Detecting caves using seismic surface waves: A feasibility study

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ABSTRACT

A non-destructive surface-based seismic site investigation technique called the SASW method was applied over a limestone cave in northern Arizona. This technique involves measuring seismic surface waves to establish variations in phase of the ground motion with respect to frequency and, ultimately, establishing variations in shear stiffness of the site with depth. SASW measurements were conducted along a linear array above and beyond the edge of the cave. The cave boundary was successfully detected by observing high-frequency fluctuations in the data caused by reflections of body waves off of the cave boundary. Thanks to modern digital signal processing equipment, the authors were able to detect the cave boundary in real time, as the data were collected in the field. Confirmation and further delineation of the cavity boundary were obtained by studying the lateral variability of shear stiffness along the array.

INTRODUCTION

Subsurface cavities such as caves and sinkholes can pose hazards if land development proceeds without knowledge of their presence. Non-intrusive identification of cavities has been attempted in the past using a variety of geophysical methods, but these efforts have met with only limited success. As one leading research geophysicist describes it, "Despite decades of effort and technology advance, detection and delineation of subsurface cavities... remains the most difficult class of problems addressed by engineering geophysics." (Butler, 1994). In light of this continuing challenge, the authors are investigating a new and promising approach for detection of subsurface cavities: the use of seismic surface waves. This report describes a field test that was undertaken to establish the feasibility of the so-called SASW method for cave detection and delineation.

The SASW Method

The Spectral-Analysis-of-Surface-Waves (SASW) method is a non-intrusive testing method used by geotechnical engineers to evaluate shear moduli in layered systems such as soils and pavements (Stokoe et al., 1994). The approach is based on the *dispersive* nature of Rayleigh-type surface waves in a layered medium. This means that the velocity of a wave depends on its frequency; or wavelength, since velocity is the product of frequency and wavelength. The energy of a Rayleigh wave is concentrated near the surface along which it travels. Dispersion results because waves of different wavelengths sample different portions of the layered system. High-frequency waves (short wavelength) sample shallow material, while low-frequency waves (long wavelength) sample deeper material.

In the SASW method, the dispersive nature of Rayleigh waves is employed to establish variations in seismic shear wave velocity with depth. The shear wave velocity of a material is, in turn, closely related to its stiffness in shear. Through frequency-domain analyses, economy is gained by sampling a range of wavelengths simultaneously with a single measurement. Following is a brief description of the SASW method as it is typically conducted for geotechnical site investigations. The reader is encouraged to consult the work of Stokoe et al. (1994), among others, for more detail.

Figure 1 provides a schematic representation of the SASW measurement process. First, the ground motion is generated by applying a stress pulse some distance away from a pair of seismic receivers (Fig. 1a). The pulse can be applied using an impulsive source, such as a sledge hammer; a random noise source, such as a moving piece of heavy machinery; or a programmable vibrating source. The receivers are vertically oriented geophones. Using a dynamic signal analyzer, the ground motion at the receivers is recorded digitally (Fig. 1b) and then transformed into the frequency domain by means of the Fast Fourier Transform. The analyzer displays the phase difference between the two signals (in the form of the cross power spectrum) and the coherence function (Fig. 1c). The measurement is repeated so that results can be averaged to minimize effects of incoherent noise.

Data are collected at several receiver spacings along a linear array, maintaining a common center point. For each spacing, the source energy is first applied on one side of the receiver pair, then again on the opposite side of the pair. The two records are defined as "forward" and "reverse," depending upon the direction of wave travel. These records are averaged to minimize the effects of dipping layers within the profile, phase differences in the measurement equipment, and lateral inhomogeneities or other geometric anomalies.

