3D MASW Characterization of Sinkhole:
A Pilot Study at USF Geology Park, Tampa, FL

Choon B. Park, Park Seismic LLC, Shelton, Connecticut, USA
Chris Taylor, GeoView Inc., St. Petersburg, Florida, USA

ABSTRACT

By running three parallel and one crossing lines of conventional 2D MASW surveys followed by normal 1-D MASW inversions, a 3D characterization was attempted as a pilot study over an area of a known sinkhole 10-40 ft deep with lateral dimension smaller than 50 ft. Shear-velocity (Vs) data sets from each line were then used as constraints to calculate a cubic grid data in x (east-west), y (south-north), and z (depth) directions by using a 3D inverse-distance-weighted (IDW) interpolation scheme. When displayed in depth-stripping mode at 5-ft depth intervals, velocity anomalies of substantially lower values than those in the ambient are recognized in the surface and depth locations that correlate fairly well with those identified in a geologic cross section previously compiled from other methods of well drilling, CPT, and GPR surveys. Properly selecting offset range during data acquisition and subsequent dispersion analysis seems critically important for the successful detection of a sinkhole.

INTRODUCTION

Sinkhole development in cultural area always threatens human life and property integrity. Early detection and accurate characterization of its subsurface development, therefore, have become crucially important issues among relevant communities including geotechnical engineers. Its inherent nature of being localized and three-dimensional strongly calls for a 3D survey in order to make any subsequent remedial process, if necessary, become as effective as it can be. Recent introduction of simple and cost-effective 3D approach (Park and Carnevale, 2009) with the multichannel analysis of surface waves (MASW) method (Park et al., 1999) has shown that 3D seismic investigation—normally known as exceptionally expensive in field and data-processing efforts—can become an affordable option that implements multiple conventional 2D shear-velocity (Vs) surveys along several linear trajectories intersecting or paralleling each other on the surface.

The State of Florida may have possibly the most sinkhole areas developed within the cultural area of the world (Figure 1). Concern for sinkhole-related public safety is growing rapidly and the number of litigations in residential and commercial areas has grown exponentially in recent years. A variety of geophysical methods—including ground-penetrating-radar (GPR), resistivity, and MASW—have been applied to effectively characterize sinkhole-related subsurface features. Considering the most important subsurface property is usually the stiffness distribution in and around an existing or developing sinkhole area, the MASW method that generates shear-wave velocity (Vs), a direct indicator of stiffness, seems to be one of the most useful geophysical approaches.


(source: http://www.technos-inc.com)

Figure 1. The distribution of karst areas in the United States (from Davies, 1984)

GeoView Inc. and Park Seismic LLC conducted a pilot study with the 3D MASW approach over a sinkhole area with a mild surface depression (≤ 3ft) known to exist in Geology Park (GeoPark) at the University of Southern Florida (USF), Tampa, Florida (Figure 2), to evaluate the approach's potential effectiveness and future calibration. This area was intensively investigated previously by geologic (e.g., well drilling), geotechnical (e.g., CPT), and geophysical approaches (e.g., GPR) (see, for example, Parker, 1992). Figure 3 shows a geologic cross section of the area compiled from all previous survey results.

Figure 2. Location map of the studied sinkhole area.

PREVIOUS STUDIES

Sinkhole investigation has been one of the major issues in multidisciplinary fields including geophysics, geology, geotechnical engineering, geomorphology, remote sensing, etc., resulting in a vast number of publications in all these fields. Particularly, it has been the major purpose in geotechnical karst investigation sometimes considered analogous to the needle in the haystack problem (Yuhr et al., 2003). From the standpoint of geophysical investigation, it has been the detection of highly localized anomalies such as voids and cavities that often challenged resolution limits of such commonly used methods as GPR, resistivity, and seismic surveys. Although each of these geophysical approaches is continuously evolving in its own way in methodology and measuring instruments, none of them is exclusively superior in every aspect over others. We report our early-stage efforts to make the MASW approach further evolve and become better suited for future sinkhole and karst investigations.

