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Final Report to

Williams Gas Pipeline Central
Tulsa, Oklahoma

Cherokee County Engineer
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Summary

Historical lead/zinc mining activities have left surface scars and underground hazards across a portion of southeastern Kansas, southwestern Missouri, and northeastern Oklahoma, known as the Tri-State Lead/Zinc Mining District. Fractures and voids in otherwise competent near-surface rock layers can pose a stability risk to overlying surface structure. Confident detection and delineation of voids or open fractures prior to surface expression permits the evaluation and possible reduction in risk such features pose to people and property. Surface growth associated with a sinkhole located within 100 ft of State Line Road and a gas metering station south of Baxter Springs, Kansas, raised concerns for public safety and prompted an extensive drilling and geophysical investigation. The mine workings of interest ranged in depth from 100 to over 150 ft below ground surface and are in an area where Mississippian Limestone acts as both host and roof rock. Overlying the limestone is a soil and clay layer varying in thickness from 10 to 20 ft. Subsidence in this area has a historical precedent dating back prior to the mid-twentieth century.

Abandoned lead/zinc mines (drifts) known from mine maps to pass beneath State Line Road and generally coincident with the sinkhole of concern were the primary targets of this study and were suggested to embody a risk to surface structures in this area. Extensive drilling in the immediate area provided excellent 1-D ground truth but lacked the lateral resolution necessary to map the subsurface extent of fracture zones and voids. Surface wave imaging detected lateral variations in rock rigidity at depths and locations generally consistent with mine maps and drill-encountered sediment-filled and open fractures. Stable voids, regardless of origin, represent no risk to public safety; however, if stable voids begin to grow and surpass a size or roof span that can be supported by its roof rock, subsidence will occur. At the present time, science provides no method to confidently predict subsidence rates, extent, and volume. However, by using geophysical methods such as surface wave imaging as a monitoring tool, iterative "snap shots" of the subsurface allow discrimination of change and estimates of current subsidence rates.

Surface wave analysis using MASW allowed relatively quick and accurate (in relation to other geophysical methods) acoustic images to be produced of the upper 50 ft to 150 ft.

Cover photo courtesy of Tom Cook, Williams Gas Pipeline Central

Considering the sensitivity of surface wave propagation to shear wave properties, changes in the phase velocity of surface waves is directly proportional to changes in rock stiffness or rigidity. Abrupt changes in shear wave velocity will occur at the boundary between voids (water or rubble filled) and consolidated rock. As well, fractured or highly altered zones where competent rock is broken up and replaced by unconsolidated sediments and/or fluids will produce distinctive changes in the shear wave velocity field. Very localized anomalous features detected at depths of over 100 ft in two locations at this site were generally consistent with the geometry of drifts suspected to pass under the lines. Images produced as a result of this study clearly indicate that rock layers beneath the profile lines possess localized lateral discontinuities in rock properties. With no obvious connectivity existing between these structurally weak zones, it is not feasible to suggest the orientation and potential commonality of these features.

Interpretation of surface wave and drill data was complementary in depth and extent of void areas, but unique in terms of resolution. The single snap shot in time provided by the surface wave technique provides a relatively clear picture of subsurface rock strengths, but without a prolonged study evaluating change over time it is not possible with either data set (drilling or subsurface) to confidently discern the long-term risk of collapse at a specific spot. It is reasonable to suggest, based on both data sets, that a sizeable thickness (> 10 ft) of competent limestone separates the bedrock surface and the shallowest of the void/fracture areas encountered by either study. Two areas have been identified on surface wave data where some strain exists above void/fracture zones. It is not clear in this setting how much of a strain gradient is indicative of failure versus being consistent with a long-term sustainable load. An analogy would be the strain present between bridge pillars. A bridge is designed to span a specific distance and support a given load. This load will manifest itself as increased strain between the bridge supports.

Based on the data presently available, there is no way to confidently predict long-term subsidence rates or location along these profiles. With only a single snap shot in time, it is not possible to detect vertical migration. Considering the small size of the anomalous features and the thickness of overlying competent rock, returning to the site in six to nine months and acquiring identical surface wave data will provide a measure of change in rock properties (if any exists). This study was successful in developing an accurate shallow subsurface image consistent with the ground truth provided by drill data. The feasibility of this technique to delineate lateral changes in shear wave velocity and its relationship to drill data was evaluated.

Introduction

Subsidence-prone areas with limited subsurface control, significant velocity contrasts between effected and unaffected rock/sediment units, and gradual or segmented roof failure are especially well-suited targets for surface wave imaging. Two key indicators of subsidence activity or a strong potential for roof collapse are lateral decreases in the shear wave velocity related to compaction changes and localized increases in shear wave velocity associated with the tension dome surrounding subsurface cavities (Davies, 1951). When gradual subsidence is or has been active, a notable localized drop in shear wave velocity characteristic of earth materials that have collapsed into voids is generally observed. The reduced compaction zone, which starts at the void and moves generally vertically toward the surface, will disturb the shear wave velocity field in a manner consistent with the subsidence pattern or geometry. The potential of this technique to allow confident mapping the subsidence geometry depends on the following characteristics of the anomaly: abruptness of the contrast (gradient) between the disturbed and undisturbed earth materials, the complexity of geometry, dimensions, and depth of the anomaly, velocity of the layered earth, and characteristics of seismic energy.

