

## Seismic investigations of subsidence hazards

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### Summary

Seismic investigation of subsidence associated with dissolution, piping, and roof rock failure in mines/voids is beginning to reach critical mass such that it is possible to begin assimilating characteristics that can be used to better interpret data and predict which portion of the seismic wavefield will be most sensitive to particular features in a defined geology and for a particular void/collapse. Examples of seismic data with different portions of the wavefield enhanced to allow improved interpretation of subsurface anomalies related to ground instability are provided and discussed. With more than a dozen examples with characteristics considered 'normal or expected' for a particular setting, improved confidence becomes a reasonable outcome from incorporation of various components of the wavefield when investigating a particular target.

### Introduction

Geohazards come in a variety of types and detrimentally affect an enormous range of geographic areas. From climate change to earthquakes, from overpressured gas zones to slope instability, the impact of geohazards can range from very localized to planetary in size. Geophysical techniques are commonly brought to bear to identify, delineate, and predict these hazards. Subsidence is one particularly troubling geohazard that represents a risk to human habitation and property in many parts of the world, with potentially deadly consequences when the rate of subsidence is catastrophic (Figure 1).

Subsidence occurs when overburden pressures exceed the overburden strength as defined by a complex combination of individual material strengths and continuity, dimensions of the available void space, and thickness of the overburden. One or a combination of diverse drivers is generally responsible for instigating void development and growth at a scale sufficient to exceed the strength of roof rocks, eventually migrating to the ground surface. In the majority of cases these mechanisms for void development include dissolution (natural and anthropogenic), mining, and erosion (Figure 2).

Seismic imaging has proven effective in identifying areas with elevated subsidence potential associated with existing collapse structures and in areas with heightened potential of upward void migration where no surface expression is evident. Seismic reflection and diffraction, MASW shear wave velocity sections, and surface-wave backscatter analysis have provided interpretable images of the subsurface expression of voids and collapse structures. Each method and energy mode appears sensitive to different geologic settings, target depth and geometry, and stress regime.

Investigations of voids in bedded salt in Kansas, limestone karst in Florida, coal and lead/zinc mines in Kansas, and enlarged pore space due to leaching in a Missouri dam will provide the evidence for suggesting methods, modes, and approaches used in the detection, delineation, or discrimination of voids from seismic. For all the studies discussed, the observations are consistent with theory and all available ground truth.

### Seismic Investigation

Seismic imaging of collapse structures and unstable ground with the potential to evolve into collapse structures has focused on reflection geometries and wavelet characteristics, changes in the shear wave velocity associated with elevated



Figure 1. Macksville sinkhole formed after uncontrolled dissolution of a bedded salt from oilfield brine.



Figure 2. Mobilized soils from surface water cascading down an old vertical mine air vent.

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stress, and diffracted or backscattered energy. High-resolution seismic reflection has been effective in determining the extent and status of subsidence features. Based on model studies, dissolution-instigated collapse evolves through various stages, each with well-defined geometries (Ge and Jackson, 1998). Carefully acquired and processed high-resolution seismic data result in images that possess the fidelity and signal-to-noise ratio necessary to distinguish different collapse and dissolution stages.

Stress increases along the roof of a void prior to strain will result in an increase in shear velocity. Shear-wave velocities are directly related to the ratio of stress to strain. Since failure of consolidated rock is dependent on the rock matrix more so than the pore conditions, monitoring changes in  $V_s$  should represent a highly sensitive method of detecting failure potential due to non-linear changes in strain relative to stress (S. Sloan, personal communication, 2009). Changes in  $V_s$  for a particular rock are related to differential stress and associated non-linearity in the stress-strain curve (Dvorkin et al., 1996).

Diffracted body waves or backscattered surface waves are a predicted outcome when seismic energy interacts with subsurface voids acting as a point source scatterer or bed terminations that are invariably present when rock failure leads to subsidence features. Voids in an otherwise homogeneous earth will scatter surface wave energy at frequencies and therefore wavelengths tuned to the target depth (Ivanov et al., 2003). Likewise, body waves will diffract from voids in a predictable fashion with mode conversions observed at specific source-to-receiver offsets and under different ranges of velocities (S. Peterie, personal communication, 2010).