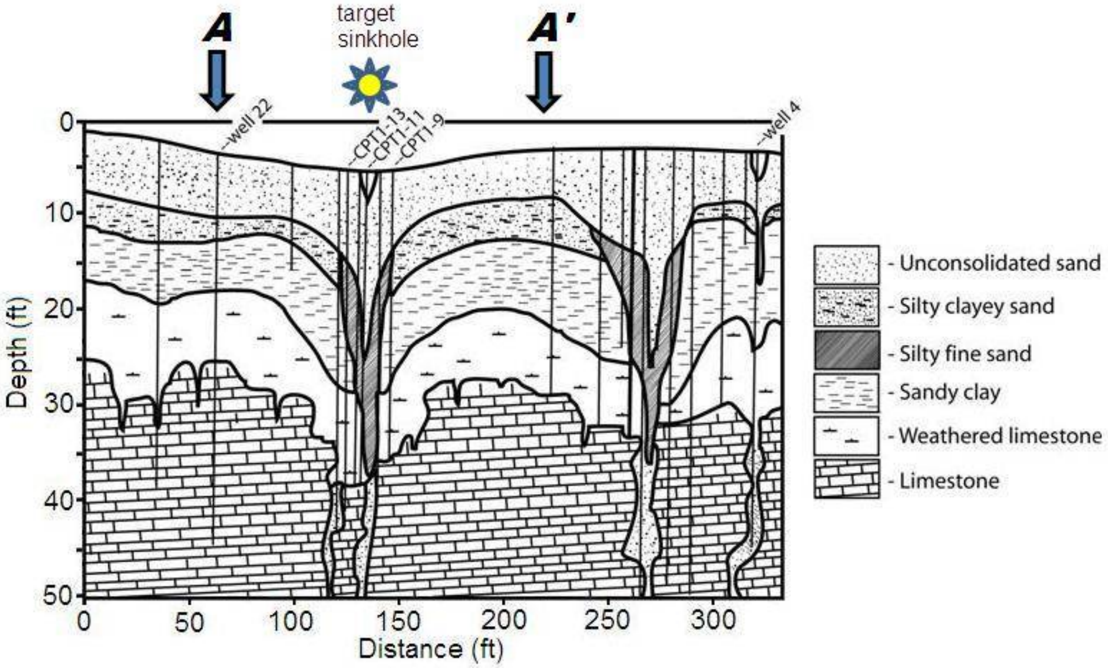

Figure 3. The geologic cross section of the sinkhole area compiled from results from the previous other surveys (from Parker, 1992).

Some of the most recent sinkhole- and karst-related studies include the investigation of large sinkholes (50 to 200 m in diameter) in Texas using satellite-based radar interferometry (Paine et al., 2009). De Kleine and Bakker (2009) used GPR to map and classify caves and cavities over a karst area in Bonaire, Netherlands Antilles. Campbell (2008) applied several different approaches of GPR, MASW, and resistivity surveys over karst limestone terrains in Australia. Xu et al. (2008) introduced a unique Rayleigh wave inversion approach to image subsurface cavities through a new dispersion analysis sensitive to existence of cavities, and Putnam et al. (2008) analyzed surface waves on several 24-channel field records acquired over a shallow (≤ 2 m) spillway tunnel 1-m in diameter with focus on the surface wave scattering and corresponding attenuation phenomena. High-resolution seismic reflection approaches were also used to image subsurface boundaries related to sinkhole subsidence (Lambrecht and Miller, 2006; Dobecki and Upchurch, 2006; Miller, 2002). Kim et al. (2006) applied cross-hole resistivity tomography to detect an abandoned mine below a 25-story building in South Korea. Gelis et al. (2005) reported a numerical modeling study to delineate surface wave responses over shallow voids in association with their dispersion properties, and Nasseri-Moghaddam et al. (2005) performed similar numerical study over void zones with focus to surface wave scattering and attenuation properties. The first 2D application of MASW to a sinkhole investigation was done by Xia et al. (2001) during a feasibility study to define a sinkhole impact area at a nuclear power plant in Maryland. 3D MASW characterization of sinkhole and karst areas is unprecedented.

3D MASW METHOD

Park and Carnevale (2009) indicated that the conventional 2D MASW investigation focuses on the inline propagation of planar surface waves and therefore the resultant 2D shear-velocity (Vs) map best represents the cross sectional image of the subsurface stiffness distribution with a minimal influence from the offline features like side scattering. It showed that a 3D cubic data set of practical value can be constructed from multiple surveys (e.g., 4 or more) of conventional 2D mapping designed in a parallel or intersecting manner. It concluded that proper 3D interpolation and effective data presentation play key roles if the approach is to be of any practical value. It was suggested that the approach is more cost effective and possesses a greater practical value than the previous attempts of pseudo-3D MASW surveys by Miller et al. (2003) and Suto (2007).

For the pilot study to characterize the sinkhole feature in GeoPark at USF, we used proprietary software developed at Park Seismic LLC for 3-D interpolation and display purposes. To demonstrate its performance, we created a synthetic cubic grid data set of 100x100x100 size in x (east-west), y (south-north), and z (depth) directions that had only two different velocity values of 100 m/sec (blue) and 500 m/sec (yellow), with the latter value assigned to the hemispheric feature sitting on top of a half space of the same velocity value. Figure 4 shows this data set displayed in cubic, x-, y-, and z-layer stripping modes. Figure 5 shows results from a simulated 3D MASW survey that consisted of total six linear survey lines of 2D mapping indicated on top of the original cubic display. It was assumed that each 2D mapping along these six lines duplicated the exact cross sectional image of the original data. Then, the subsequent 3D interpolation process constructed a cubic grid data set of 100x100x100 size whose layer stripped images are shown in Figure 5. In comparison to the original data set displayed in Figure 4, the interpolated data set restored the original feature fairly well. The inverse-distance-weighted (IDW) scheme was used for the 3D interpolation.