Key to exploiting surface waves as a site characterization tool is their sensitivity to shear wave velocity, compressional wave velocity, density, and layering in the half space. The strength of individual rock layers can be qualitatively described in terms of stiffness/rigidity and empirically estimated from measurements of the shear wave velocity. Shear wave velocity is directly proportional to strain and inversely related to stress. Since the shear wave velocity of earth materials changes when the strain on those materials becomes “large,” it is reasonable to suggest that load-bearing roof rock above mines or dissolution voids may experience elevated shear wave velocities due to loading between pillars, or, in the case of voids, loading between supporting side walls. This localized increase in shear velocity is not related to increased strength, but quite the contrary, increased load. High velocity shear wave “halos” encompassing low velocity anomalies are key indicators of near-term roof failure.

Several key characteristics of surface waves and surface wave imaging make application of this technique possible in areas and at sites where other geophysical tools have failed or provided inadequate results. First and probably foremost is the ease with which surface waves can be generated. The relative high amplitude nature of surface waves (in comparison to body waves) makes possible their application in areas with elevated levels of mechanic/acoustic noise. A layer over half space is all that is necessary to propagate surface waves. It is one of the few acoustic methods that does not require increasing velocity with depth and/or a contrast (i.e., velocity, density, or combination [acoustic impedance]). Conductivity of soils, electrical noise, conductive structures, and buried utilities all represent significant problems or at least important considerations for electrical or EM methods. These have little or no impact on the generation or propagation of surface waves and generally have no influence on the processing or interpretation of surface wave data. This flexibility in acquisition and insensitivity to environmental noise allows successful use of shear wave velocity profiling in areas where other geophysical methods might be limited.

Surface Wave Imaging

Surface waves have traditionally been viewed as noise on multichannel seismic data designed to image targets significant to shallow engineering, environmental, and groundwater studies (Steeples and Miller, 1990). Recent advances in the use of surface waves for near-surface imaging have incorporated spectral analysis techniques (SASW) developed for civil engineering applications (Nazarian et al., 1983) with multi-trace reflection technologies (CDP) developed for petroleum applications (Mayne, 1962). Combining these two unique approaches to acoustic imaging of the subsurface allows high confidence, non-invasive delineation of horizontal and vertical variations in near-surface material properties (MASW) (Park et al., 1996; Xia et al., 1999; Park et al., 1999).

Surface wave imaging has shown great promise detecting shallow tunnels, the surface of bedrock, remnants of underground mining, and fracture systems/karst. Extending this imaging technology to include lateral variations in lithology has required a unique approach incorporating SASW, MASW, and CDP methods. Integrating these techniques provides a 2-D continuous shear wave velocity profile or image of the subsurface. Signal enhancement from determining the dispersion curve using up to 60 closely spaced receiving channels rather than one or two, and calculating a dispersion curve every 4 ft to 8 ft along the ground surface provides a unique, relatively continuous view of the shallow subsurface with high redundancy. This highly redundancy enhances the signal-to-noise of the calculated shear wave velocity field, minimizing the likelihood irregularities associated with an occasional erratic dispersion curve will corrupt the data analysis or interpretation.

This applied research program focused on an area approximately one mile south of Baxter Springs on the Kansas/Oklahoma border at the intersection of State Line Road and Roberts Road

(Figures 1 and 2). The primary objective was to determine if this emerging technology developed at the KGS could delineate lateral variations in shear wave velocity within consolidated sediments at a resolution sufficient to confidently map the very irregular, localized fracture meanders and the well defined and dramatic expressions of mine drifts. These types of anomalies would be represented by drops in velocity within otherwise uniform materials. Originally, this study was divided into two phases: 1) testing and evaluation and 2) sitewide mapping to delineate the three-dimensionality of any voids and/or fractures. Deployment of the test lines was guided by the location of existing boreholes, surface expression of a sinkhole, available mine maps, and gas metering station, county road, and line access by seismic source. It was determined that, due to the complexity of the shear wave velocity field as measured during testing, moving to phase two (3-D mapping) would not economically obtain the desired results with the necessary confidence.

Forward modeling and on-site acoustic wavefield studies provided an image of the subsurface that can only in part be confirmed with drilling. During the testing stage two intersecting profiles were acquired parallel to the eastern north/south fence of the gas metering station (line 1) and immediately south of the gas metering station along the north road shoulder

Figure 1. Looking northwest across the site with the sinkhole and gas station to the right out of this frame.