Once measurements have been completed for all receiver spacings, the data are carefully screened so that only those portions that are rich in fundamental-mode Rayleigh-type surface wave energy are used in the calculations. This masking process is illustrated schematically in Fig. 1c, where all but the highlighted portion of the wrapped phase diagram is discarded. Next, the surface wave velocity is calculated by multiplying the frequency by the receiver spacing and the reciprocal of the unwrapped phase. The experimental dispersion curve for the site can then be plotted (Fig. 1d). Finally, the shear wave velocity profile for the site is developed through an inversion process (Fig. 1e & f). The site is assumed to consist of a series of horizontal layers, each internally homogeneous, isotropic, and laterally infinite, overlying a semi-infinite halfspace. Each layer is characterized by its elastic properties, density, and thickness. In the model, the site is perturbed by a plane wave, and linear elastic behavior is implied.

Certain aspects of the SASW method would not be germane to the problem of cavity detection. First, the averaging of forward and reverse data records is inappropriate, since our objective is to detect stiffness anomalies rather than reduce their impact on the results. The second aspect is in the idealized model assumed for the inversion process. Clearly, the assumption of homogenous layers of infinite lateral extent will not apply when the subsurface contains a large cavity. Investigation of the effects of cavities on results of SASW measurements represents a first step in development of the method for cavity detection.

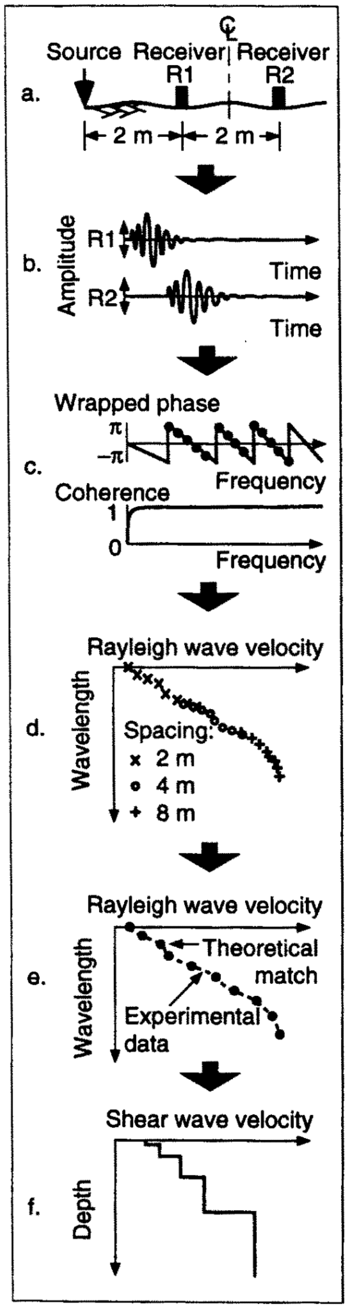

Fig. 1. Schematic representation of the SASW measurement process: a) surface wave energy is generated; b) time records are collected; c) phase difference and signal coherence are calculated and displayed; d) the composite experimental dispersion curve is generated; and e) inverse theory is applied to generate f) the shear wave velocity profile.

Use of the SASW Method for Cavity Detection

Seismic methods have been investigated for cavity detection and delineation in the past, with limited success (e.g., Curro, 1983). Recent efforts have been directed toward developing the SASW method for this purpose, by the authors and others (e.g., Gucunski et al., 1996, Al-Shayea et al., 1994). Limited success has been achieved in detecting buried objects of known size, depth, and location in controlled environments.

Advantages of the SASW method over other geophysical methods that might be used for cavity detection are:

- The testing method is surface based and non-intrusive.
- Both soft-to-stiff and stiff-to-soft transitions can be detected. (This is not possible with other surface-based seismic techniques.) This implies that upper and lower boundaries of the cave should both be detectable.
- The method is sensitive to changes in shear stiffness. Therefore, water-filled cavities in soft materials, which may be invisible to seismic methods using compression waves, should be detectable.
- Results are not affected by ambient electrical, magnetic, or gravitational fields.