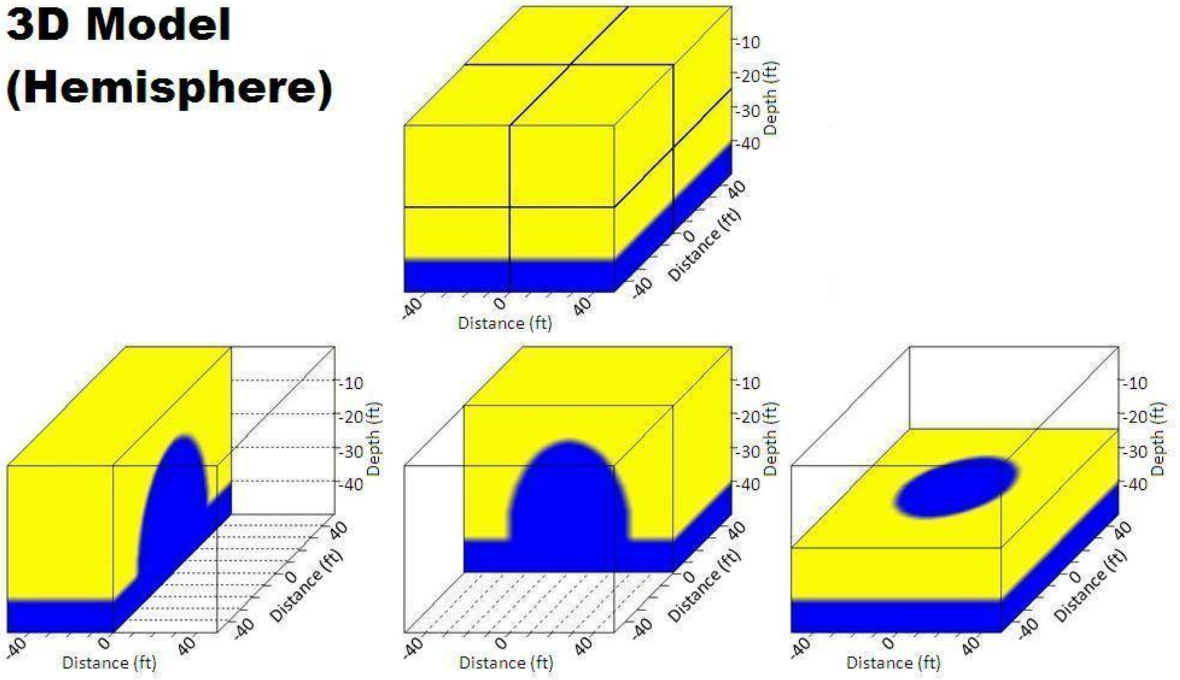

Figure 4. (Top) A synthetic 3D cubic grid data set with two velocity fields. (Bottom) 3D shape of the higher value field (blue) is illustrated by three layer-stripped displays along the x, y, and z axes.