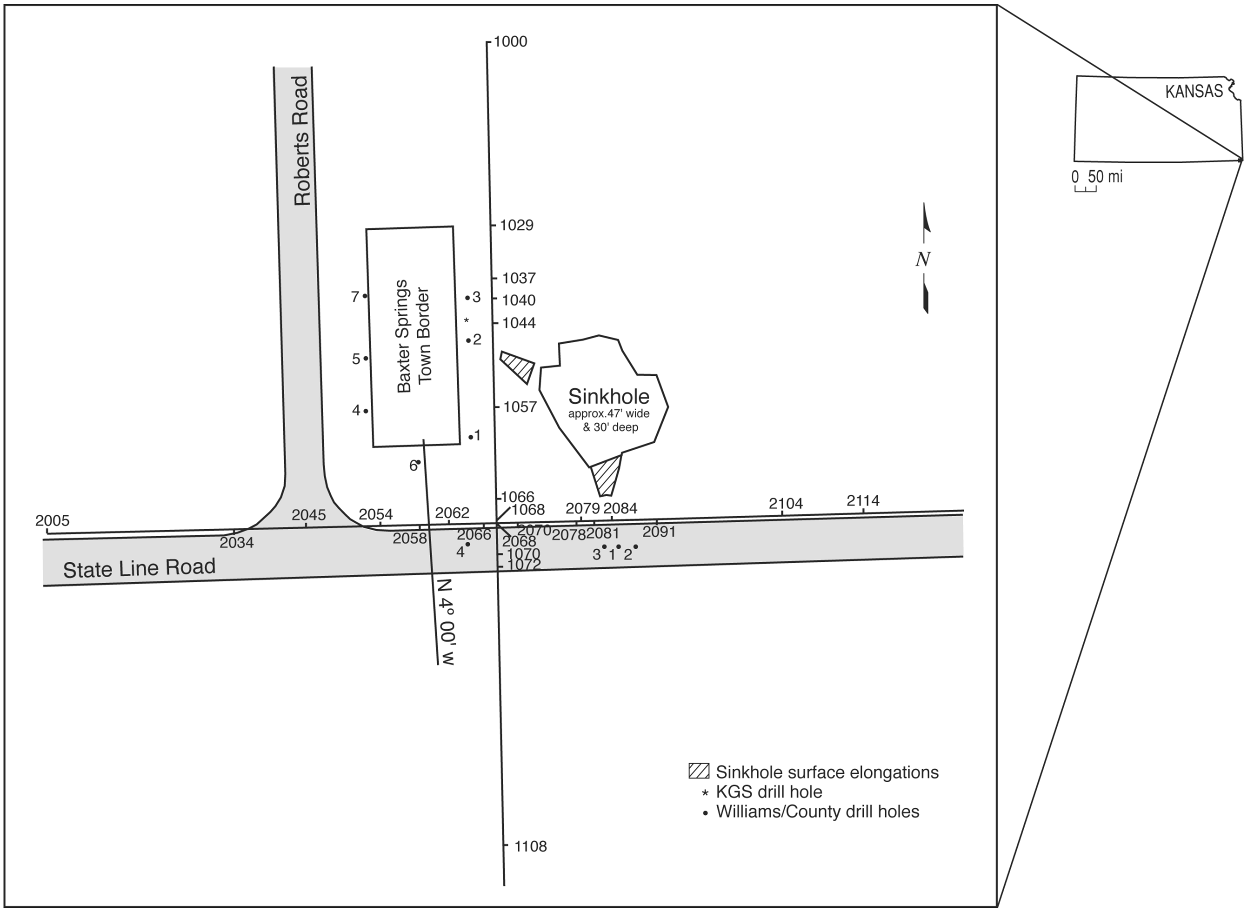

Figure 2. Site map, Baxter Springs, Kansas, with line locations, drill holes, sinkhole, roads, and gas metering station (inside "Town Border").

(line 2) (Figure 2). During the testing phase, technique evaluation and measurements included: confidence estimations at various penetration depths (imaging depths), generalized velocity model, and feasibility of distinguishing velocity changes within the limestone correlated to changes observed in the borehole data. With the extremely disturbed nature of the near surface in this area, confident correlation of individual anomalies mapped using 2½-D surface wave data with core- and drill-derived geologic descriptions would not be a cost effective next step. Considering the resolution and accuracy necessary to produce a meaningful map of fractures and voids, the testing phase has been extended to include several time-lapse images of the subsurface along the two crossing profiles. Using this approach, the degree of change in strain over time and its implications to the structural properties of roof rock can be evaluated.

General Geologic Setting

From 1850 to 1950 the Tri-State Mining District of Missouri, Kansas, and Oklahoma was one of the foremost mining areas in the world (Stewart, 1986). During that period this area produced 50 percent of the zinc and 10 percent of the lead sold in the United States. The mining district has been inactive since the 1970s and all the mines are flooded with water. Across the span of active mining in this area more than a half-billion tons of ore were removed and smelted. Due to the inherently small ore body sizes (averaging less than 1/5 million tons) and shallow ore depths, small, portable mining operations were scattered around the area and on the average would deplete an ore body and move on in five to ten years. This transient style of mining is why many details of these mine operations—normally documented—are missing, and what little documentation that does exist is incomplete, inaccurate, or currently unavailable. With the necessity for efficient production, operations not directly related to or necessary for extracting or delivering marketable ore were, at times, only minimally attempted.

In a general sense, the geology of the area as it relates to surface activities and lead/zinc mining is relatively simple. For the most part it consists of a cyclic sequence of Mississippian cherty limestones that gradually become exceedingly more complex in areas were deformation (faulting and fracturing) and resulting dissolution have been active. Ore bodies are generally characterized to possess small complex geometries and distributed around areas coincident with localized rock alterations where mineralized fluids had easy access to shallow rock units. Ore deposits can occur as single bodies or clusters extending for miles along fault traces and fracture patterns. Using geophysical techniques to delineate rubble and water-filled mine voids in an area riddled with fractured rock and its associated anomalous physical properties requires good ground truth and high resolution.