Imaging bed distortion related to differential compaction and/or collapse of voids with vertical migration has been very effectively done using seismic reflection. It has proven successful delineating both active and paleo collapse structures associated with bedded salt in central Kansas, underground mining operations, and earthen structures like dams and dikes. Key to reflection profiling is avoiding the tendency to process data using conventional exploration routines and techniques developed for laterally continuous bedding

or changes in bedding or interfaces that occur over distances many times larger than the Fresnel zone. Collapse structures are generally very vertical and have subwavelength horizontal extent.

Interaction of surface waves with voids, collapse, structures, and changes in material characteristics due to internal erosion is detectable in many cases and allows various unique analysis routines to be used that in conjunction with other data have allowed confident and confirmed interpretations at/on/over dams, levees, mine drifts, and limestone karst. The sometimes dramatic effects observed in shear-wave velocity when collapse structures that have not migrated to the ground surface and possess unusual stress have been used to predict collapse potential.

### Dissolution

Redbed evaporites overlaying the Hutchinson Salt Member ranging in depth from 30 to 500 m in Kansas are a primary target of any study looking at salt dissolution sinkhole development and associated risks to the environment and human activity. Failure and subsidence of these evaporite units are responsible for the eventual formation of sinkholes and provide a pathway for groundwater to gain access to the salt (Figure 3). In proximity to the dissolution front fractures, faults, and collapse structures compromise the confining properties of the Permian shale bedrock and put the major fresh water aquifer (Plio-Pleistocene Equus Beds) in this part of Kansas at risk

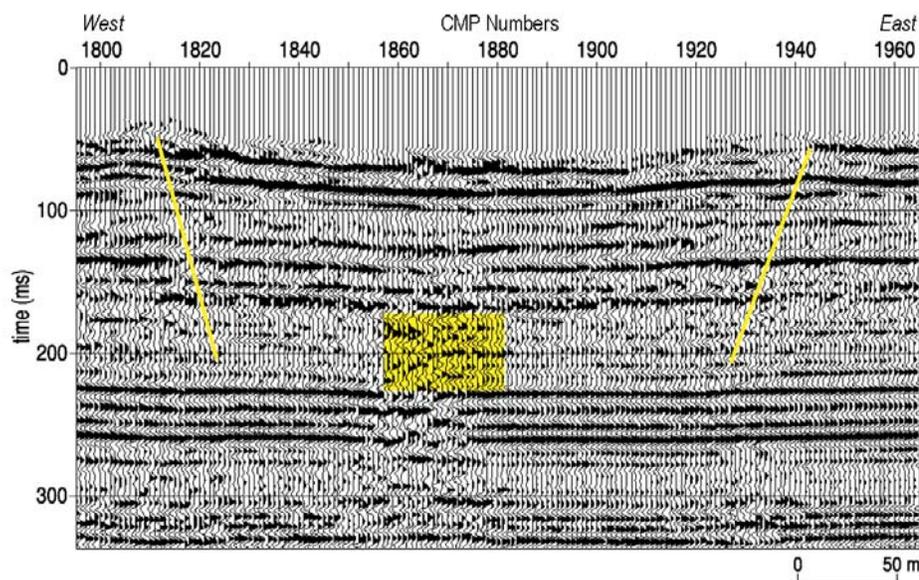


Figure 3. A portion of this stacked section highlights the subsidence-feature geometry. The box includes what is interpreted as a dissolution volume, seismic unique with diffractions from bed terminations and low-frequency, more chaotic events.

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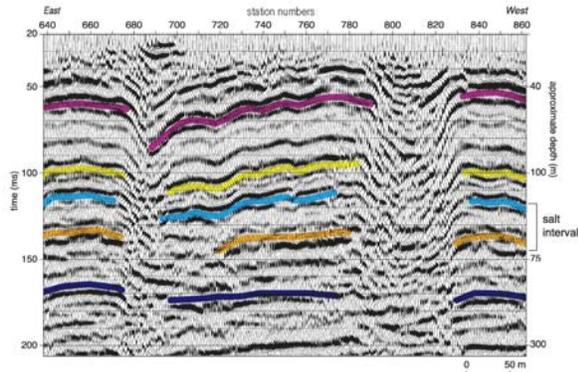


Figure 4. Complex paleosubsidence events spanning a distance of about 300 m located near the town of Punkin Center, Kansas. Undulating upper Permian reflectors are representative of a very gradual subsidence process involving repetitive cycles of dissolution and subsidence.