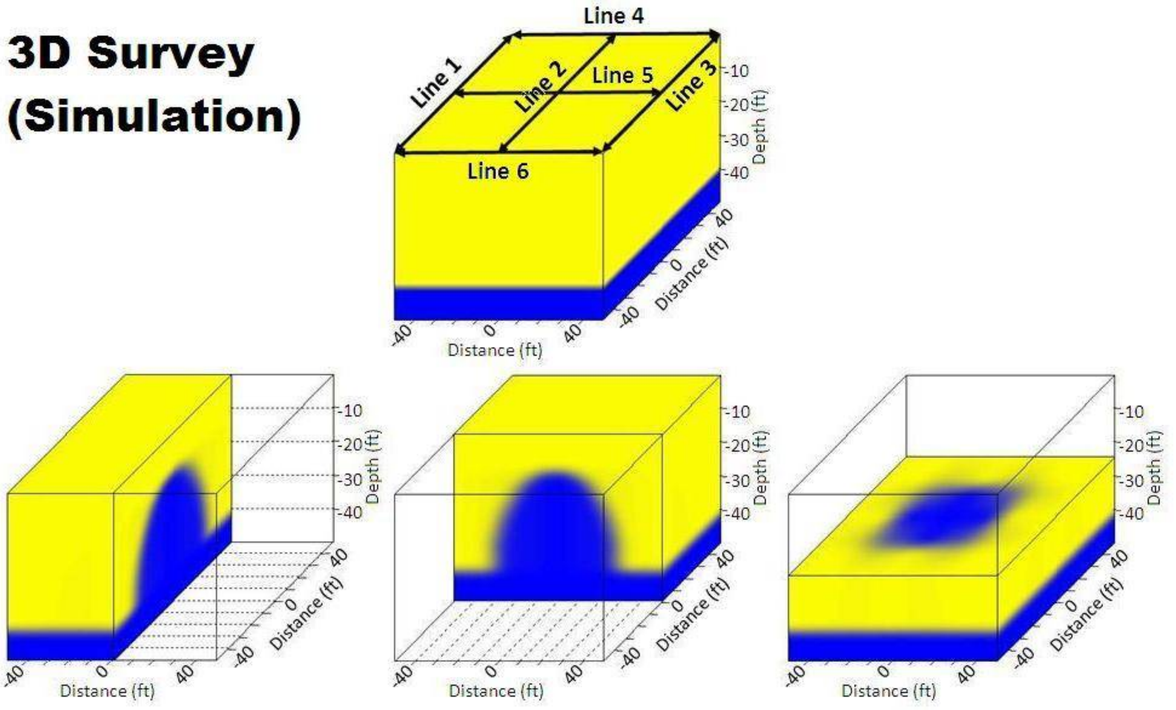

Figure 5. Simulation of 3D (MASW) survey on top of the synthetic cubic data displayed in Figure 4. Location of the six (6) lines used for the simulation (top), and results from the 3D interpolation (bottom).

3D MASW SURVEY AT USF GEOPARK

The GeoPark (Figure 2) in the campus of USF, Tampa, FL, was built in 2001 as a resource site for on-campus geological teaching and research, and nowadays continues to serve as a demonstration site for a variety of courses including hydrogeology, geophysics, and geomorphology (www.karst.usf.edu/USFGeoPark).

A 3D MASW survey was conducted in May 2009 over a sinkhole area located inside this park by running four (4) lines of a conventional 2D MASW survey, as indicated in Figure 6. The geologic cross section shown in Figure 3 compiled from results from other surveys previously performed over the same area indicates that there are approximately three sinkhole features. Although the MASW survey lines were laid to target the major sinkhole feature shown in the central part of the cross section (located at about 120 ft of surface distance), their actual locations were determined by those surface areas with the least surface obstacles such as trees and rocks. Their locations and surface transect of thecross section are indicated in Figure 6.

Using a 24-channel land streamer equipped with 4.5-Hz geophones spaced at 5-ft intervals, a total of twenty-four (24) field records were acquired per line by moving the streamer by 5 ft, while maintaining the source offset at 60 ft. A 20-lb sledge hammer was used as a seismic source and each saved field record was a stack of data from two hammer impacts. A sampling interval of 1-ms and total recording time of 1-sec were used throughout acquisition with a 24-channel Geometrics Geode.

Considering the maximum lateral dimension of the subsurface sinkhole feature was smaller than 60 ft, as indicated by the geologic cross section in Figure 3, it was speculated at the beginning stage of data processing that using all 24 traces of each field record spanning 115 ft of surface distance might smear off the target subsurface feature. Therefore, only the first twelve (12) traces of each record spanning 55 ft of surface distance were used for the subsequent dispersion imaging process performed with the method by Park et al. (1998). Then, one fundamental mode (M0) dispersion curve was extracted from the image. Most of the extracted curves had frequencies in the range of approximately 10-70 Hz, corresponding to approximately 5-100 ft in wavelength range. These curves were then inverted for the depth (1D) variation of shear velocity (Vs) by using the algorithm by Xia et al. (1999). Those 1D (depth) Vs profiles at different surface coordinates of x and y were then used to create a cubic grid data set of 100x100x100 data points in all three directions so that it covered the 120 ft x 120 ft surface area indicated in Figure 6 and 60 ft of depth. The IDW scheme previously tested was used for the 3D interpolation. Figure 7 shows this data set displayed in cubic modes of two different perspectives, whereas Figure 8 shows the data set displayed in depth-stripping mode at 5-ft intervals.