At this point, it appears that the greatest disadvantage of using the SASW method for cavity detection lies in the fact that measurements proceed along linear arrays. As a result, multiple arrays would be required to cover large areas, so the process could become quite time-consuming. Another limitation of the method is that it is not yet adequately understood for use on sites with abrupt topographic variations.

In the work described in this report, we take two approaches to cavity detection. The first approach involves study of fluctuations in the dispersion curve which are caused by reflections of body waves (compression and shear) off of the cavity boundary. The second approach involves observation of lateral variability of shear wave velocity profiles developed in the inversion process. These two approaches have been studied separately by other researchers (e.g., body wave fluctuations by Gucunski et al., 1996 and Al-Shayea et al., 1994, and lateral variability by Chiang, 1994). To date, however, it appears that more effort has been directed toward understanding the theoretical problem than confirming its existence in the field.

The first approach was developed while carrying out a series of SASW experiments over a highway culvert (unpublished), over buried drums (unpublished), and in search of archaeological features at a pre-Columbian settlement in Central America (Luke et al., 1997). In these experiments, we studied similarities and differences between phase-frequency data in forward and reverse configurations. In a homogeneous, horizontally layered medium, the forward and reverse components of a SASW measurement at a station would yield identical phase-frequency relationships. In the presence of cavities, however, results will be different: the higher-velocity body waves will reflect from the cavity boundaries and thus elevate the velocity measured at the ground surface. Unless the cavity is far from the receivers or centered between them, the effects of the reflections will be stronger in one direction than another. These effects will be strongest for the configuration in which the source is closest to the cavity, since the signal reaching the cavity (and converting a portion of its energy into reflected body waves) will be stronger than in the opposite configuration. A higher velocity translates to a smaller magnitude of phase difference (recall that velocity and phase are inversely related). Therefore, measurements that are strongly affected by body wave reflections will have smaller changes in phase. This concept is shown schematically in Figure 2.

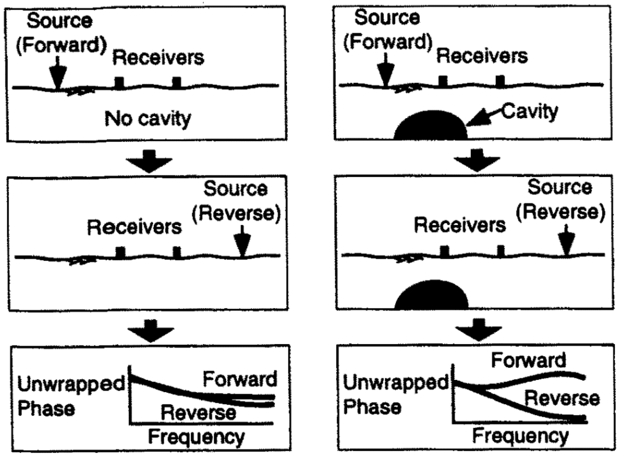

Fig. 2. Effect of a cavity on unwrapped phase data.

The second approach is a straightforward extension of the SASW method as it was originally developed. A shear wave velocity profile is generated using data collected far from the cave and compared to a profile generated from data collected over the cave. This approach may lead to development of a rough image of the cross section of the opening, despite the fact that the model is founded on the premise of an earth composed of laterally homogeneous layers. A similar approach has recently been followed to investigate the lateral variability of ocean sediments (Luke, 1994).

FIELD EXPERIMENT

The foregoing approaches to cavity detection using the SASW method were applied over a limestone cave in Arizona.

Site Description

Cathedral Cave was selected for study. This cave is located approximately 50 miles west of Flagstaff, Arizona. It is a fairly linear solution feature in the Redwall Limestone. The cave has a narrow, near-vertical entrance which opens into a dome-shaped chamber approximately 32 m wide by 6 m high and more than 90 m long (Fig. 3). The chamber trends generally north and descends toward the north, roughly on a three-degree grade. Above the cave, the ground surface dips approximately 5 degrees to the west, with dip increasing toward the west. The thickness of rock cover over the cave is estimated to be about 5 m at the crown. The limestone bedrock is exposed at the ground surface above the western boundary of the cave. Toward the east, a layer of soil (loosely cemented silty sand with clay and surficial organics) thickens gradually, to an estimated depth of 0.3 m above the eastern boundary of the cave.