(Figure 4). Along the eastern boundary (dissolution front) the salt, which ranges from 0 to over 100 m thick, is buried beneath about 120 m of Permian red bed evaporites.

Seismically all the Permian and younger reflectors are important to the accurate interpretation of the stacked sections. “Pull downs” in time result from the localized decreases in material velocities within a sinkhole (Figure 5). The velocity structure and small radius of curvature of synforms, which are characteristic of salt dissolution and subsidence in this area, can produce diffractions and distort reflections. Reflections from beneath the salt will have a subdued expression of the subsidence.

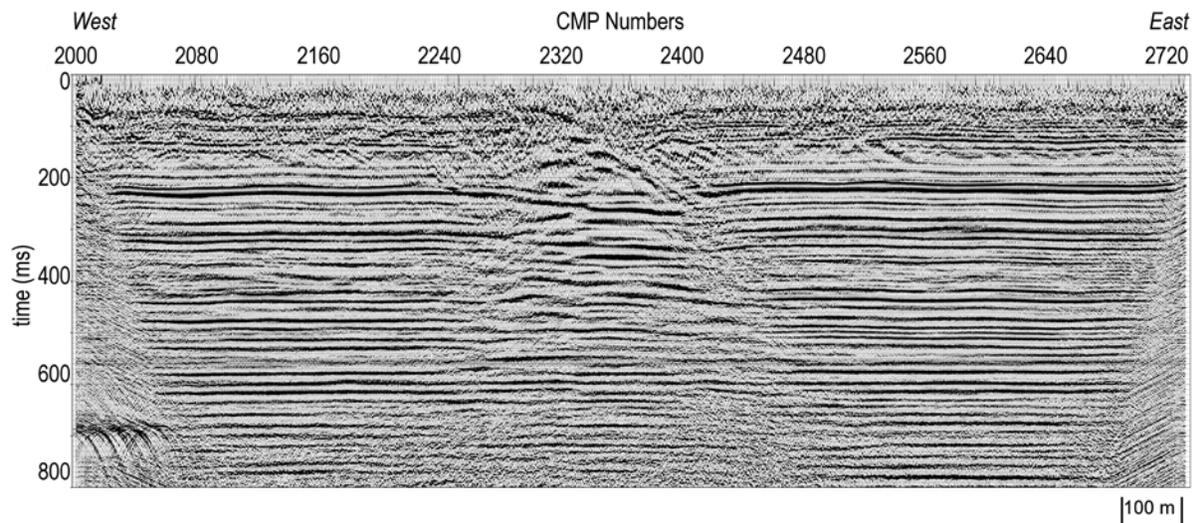


Figure 5. Nominal 60-fold CMP stack at the Leesburg sinkhole. Asymmetry of the collapse structure is unusual for a subsidence feature from borehole-induced dissolution. East side of profile clearly defined by reverse-fault geometry.

Karst features in shallow limestones in Florida represent significant financial and safety risks. Due to the porosity of the sands, silts, and gravels that overlay many of these dissolution etched limestones, simple changes in the drainage associated with construction can instigate the movement of unconsolidated sediments into the many water sculpted passageways within the carbonates in this area. This vertical leaching is very difficult to detect with geophysics or drilling. Seismic MASW imaging has been effective in identifying areas in the limestone where karsting is present. By mapping the karst geometries pre-commercial development, construction can be altered (change in location or design modifications to bridge karst areas) to minimize any future effects of ground instabilities.

### Mining

Dissolution mining and room-and-pillar mining leave behind voids susceptible to collapse if the mined voids possess a span great enough to set up a stress regime where forces exceed the strength of the roof rock. Most problematic are mine voids created decades in the past where, due to the gradual degradation of some roof material, migration to the ground surface can appear more than a century after the mining activity ceased. Room-and-pillar mining many times can accelerate degradation of roof rock through enhanced exposure of previously isolated zones to unique hydrologic pressures.

