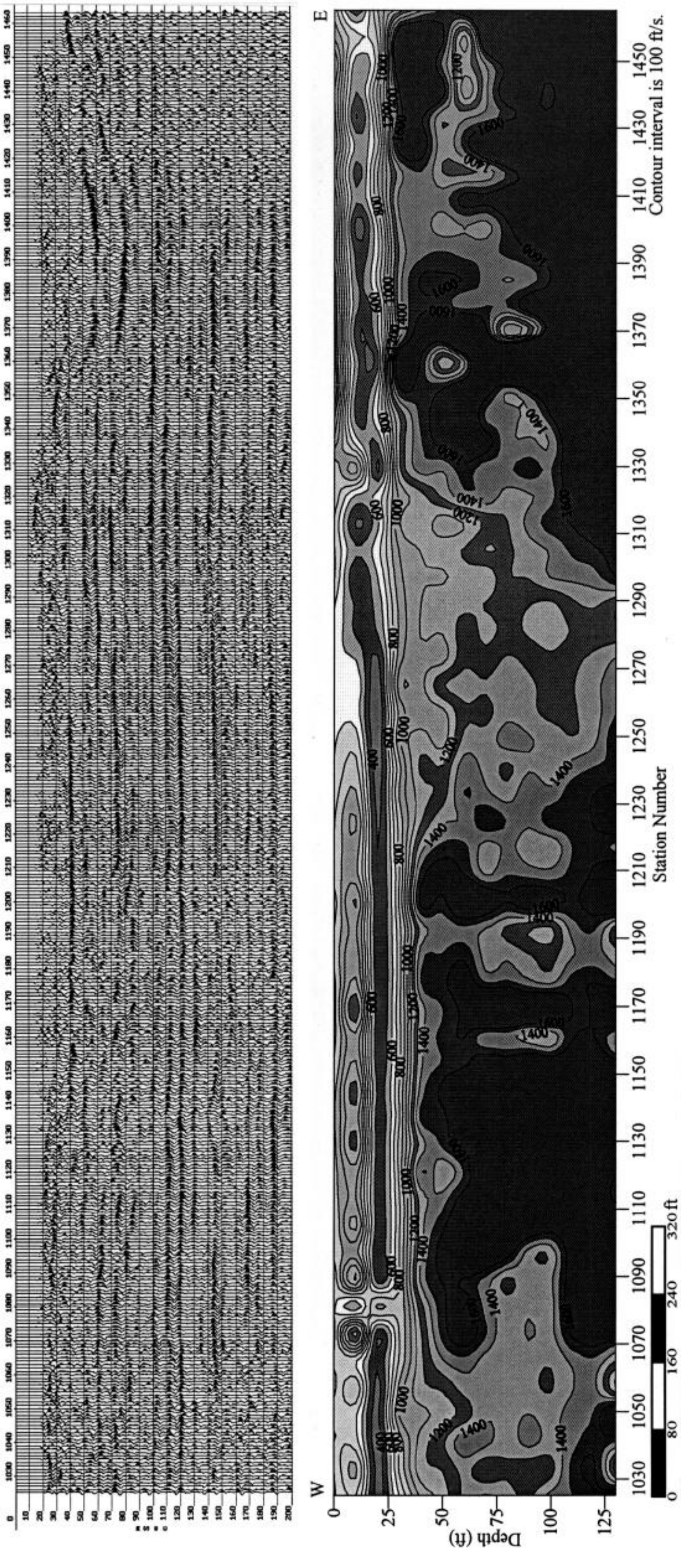


Figure 3. Shot gather.



Contour interval is 100 ft/s.

Figure 4. CMP stacked section and shear-wave velocity profile from line 1.