Current Procedure

The current operational procedure requires extremely broadband acoustic signal rich in lower frequency components of the spectra critical for penetration and imaging deeper targets. High frequency signals are necessary for applications focused on detecting smaller anomalies at shallower depths. The Rayleigh wave is the primary wave type of interest. The dispersive nature of this wave is a measure of the layered nature of the earth. It is the phase velocity of surface waves that most closely corresponds to the shear wave characteristics of the subsurface. By calculating the dispersion curve (phase velocity as a function of frequency) and then inverting that curve, a shear wave velocity profile can be calculated for the area directly beneath the acquisition spread. Acquiring data by progressively moving the source from one station to the next while maintaining a consistent number of receivers and source-to-receiver separation permits the generation of a two-dimensional profile of the shear wave velocity structure as a function of depth and station location. Presenting this shear wave profile as a 2-D image enhances visualization of geologic features responsible for the anomalous gradients and absolute changes in shear wave velocity. Large variations in the gradient of the velocity field are generally indicative of abrupt changes in material properties.

Data Acquisition

Data were recorded on a 60-channel Geometrics StrataView seismograph using single GeoSpace 4.5 Hz GS-11D geophones equally spaced along the profile line (Figure 3). Energy for this study was provided by an accelerated weight drop source (Rubber band Accelerated Weight Drop—RAWD) designed and built at the Kansas Geological Survey (Figure 4). Source selection was based on depth of interest, velocity structure, site logistics, and source characteristics (total energy, frequency, destructive nature, etc).

Figure 3. Seismograph and recording equipment mounted on a six-wheel ATV.

Figure 4. Rubberband Asisted Weight Drop (RAWD) mounted on a skid steer loader. Gas metering station is in the background.

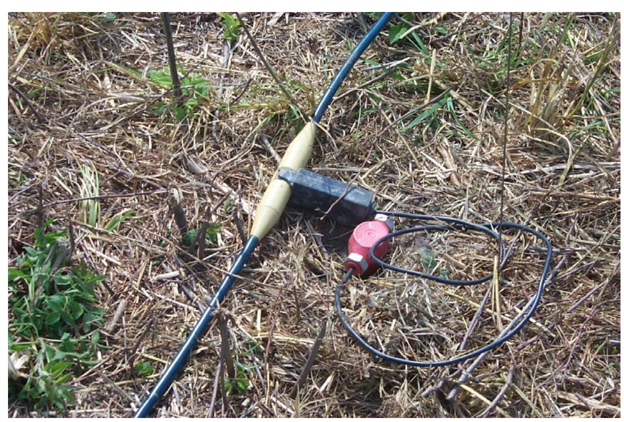
Figure 5. 4.5 Hz geophone planted in soil and connected to seismic cable.

Figure 6. View looking south from the north end of line 1. Sinkhole is to the left near the tree line. State Line Road runs perpendicular to line 1 where people are gathered. Gas metering station is to the right.

Receivers were coupled to the ground with short (3 inch) spikes in dirt areas and on plates where asphalt covered the ground surface (Figure 5). Research has shown geophone coupling is not as critical for high signal-to-noise ratio surface wave energy recording as it is for reflection profiling (Miller et al., 1999). Continuous profiling techniques adapted from CMP reflection profiling (Steeples and Miller, 1990) permitted a relatively large area to be imaged with dense sampling within a short period of time (Figure 6).

Initial walkaway tests were performed to establish signal-to-noise ratio, useable frequency band, and estimates of surface wave phase velocities as a function of depth. This information was integral to designing the acquisition parameters used to record these data. Significant changes in data characteristics across the survey area resulted in extreme variability in the useable imaged depths (over 150 ft in some areas and limited to less than 40 ft in others). This inconsistency in penetration was attributed to source-ground coupling. In areas with a dirt or gravel surface, the source was sufficiently energetic to produce the necessary low frequencies and therefore achieve signal penetration in excess of 150 ft. Areas with an asphalt covering were stiff, reducing the radius of deformation for a given energy level below that necessary to generate the lower frequency signals required to achieve penetration. On future surveys at this site a Bolt land airgun will be tested and likely used to enhance the desired low frequency signals across the entire area.

Data were collected along two profiles intersecting at a right angle near the north edge of the pavement (Figure 2). This line orientation provided a good sampling of the area of interest. Critical subsurface layers between the sinkhole and road and sinkhole and gas metering station were imaged and evaluated for obvious and imminent hazard. With all the drilling except the KGS drill hole completed prior to the collection of the surface wave data, this line orientation optimized the tie between the drill data (ground truth) and seismic images. This deployment provided the greatest horizontal contrast and least smearing of potential subsurface features mirroring the linear projections of the sinkhole's surface elongations (Figure 2).

Data Processing

Reduction of raw shot gathers into 1-D velocity profiles was accomplished using experience-proven processing and analysis techniques (Park et al., 1999; Xia et al., 1999). SurfSeis (a set of processing and display algorithms), developed by the KGS to facilitate this imaging technique, was used in conjunction with a commercial contouring package to produce the shear wave cross-sections. Interpretations of these data were based on correlation of ground truth data (drilling, outcrop observations, trench studies, etc.) with the various unique, well-defined features or anomalies evident in the velocity field cross-sections. These interpretations consider the signal-to-noise ratio, processing flow, and the data characteristics determined through pre- and post-signal processing and analysis. Processing flows were designed to enhance unique shear wave velocity characteristics without bias toward drill-identified anomalies. Shear wave velocity gradients and lateral changes in velocity were used as the basis for correlating unique seismic features in conjunction with drill findings.