Interpretations have been made on some of the depth stripped displays in correlation with those sinkhole features identified in the geologic

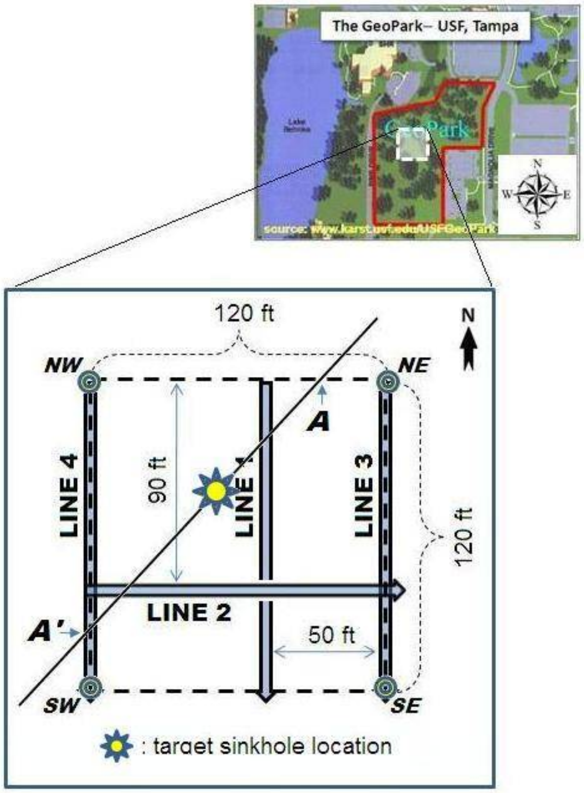

Figure 6. Location map of the four (4) MASW survey lines in the sinkhole area.

cross section. Localized velocities of noticeably lower values than those in the ambient area were interpreted as being possibly related to the sinkhole feature. This was based on the notion that shallower materials of lower stiffness would migrate down once influenced by the sinkhole activities below.

Prominent velocity anomalies marked on depth-strip displays in Figure 8 start to appear at a depth range of 10-40 ft that is in good accordance with the depth range of overburden soil most disturbed by the target sinkhole as shown in Figure 3. It seems that the sinkhole area on top of the weathered zone of limestone bedrock deeper than approximately 40 ft might not have a sufficient lateral dimension of disturbance to be resolved by the MASW method implemented with the particular acquisition parameters used during the survey. Surface (x and y) location of these interpreted anomalies correlates well with the location in the geologic cross section except for those appearing on the north-west corner of displays, which may indicate the possibility of another sinkhole area not yet identified.

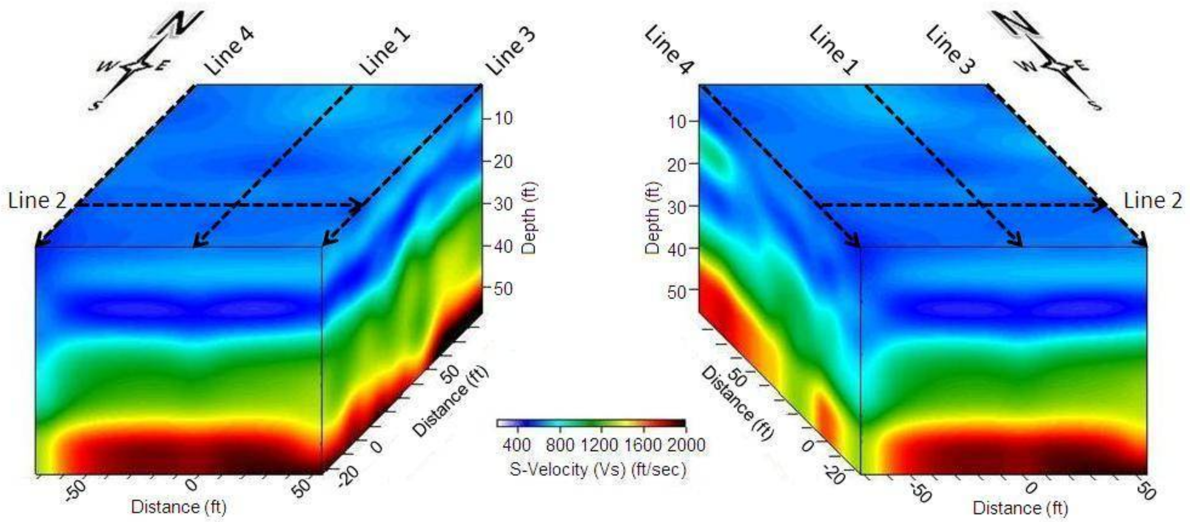

Figure 7. 3D cubic grid data set constructed by a 3D interpolation of shear-velocity (Vs) data obtained from the four (4) lines of MASW surveys marked on top of the cubic displays with two different perspectives.