SASW Testing

A single SASW array was aligned roughly perpendicular to the long axis of the cave, north of its only entrance (Fig. 3). To study fluctuations in the dispersion curve, SASW measurements were performed in forward and reverse directions, with a receiver spacing of 8 m, at selected stations along the array. The receivers were 4.5-Hz geophones, coupled to the ground with spikes. A sledge hammer was swung to provide the seismic source. The source energy was applied 8 meters from the nearest receiver, to match the spacing between the receivers. Data were collected at frequencies up to 400 Hz. By convention, the forward direction was defined by waves traveling toward the east (receivers to the east of the source). The origin of the array was positioned roughly over the center of the cave. Measurements were performed at Stations -12, -8, 0, 10, 18, 26, 30, and 34, with station numbers indicating number of meters from the origin, increasing toward the east.

To investigate lateral variability at the site, two shear wave velocity profiles were generated: one at Station 0, over the cave, and one at Station 34, away from the cave (Fig. 3). Receiver spacings of 2, 4, 8, and 16 meters were used to gain the greatest definition possible of the site, given the available source mechanism. (A higher energy, lower frequency source would have permitted longer receiver spacings, and, hence, resolution of the shear wave velocity profile to greater depths.)

All of the field measurements were completed by a team of three people in approximately six hours. At the same time, a second team was surveying the cave, using hand-held survey instruments and fiberglass tape. Ceiling heights were estimated by eye.

MEASUREMENT RESULTS

The operator of the analyzer (Chase) was able to distinguish the eastern boundary of the cave while testing, by observing the phase-frequency data as they were collected. Using experience from previous testing, he recognized a large difference between forward and reverse measurements at Station 18 that had not been present at Station 10. From this, he concluded that the cave boundary was located between these two stations. Later, when the map was generated and the testing array superimposed (Fig. 3), this prediction was confirmed: the eastern boundary of the cave lies approximately beneath Station 14. This rapid result is an encouraging step toward developing a method for real-time, in-field, cavity detection.

Unwrapped phase diagrams for Stations 10, 18, and 26 are shown in Fig. 4. Some of these data have been post-processed so that forward and reverse curves are approximately matched at the low-frequency limit of approximately 40-50 Hz. (Adjustments are made in integer multiples of π.) A first glance indicates that the forward and reverse signatures are similar at Stations 10 and 26, and different at Station 18. These results imply that the earth is homogeneous beneath Stations 10 and 26, but not beneath Station 18. Recalling that a smaller change in phase corresponds to a higher velocity, we see the velocities are highest for Station 10 and the forward component of Station 18, ostensibly due to the interference of higher-velocity body waves; and lowest for the reverse components of Stations 18 and 26, which would be least affected by reflections.

Results of inversion of the SASW data at Stations 0 and 34 are shown in Fig. 5. Condensed composite dispersion curves are plotted along with theoretical curves, which were fit by trial and error, in Fig. 5a. The shear wave velocity profiles corresponding to the theoretical fits are shown in Fig. 5b. Shear wave velocities range from 140 meters per second (m/s), appropriate for the soft soil cover; to 2500 m/s, appropriate for hard rock at low confining pressures. An abrupt transition from soft to stiff occurs at a very shallow depth (less than one meter). Clearly, shear wave velocities are lower for Station 0 (over the cave) than for Station 34 (away from the cave). However, a very low velocity layer appropriate for an air-filled cavity is not indicated. It is interesting to note that the boundary of the halfspace is encountered at approximately the same depth as the roof of the cave.