Phase and spectral properties of shot gathers from the two lines were analyzed to determine the dispersive characteristics of the subsurface beneath each receiver spread. The dispersive characteristics of surface waves can be directly correlated to changes in the physical properties associated with distinct earth layers. Changes in surface wave phase velocity as a function of frequency relate to shear wave velocity, compressional wave velocity, density, and layer geometry. Of these properties, the dominant control of the surface wave phase velocity is in response to the shear wave velocity component.

Dispersive properties of surface waves can be inverted to estimate the shear wave velocity structure of the near surface. Assumptions integral to this process are largely related to the dominant influence shear wave velocity has on the surface wave phase velocity as a function of frequency. The inversion produces a one-dimensional shear wave profile with a distinct change or velocity step at each defined layer. Inversion requires sufficient preprocessing information to define an initial subsurface model which is used as the starting point for the iterative process. This initial model optimizes the convergence of the shear wave velocity solution as a function of depth and provides limits or bounds to which the process must adhere.

Data Analysis and Interpretation

Shot gathers were acquired using parameters which were selected during initial site testing based on optimized surface wave sampling of earth materials in a depth range from about 3 ft to over 150 ft below ground surface (BGS). Wavefield properties observed on shot gathers collected along line 1 were consistent with pre-test models developed for this site (Figure 7). The dispersive nature of data along line 1 resulted in a high-confidence layered shear-wave profile throughout the target depth range (Figure 8). Due to end effects, interpretations of layer depths and velocities below about 140 ft along this profile must be considered tenuous at best.

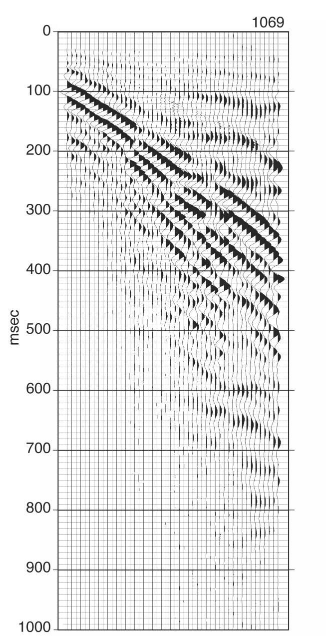

Figure 7. Shot gather from line 1.

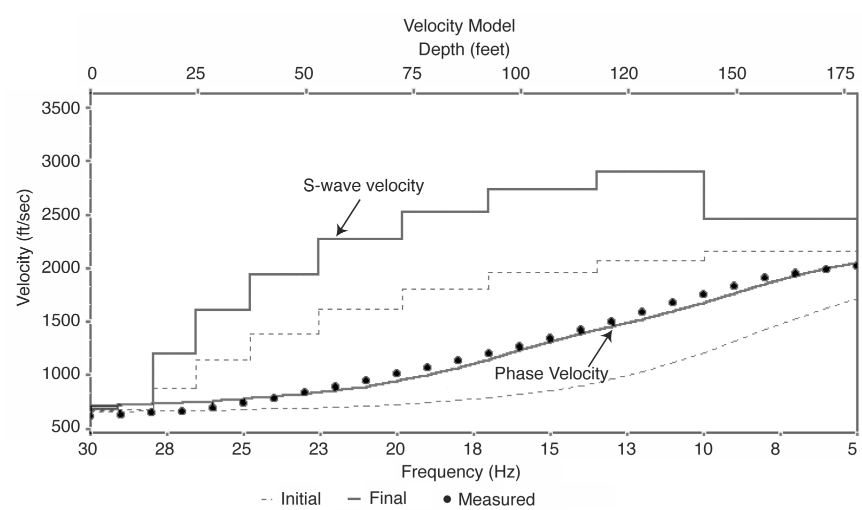

Figure 8. Dispersion curve and shear wave velocity as a function of depth for line 1.

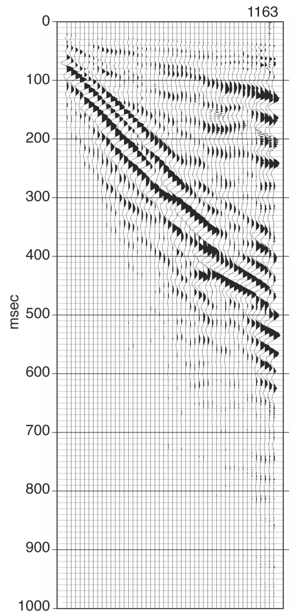

Figure 9. Shot gather from line 2.

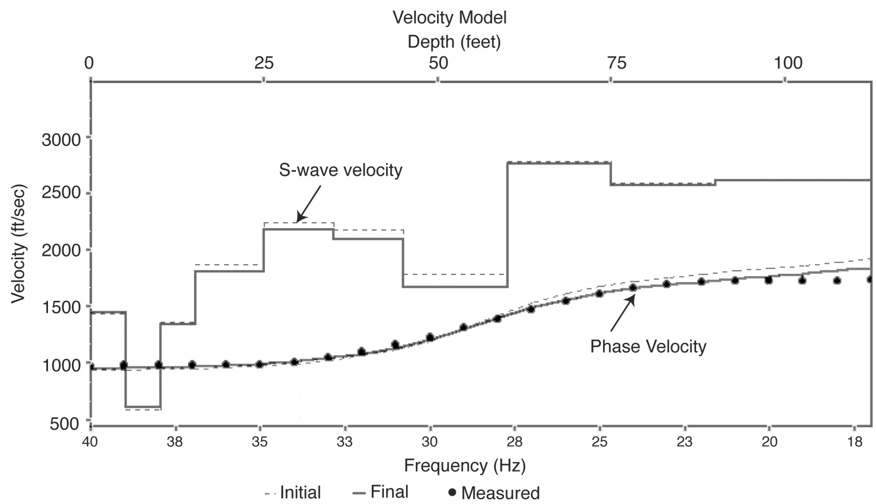

Figure 10. Dispersion curve and shear wave velocity as a function of depth for line 2.