Shallow room-and-pillar mines from early in the twentieth century are notoriously susceptible to surveying errors that have resulted in construction of structures and facilities over areas prone to surface subsidence. Pattern drilling with sufficient spatial sampling is not economically practical for many

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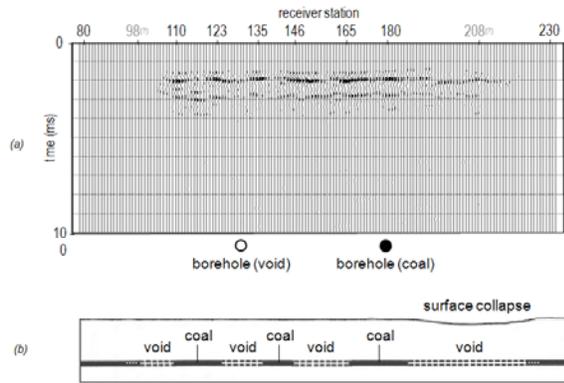


Figure 6. (a) Diffraction cross-section. (b) Graphical interpretation of the section.

urban areas that have encroached on lands undermined at the turn of the century. Newly developed imaging methods focused on the diffractions that result from bed terminations show promise for development of near-automated systems with real time results (Figure 6).

### Erosion

Subsidence due to degradation by erosion of anthropogenic structures or installations is difficult to remediate unless the flow path is delineated and all areas of the affected structures identified. Sinkholes that form in areas susceptible to collapse from roof rock failure can at times have their source misidentified. In room-and-pillar and longwall mine areas, vertical vent shafts are routinely installed. These installations will penetrate rock layers that have prevented vertical movement of fluid at rates faster than natural percolation. These vertical fluid passageways can provide surface drainage and associated vertical erosion, resulting in depressions that are misidentified as surface subsidence from mine collapse, as was the case in a southeast Kansas coal mine area.

Potentially devastating internal conditions can exist in earthen water retention structures when subsidence features appear on the face. These sinkholes are not particularly threatening in themselves, but the degradation of the dam structure that produced the voids or sufficient pore space that, in turn, allowed the sinkhole to form can result in failure of the structure. A sinkhole that formed in the upstream face of a floodwater retention dam in southeastern Missouri appeared directly above the toe of the cutoff trench. MASW imaging combined with seismic reflection profiling clearly showed the sinkhole was the result of the piping of permeable fill material through incompletely sealed elongated karst structures in bedrock below a dam's cutoff trench (Figure 7).

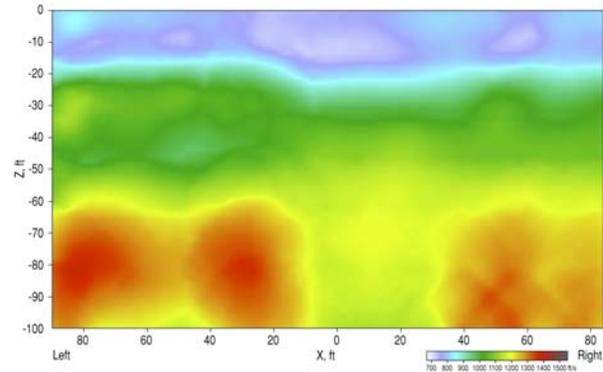


Figure 7. Clearwater Dam, Line C3, Vs, ft/s, 6-28 Hz frequency range.

### Conclusions

Acquiring seismic data with the intent of using all components of the seismic wavefield has proven extremely valuable in discerning the source, conditions, and geometry of subsidence both below sinkholes and in areas where migration of voids to the surface is possible. High-resolution seismic reflection has been used to image dissolution features at depths from 20 m to over 1000 m that have and do lead to ground instability. In most cases hydrology is key, and without knowledge of the entire collapse structure and therefore potential fluid pathways remediation is not possible with any confidence. Old mine structures uniquely disturb the seismic wavefield. Diffractions, backscatters, and velocity perturbations are commonly artifacts of voids and mines.

With the wide range of at risk subsurface features that have been investigated over the last 30 years, a pattern has begun to emerge with respect to seismic wavefield sensitivities. These sensitivities provide a variety of ways to simultaneously interpret the presence and delineate the geometry of many subsidence features, whether surface expression exists in the form of a sinkhole or of a void susceptible to vertical migration.

### Acknowledgments

We want to thank all our various sponsors—Burlington Northern Railroad, the U.S. Army Corps of Engineers, the Kansas Department of Transportation, Burns & McDonnell, and the Kansas Corporation Commission. A great deal of appreciation goes to Mary Brohammer for desktop publishing and copy editing of this manuscript.

#### **EDITED REFERENCES**

Note: This reference list is a copy-edited version of the reference list submitted by the author. Reference lists for the 2010 SEG Technical Program Expanded Abstracts have been copy edited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

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