DISCUSSIONS

The lateral resolution of a MASW survey is highly sensitive to the receiver spread length (L) because the subsurface model within the spread is considered to be a layered earth that has no lateral but vertical change in seismic velocities. This is an inherent premise in all surface wave methods currently in common use. In consequence, one multichannel field record is processed during the dispersion analysis by averaging out any lateral variation, if it exists, of surface wave propagation due to the plane-wave assumption used during the analysis, which results from the layered-earth assumption. Therefore, if the lateral dimension of the target anomaly (e.g., sinkhole) is excessively small in comparison to the spread length (e.g., $\leq 0.5L$), then the analysis may not detect any anomalous properties in the frequency-phase velocity relationship caused by the target anomaly. This can result in a Vs map (2D or 3D) that sometimes completely fails to detect the anomaly. Although we chose a spread length (115 ft) long enough to ensure a sufficient depth coverage, it was obviously too long to detect the target feature whose

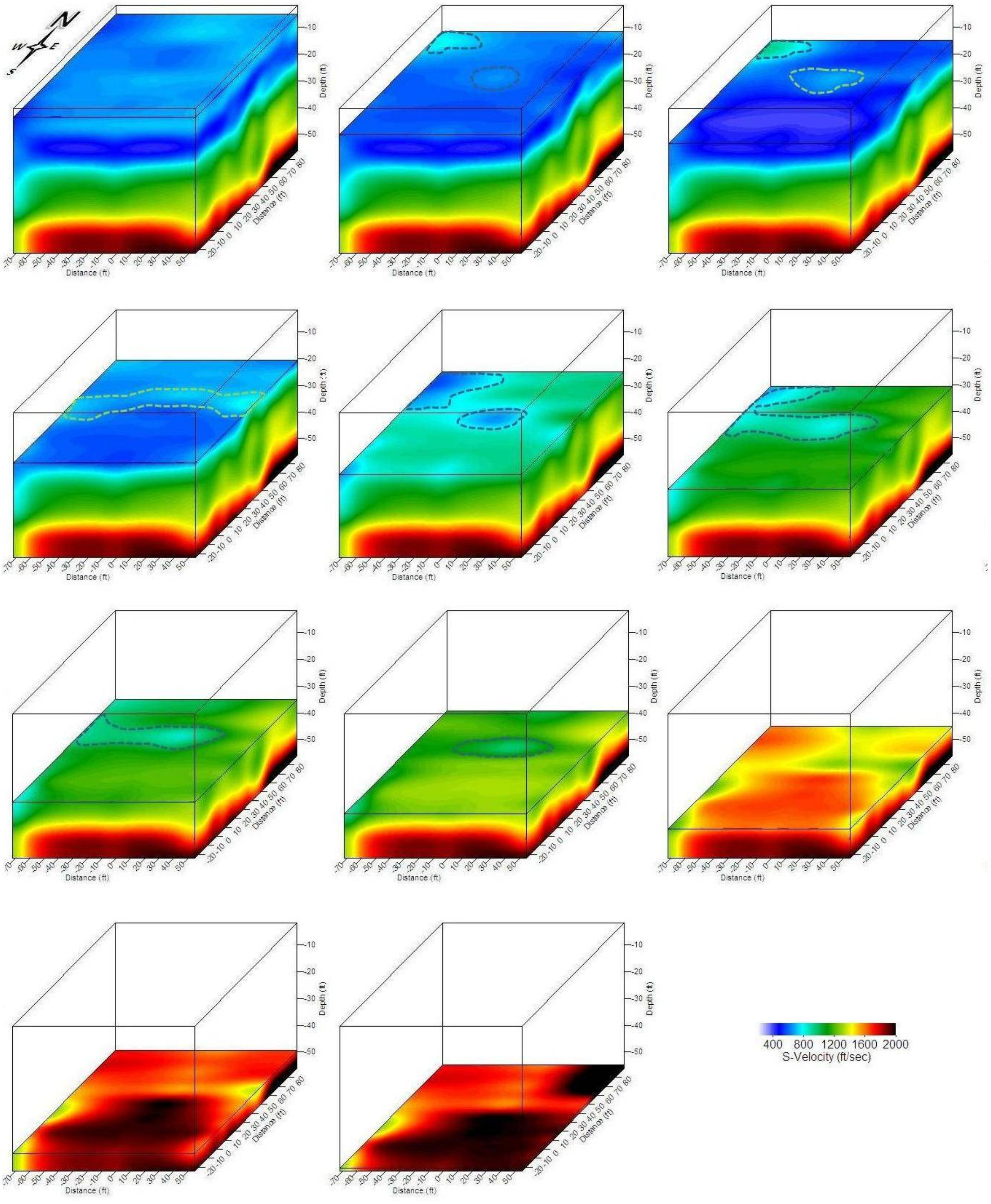

Figure 8. The 3D cubic grid data set of the sinkhole area in Figure 8 displayed in depth-stripping mode at 5-ft intervals. Suspected sinkhole features are indicated by dotted lines in certain displays.

traces of each record were used, the 2D Vs map obtained from the analysis of the line 1 data set completely fails to detect the target feature (Figure 9a). On the other hand, the target becomes prominent when only the first twelve traces of the 55-ft spread length were used for the analysis (Figure 9b). Note that surface coordinates of these two maps are off by 30 ft due to the difference in midpoint of each field record used for the analysis.