Spectral properties of shot gathers on line 2 changed abruptly when the surface material beneath the source went from a grassy soil to asphalt (Figure 9). This change in bandwidth occurred as a result of the source's inability to produce and propagate the lower frequency components of the signal. Producing low frequency surface waves requires a large energy source to deform a large volume of earth in a very plastic fashion. The asphalt represents a relatively rigid surface which does not easily deform over a large area. Inversion of dispersion curves when the source was on the asphalt produced a shear wave velocity profile with a penetration depth around 50 ft with a reliable velocity function down to about 40 ft (Figure 10).

Line 1 data produced a shear wave velocity profile with velocity anomalies consistent with voids encountered during drilling (Figure 11). The bedrock surface is interpreted from the velocity gradient to be between 15 ft and 20 ft and traced by the 600 ft/sec contour. Immediately below the bedrock surface is a relatively uniform rock unit with a gradually increasing velocity as a function of depth. Considering the averaging effects of the 200 ft spread length used to acquire these data, materials above 40 ft along this profile are laterally continuous with no obviously noteworthy characteristics. Below 40 ft the presence of significant variations in rock stiffness or rigidity become evident.

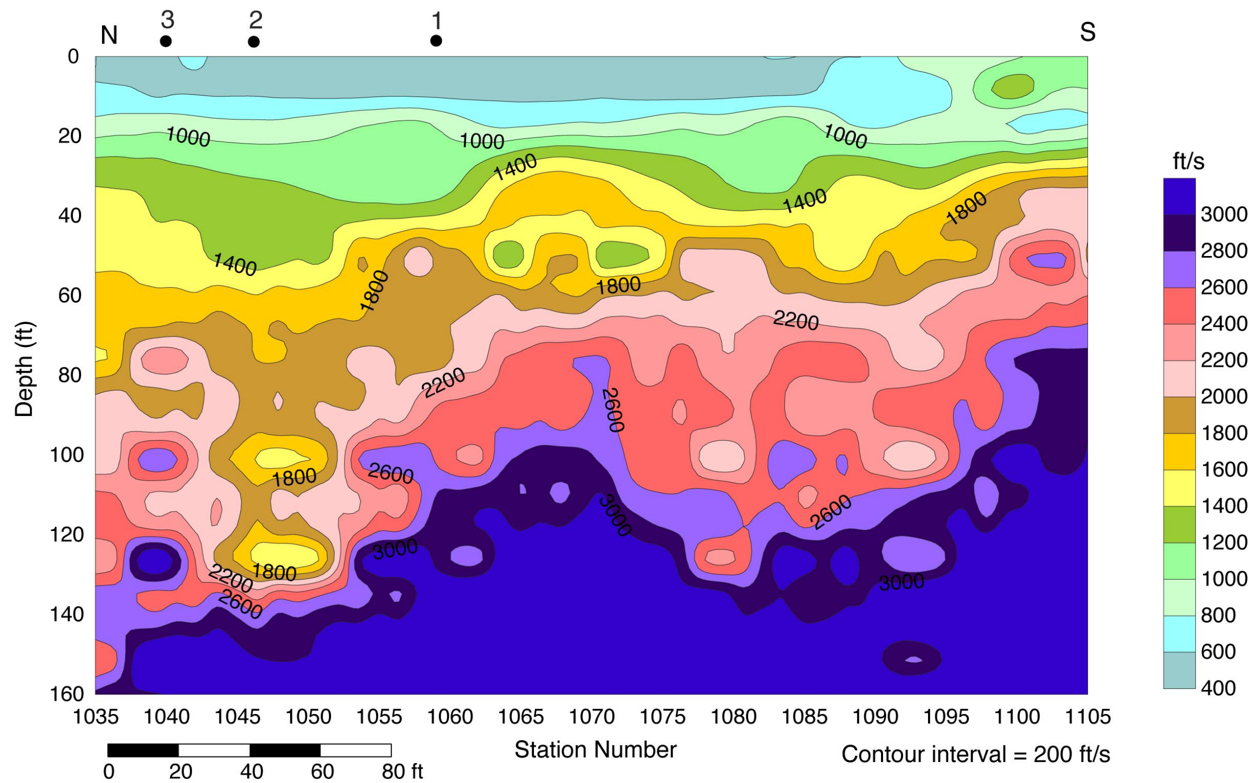

Figure 11. S-wave velocity of line 1 (parallel to Roberts Road), Baxter Springs, Kansas.