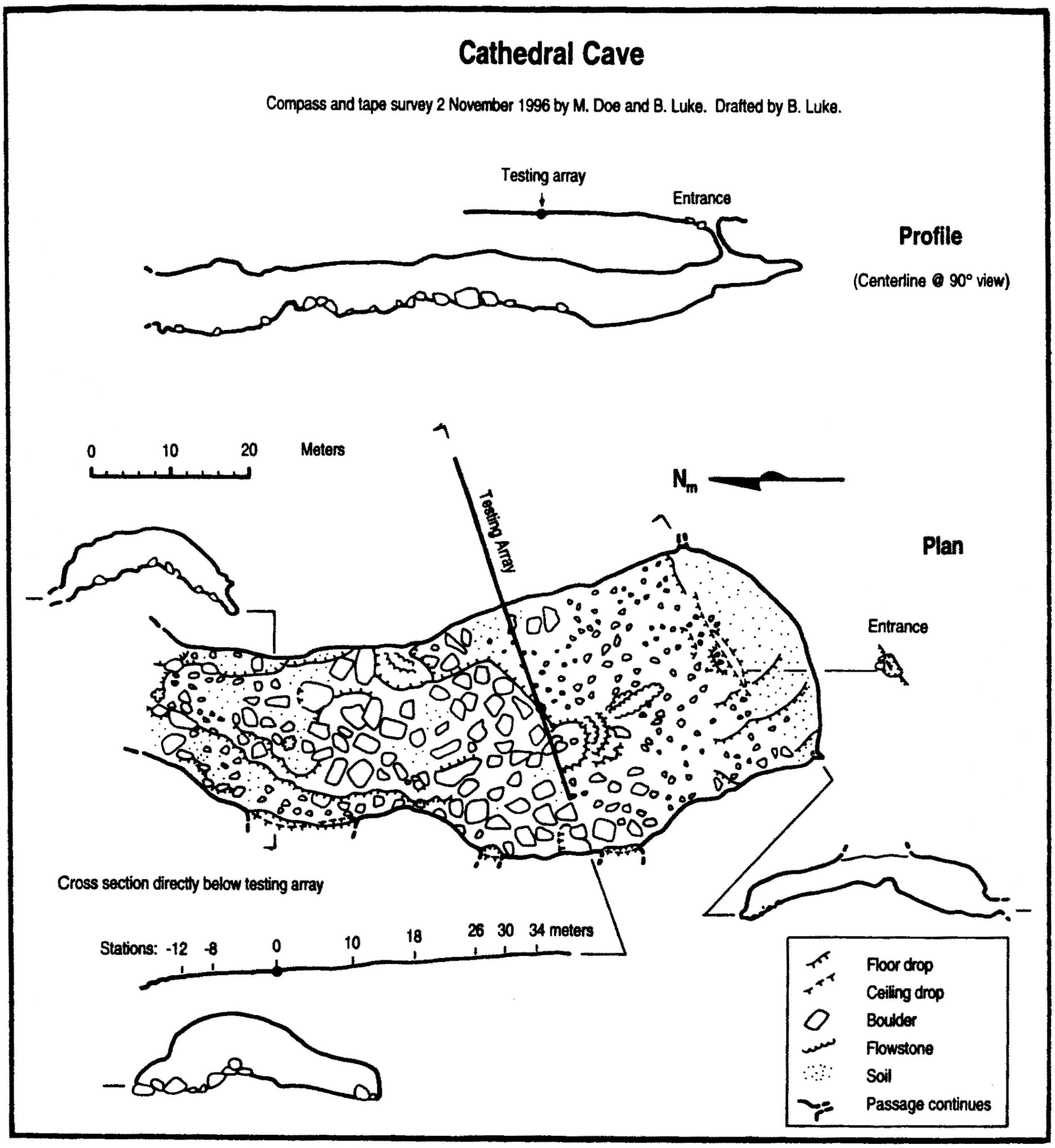

Fig. 3. Cave map and profile. Note cross section along SASW array in bottom left.