Receiver spread length is usually selected to be long enough to ensure a sufficient depth coverage, which tends to be the issue of utmost importance during the early planning stage of a field survey. For example, it is usually set to be 200-300% of the maximum investigation depth (Zmax) (Park et al., 1999; 2002). However, considering the adverse influence on the lateral resolution with an excessively long spread, it is always recommended that the same data set be processed multiple times by choosing different offset ranges to evaluate the possible smearing effect.

CONCLUSIONS

Results from a 3D MASW survey over a known sinkhole area seem promising for a pilot study. Velocity anomalies suspected as sinkhole signatures are delineated at the surface and depth locations in a fairly good accordance with the geologic cross section compiled from previous results when different methods were used. Proper selection of offset ranges during data acquisition and processing stages seems critical in successful delineation of the subsurface feature related to the sinkhole existence. For

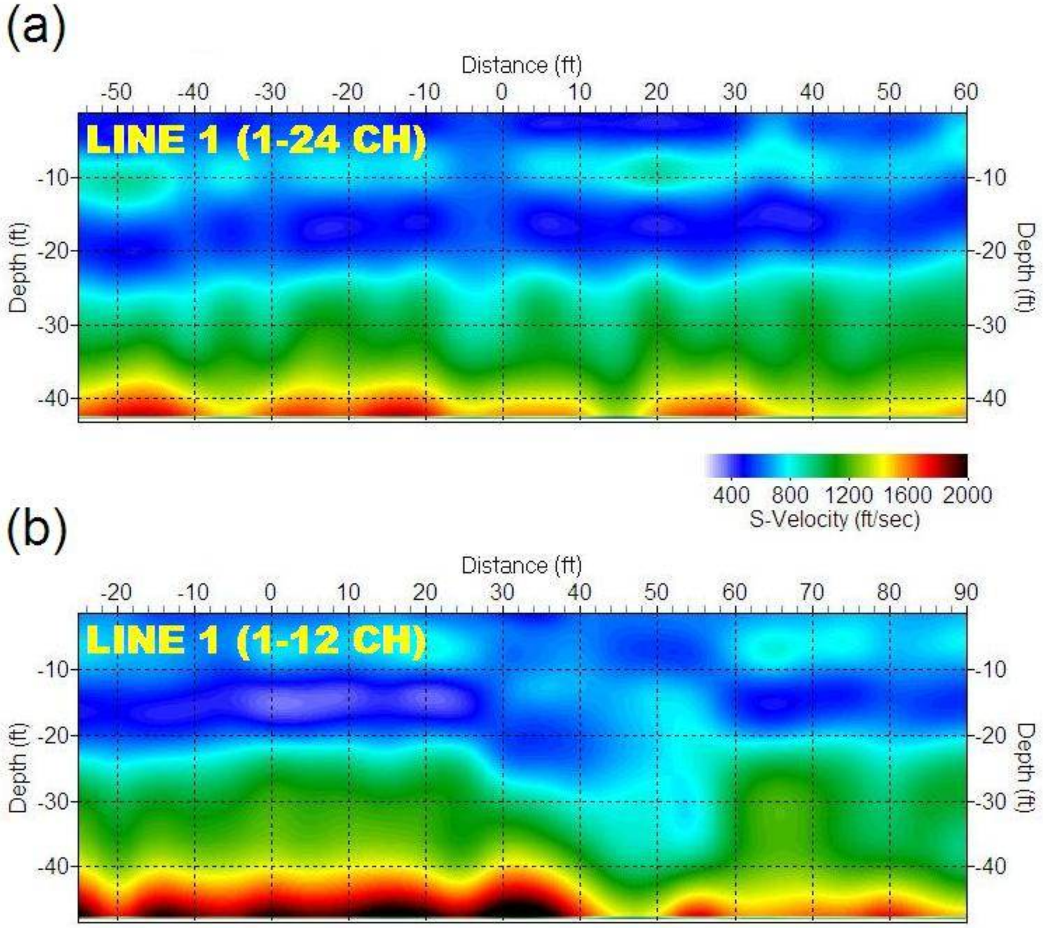

Figure 9. 2D shear-velocity (Vs) maps obtained by analyzing field records of line 1 using (a) full 24, and (b) only the near-offset 12 traces of each record.

the same area, it is recommended that another 3D MASW survey be conducted with lines more densely spaced (e.g., 10 or more parallel lines about 10 ft apart) in the future for the purpose of testing further improvement in overall resolution.

ACKNOWLEDGEMENTS

We would like to give our sincere appreciation to Professor Sarah E. Kruse at the Geology department of USF, Tampa, for her cooperation with classroom and site accessibility during the early stage of the project. We also thank Michael J. Wightman and Stephen R. Scruggs at GeoView Inc. for their help, especially during the field operation.