Features of particular interest along line 1 are located beneath station 1045, 1067, 1080, and 1093 at depths greater than 40 ft. These features are generally low velocity closures interpreted to represent reworked or missing rock material. It is not possible to determine whether reworked rock (rubble), soft sediment infilling, or water/air filled voids are responsible for these drops in velocity, or even if they are natural or man made. Several of the features appear to be of a size and shape that would lend themselves to being interpreted as collapse or void features associated with fractures or faults. In particular, the anomaly beneath station 1045 is characterized by a vertically elongated low velocity zone 5 to 10 ft wide and about 25 ft high. This could be related to fractured or faulted rock extending to depths greater than the limited penetration of this survey. Although the KGS drill hole at station 1048 did not encounter an anomaly clearly correlatable to this feature, the drill hole did penetrate several void areas along its vertical traverse. Descriptions on drilling logs of these two features are consistent with the conceptual model of a rubble filled mine drift on shear wave data. Based on the very uniform nature of the sediments portrayed on the shear wave velocity profile above about 50 ft, it is unlikely that this feature could someday be responsible for a sinkhole.

Low velocity zones beneath stations 1080 and 1093 appear to be relatively small fracture zones infilled with soft sediments. This is postulated based on their minimal gradient and somewhat subdued expression. These two features are likely related and could easily be a large healed fracture zone composed of an extensive series of very small fractures. These features do not appear to possess a subsidence risk.

Of particular interest is the feature located beneath station 1067. The pair of low velocity closures at a depth of about 50 ft represents the shallowest low velocity anomaly imaged along this line. The 400 ft/sec velocity gradient across a 20 ft expanse correlates to a 30% deviation in velocity, easily interpretable as an air or water filled void (in this case water filled is most probable). Alone these low velocity zones are of interest but not of concern; however, in concert with the anticlinal (inverted bowl or halo) shape of the velocity contours above these low velocity closures, further examination in the form of drilling or seismic monitoring would be prudent. During development and evaluation of this technique in subsidence prone areas of Alabama, low velocity closures capped by high velocity halos were characteristic of strain build-up generally observed in proximity to swarms of active karst related sinkholes.

Line 2 suffers from inconsistent depth of signal penetration across most of the profile (Figure 12). Along the western quarter of line 2 the source was located on the dirt berm forming the road ditch. Source coupling along this berm was conducive to the generation and propagation of frequencies low enough to image depths in excess of 140 ft. The asphalt did not permit generation of those same low frequencies, as evident from the very uniform high velocity nature of the section below 60 ft along the entire eastern three-quarters of the profile.

Clearly, several significant anomalies exist along line 2 at depths where confident interpretations can be made. Of particular interest: the anomaly beneath station 2040 as well as the low velocity pattern observed between station 2065 and 2085. The low velocity closure beneath station 2075 is approximately equivalent to the feature observed beneath station 1067 on line 1. Unlike its counterpart on line 1 (station 1067), the feature on line 2 does not have a well-defined high velocity halo. A final feature, physically the smallest of the anomalies noted on line 2 but probably of the most concern, is the low velocity closure at about 50 ft BGS capped by an extremely high velocity geometrically erratic zone beneath station 2090.

The feature beneath station 2040 is the largest and probably the best target for a confirmation drill hole targeting mine workings. This anomaly is very similar in character to the one at station 1047 on line 1. The anomaly beneath station 2040 has all the physical characteristics of