The depth of the cavity might be related to the maximum wavelength that could be resolved in SASW measurements over the cave. Under normal conditions, one might expect to be able to resolve data at wavelengths up to twice the largest receiver spacing, which would be 32 m in this experiment. However, at Station 0, no coherent data were obtained beyond wavelengths of about 16 m. In a homogeneous material, the particle motion of a Rayleigh wave is greatest at a depth on the order of one half to one third of its wavelength. The maximum wavelength, then, sampled a depth in the range of 5 to 8 meters, which is approximately the depth of the cave roof beneath the station. Similar patterns were observed in measurements made on 8-m spacings at other stations over the cave: forward and reverse data diverged at approximately 50 Hz, which corresponds to a wavelength of 16 m.

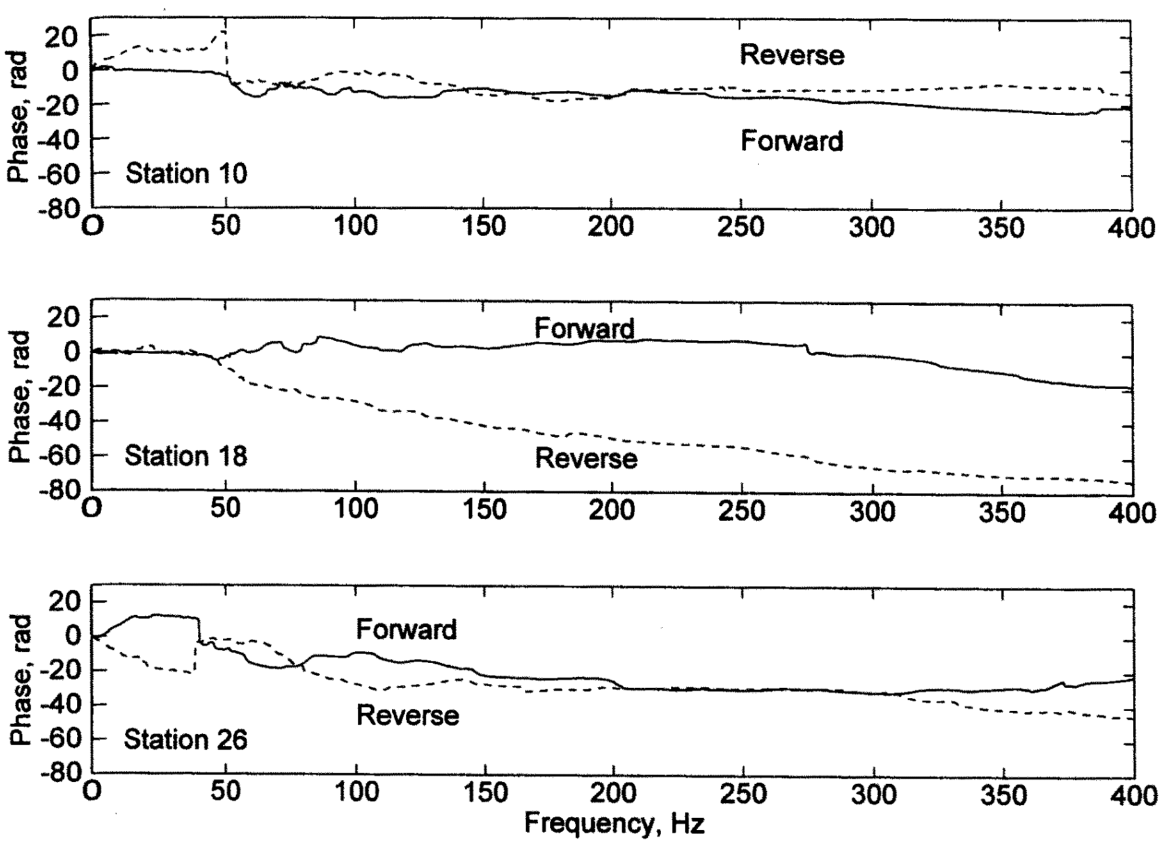

Fig. 4. Unwrapped phase data for forward and reverse measurements in the vicinity of the cave boundary.