REFERENCES

Campbell, T. (2008). Multi-faceted geophysical characterization of limestone terrains: Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP 2008), Philadelphia, PA, April 6-10.

Davies, W.E., Simpson, J.H., Ohlmacher, G.C., Kirk, W.S., and Newton, E.G. (1984). Engineering aspects of karst: US Geological Survey, National Atlas.

de Kleine, M. and Bakker, M. (2009). Subsurface characterization in a karstified limestone area using ground-penetrating radar: Bonaire, Netherlands Antilles: Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP 2009), Fort Worth, TX, March 29-April 2.

Dobecki, T.L. and Upchurch, S.B. (2006). Geophysical applications to detect sinkholes and ground subsidence: *The Leading Edge* 25 (3): 336-341.

Gelis, C., Leparoux, D., Virieus, J., Bitri, A., Operto, S., and Grandjean, G. (2005). Numerical modeling of surface waves over shallow cavities: *Journal of Environmental & Engineering Geophysics* 10 (2): 111-121.

Kim, J.H., Yi, M.J., Cho, S.J., Son, J.S., and Song, W.K., 2006, Anisotropic crosshole resistivity tomography for ground safety analysis of a high-storied building over an abandoned mine: *Journal of Environmental & Engineering Geophysics* 11 (4): 225-235.

Lambrecht, L. and Miller, R.D. (2006). Catastrophic formation in Kansas: a case study: *The Leading Edge* 25: 342-347.

Miller, R.D., Anderson, T.S., Ivanov, J., Davis, J.C., Olea, R., Park, C.B., Steeples, D.W., Moran, M.L., and Xia, J. 2003, 3-D characterization of seismic properties at the Smart Weapons Test Range, YPG [Exp. Abs.]: Soc. Expl. Geophys., NSG 2.3.

Miller, R.D. (2002). High resolution seismic reflection investigation of the subsidence feature on U.S. Highway 50 at Victory Road near Hutchinson, Kansas: Kansas Geological Survey Open-File Report 2002-17.

Nasseri-Moghaddam, A., Cascante, G., and Hutchinson, J. (2005). A new quantitative procedure to determine the location and embedment depth of a void using surface waves: *Journal of Environmental & Engineering Geophysics*, 10 (1): 51-64.

Paine, J., Buckley, S., Collins, E., Wilson, C., and Kress, W. (2009). Assessing sinkhole potential at Wink and Daisetta using gravimetry and radar interferometry: Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP 2009), Fort Worth, TX, March 29-April 2.

Park, C.B., and Carnevale, M. (2009). 3D MASW: Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP 2009), Fort Worth, TX, March 29-April 2.

Park, C.B., Miller, R.D., and Miura, H. (2002). Optimum field parameters of an MASW survey [Exp. Abs.]: SEG-J, Tokyo, May 22-23, 2002.

Park, C.B., Miller, R.D., and Xia, J. (1999). Multi-channel analysis of surface waves (MASW): *Geophysics*, 64 (3): 800-808.

Park, C.B., Miller, R.D., and Xia, J. (1998). Imaging dispersion curves of surface waves on multi-channel record: [Exp. Abs.]: Soc. Explor. Geophys.: 1377-1380.

Parker, J.W. (1992). Surficial aquifer hydrogeology in a covered-karst terrain, Master's Thesis, University of South Florida, 228 pp.

Putnam, N., Nasseri-Moghaddam, A., Kovin, O., and Anderson, N. (2008). Preliminary analysis using surface wave method to detect shallow manmade tunnels: Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP 2008), Philadelphia, PA, April 6-10.

Suto, K. (2007). Multichannel analysis of surface waves (MASW) for investigation of ground competence: an introduction, in "Engineering Advances in Earthworks," Proceedings of the Sydney Chapter 2007 Symposium, Australian Geomechanics Society: 71-81.

Yuhr, L.; Benson, R.C.; Kaufmann, R.; Casto, D. and Jennings, J. (2003). A case history of a large karst investigation. 3rd International Conference on Applied Geophysics, Geophysics 2003, Orlando, Florida, December 8-12.

Xia, J., Miller, R.D., and Park, C.B. (2001). Feasibility of using the MASW method to define a sinkhole impact area at Calvert Cliffs nuclear power plant, Maryland: Kansas Geological Survey Open-File Report 2001-19.

Xia, J., Miller, R.D., and Park, C.B. (1999). Estimation of near-surface shear-wave velocity by inversion of Rayleigh waves: *Geophysics*, 64 (3): 691-700.

Xu, J.C.Q., Butt, S., and Ryall, R. (2008. Seismic Rayleigh wave method for localizing and imaging subsurface cavities in various and complicated districts: Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP 2008), Philadelphia, PA, April 6-10.