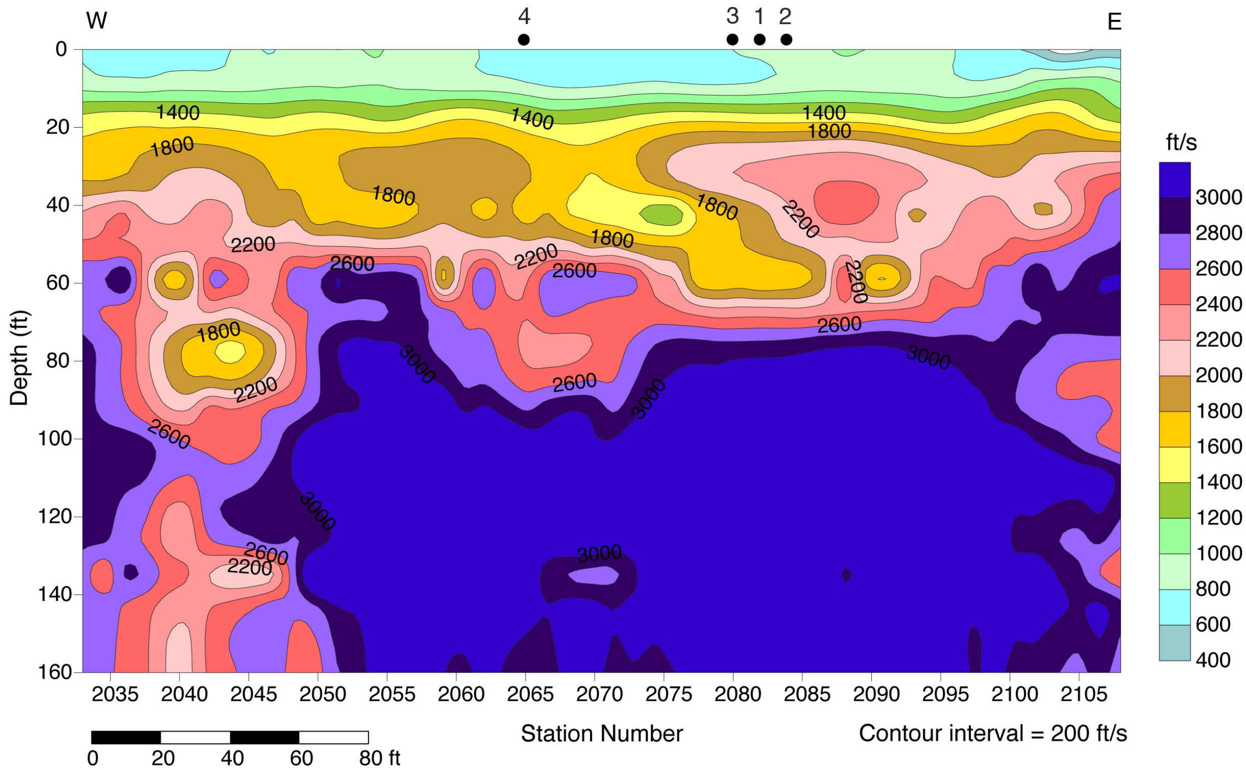

Figure 12. S-wave velocity of line 2 (along State Line Road), Baxter Springs, Kansas.

a mine drift. Of significant interest and potential psychological reassurance is the lack of any kind of a high velocity halo above this feature. It is very unlikely this feature is building strain in a fashion that would be considered a precursor to roof failure and collapse.

The low velocity closure beneath station 2075 possesses a velocity structure and surrounding contrast similar to the 1067 feature on line 1. This correlation is not certain but likely, considering these two features are less than 20 ft apart. Unlike the closure on line 1, this feature is not capped by a high velocity halo. The absence of a high velocity gradient is key to suggesting this feature is of little or no risk of imminent subsidence. The east dipping orientation of the velocity contour lines that define this elongated anomaly lacks correlation with the voids detected in drill holes 1, 2, and 3. Both drill and seismic data indicate rapidly changing rock properties above the void zone at station 2075.

A final feature worthy of discussion on line 2 is the low velocity closure directly beneath the high velocity closure at station 2090 extending from 20 ft to 50 ft BGS. In this particular case the high velocity halo over the low velocity closure does not possess a geometry consistent with what has been previously observed in subsidence-prone areas. Considering the cyclic nondipping geology in this area, it would not be unreasonable to expect strain to build along intact layers which act as the roof for lenticular voids. Sediments above 20 ft at station 2090 appear to have little risk of imminent collapse, if roof strain and the resulting failure can be directly correlated to localized, high velocity anomalies. With the bedrock surface defined by flat and uniform velocity contours in comparison to the rest of the line, it is doubtful the bedrock surface was under stress below station 2090 at the time this profile was acquired. A final troubling correlation is proximity of this high over low velocity feature at 2090 in comparison to the subsurface extension of the surface elongation of the sinkhole.

The lack of a detailed correlation between voids encountered on drilling and low velocity zones evident on the shear wave velocity image around station 2080 is likely related to the complexity and close proximity of large subsurface anomalies. A single feature with a large velocity gradient can easily overshadow (interfere with) smaller anomalies possessing minimal lines of closure and subtle signatures in the velocity domain. The borehole data from holes 1, 2, and 3 along line 2 might correlate quite well to low velocity anomalies, which would be obvious if the dramatic and extensive, shallow, high-velocity feature beneath station 2090 were not present. This again suggests the high-velocity feature beneath 2090 is not related to a more competent rock body, but is a strain build up. If significant strain is building on the roof rock directly above the void at around 60 ft BGS at station 2090, then depending on the geometry of the roof, the shear wave velocity field related to the anomalies at 2080 could be significantly distorted or interfered with.

Conclusions and Recommendations

The goal of this study was to evaluate the feasibility of this technique to detect void features and how well their potential of developing surface expressions (sinkhole) could be appraised. Of primary concern was identifying low velocity anomalies, in otherwise laterally continuous materials, that can be correlated to current sinkholes. Of particular interest was the sinkhole's relationship to old mine works or fractures inferred from mine maps and detected by drilling. The surface wave imaging technique clearly possesses excellent potential as a monitoring tool in this setting. It was not possible to correlate velocity anomalies on shear-wave profiles to drill-encountered voids with sufficient confidence to map individual voids and their extent. An additionally complicating factor at this site is discriminating the geometrically complex geology of this unique setting from void signatures.

Considering the complex geometry of the fracture and fault systems in this area it is not surprising this method does not possess the resolution necessary to discriminate each void encountered during drilling. The method does possess vast potential as a long-term monitoring tool in this geologic setting. Geophysical methods provide a much better understanding of how things change as opposed to providing unique correlations to geologic units or features. In that regard, by using the method in a time lapse format, changes associated with increased strain or vertically migrating roof failure should be easily detected. A great deal of confidence can be placed in determinations of subsidence potential if changes in the shear wave velocity field can be contrasted and compared across time.

During future studies at this site it will be critical to increase the depth of signal penetration and therefore investigation along the paved State Line Road. This will be accomplished by using greater source energy with a larger surface coupling. Previous studies demonstrated that the larger the source and area of surface coupling the lower the dominant frequency and bandwidth of the surface wave energy. Increasing penetration while maintaining uniformity in procedures will be a primary objective of future studies and necessary to evaluate change at this site.

Based on subsequent analysis of the shear wave image, the high velocity anomaly beneath station 2090 on line 2 may be the result of the low velocity closure directly beneath it. This high velocity closure is very irregularly shaped and is not consistent with previous observations of voids. However, the chance that this high velocity anomaly represents the halo effect commonly associated with strain build up above a void cannot be overlooked. It would be prudent in the near future to invasively investigate this feature and its apparent relationship to the low velocity closure directly beneath it.

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