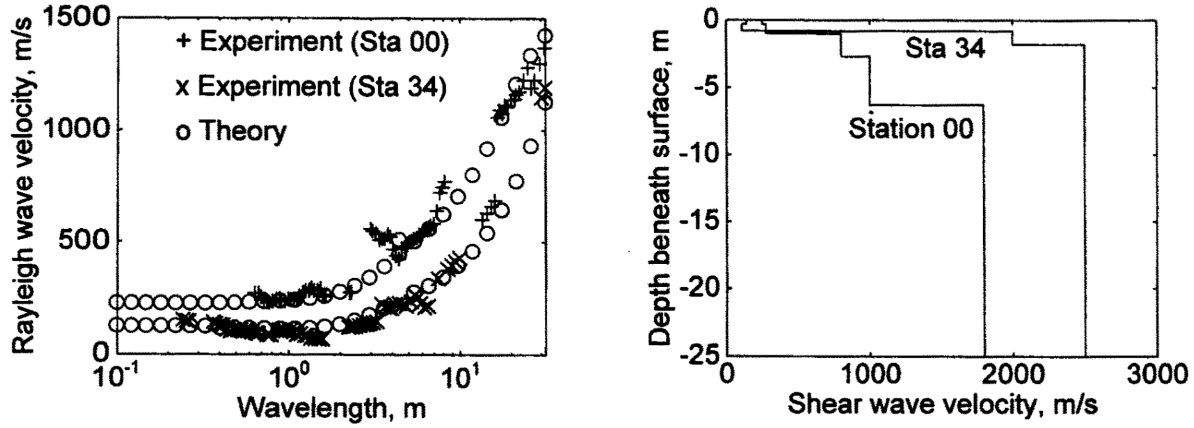

Fig. 5. Interpretation of SASW data at Stations 0 (over the cave) and 34 (away from the cave): a) composite experimental dispersion curves and theoretical fits; b) shear wave velocity profiles.

An additional modeling exercise was completed to demonstrate the maximum wavelength that would be necessary to resolve the floor of the cave. This model incorporated the profile of Station 0 with a low-velocity layer added to represent the cave (Fig. 6b). Observation of the corresponding theoretical dispersion curve (Fig. 6a) reveals that wavelengths on the order of 100 m or more would be required to resolve the base of the cave and establish the shear wave velocity of the rock beneath it. This is certainly possible, but a different source mechanism that provides more low frequency energy would be required.

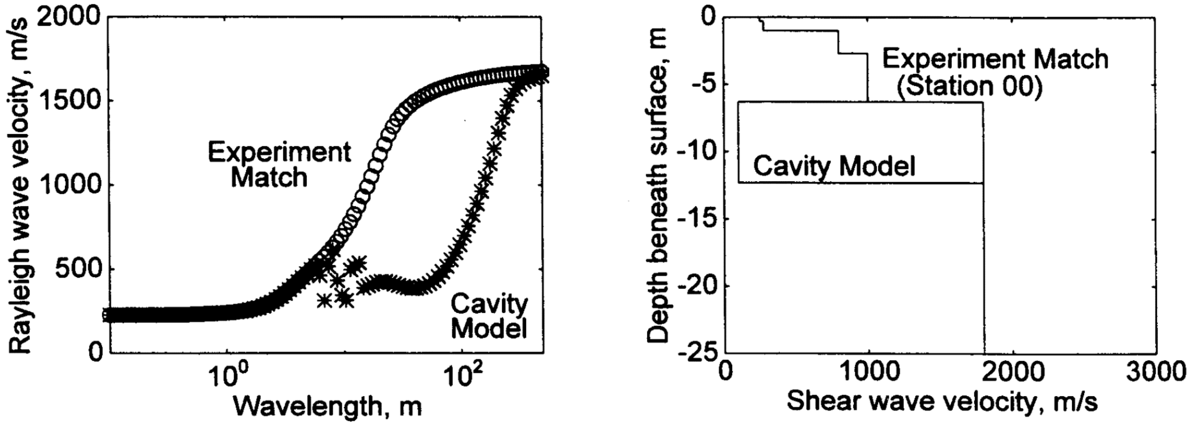

Fig. 6. Comparison of profile at Station 0 with hypothetical model containing cavity: a) theoretical dispersion curves; b) shear wave velocity profiles.

CONCLUSIONS

Use of the SASW method for cave detection represents a new application of a fairly recent testing method. The experiment at Cathedral Cave met the authors' primary objective: to investigate the potential for use of the SASW method to detect and delineate the boundaries of a large, shallow cave. We were readily able to detect the side wall of the main chamber of Cathedral Cave, in real time. The approximate depth to the roof of the cave was also established. We were not able to resolve the height of the cave, although results indicated that this should be possible, given an appropriate source mechanism.

Application of the SASW method for cave detection and delineation appears to be a two-step process. Constant-spacing measurements would be performed first, with an eye toward rapid detection of cavity boundaries. If a cavity was indicated, locations would be selected for multi-spacing measurements geared toward delineation of the cavity.

Encouraged by these preliminary successes, the authors intend to proceed with several refinements, which include: 1) applying different source mechanisms to enhance data resolution, particularly at low frequencies; 2) investigating methods for increasing speed of data collection, such as developing techniques for areal rather than lineal coverage; and 3) performing controlled parametric studies to help quantify the effects of reflected body wave energy on surface wave data.

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REFERENCES

Al-Shayea, N., R. Woods, P. Gilmore, 1994, SASW & GPR to detect buried objects. *Proceedings,* Symposium on the Application of Geophysics to Engineering and Environmental Problems; R. S. Bell and C. M. Lepper, eds. Boston, Massachusetts, 27-31 March, pp. 543-560.

Butler, D. K., 1994, Detection and delineation of subsurface cavities, tunnels and mines. *Current Topics in Geotechnical/ Geoenvironmental Engineering, Geotechnical Lecture Series,* ASCE Geotechnical Engineering Division, Illinois Section, and Illinois Institute of Technology, Chicago. 29 pp.

Chiang, C. C., 1994, *Effects of Irregularities on the Dynamic Response of Pavements in Non-Destructive Testing.* Ph.D. Dissertation, The University of Texas at Austin. 222 pp.

Curro, J. R. Jr., 1983, *Cavity Detection and Delineation Research, Report 2 – Seismic Methodology: Medford Cave Site, Florida.* U.S. Army Engineer Waterways Experiment Station Technical Report GL-83-1, Washington, D.C. 98 pp.

Gucunski, N., V. Ganji, and M. H. Maher, 1996, Effects of obstacles on Rayleigh wave dispersion obtained from the SASW test. *Soil Dynamics and Earthquake Engineering* 15:223-231.

Luke, B. A., 1994, *In Situ Measurement of Stiffness Profiles in the Seafloor Using the Spectral-Analysis-of-Surface-Waves (SASW) Method.* Ph.D. dissertation, The University of Texas at Austin. 404 pp.

Luke, B. A., C. T. Begley, D. S. Chase, and A. J. Ross, 1997, Rapid-response geophysical site investigations at a pre-Columbian settlement in Honduras. *Proceedings,* 10th Annual Symposium on the Application of Geophysics to Engineering and Environmental Problems, Reno, Nevada, March 23-26. In press.

Stokoe, K. H., II, S. G. Wright, J. A. Bay, and J. M. Roesset, 1994, Characterization of geotechnical sites by the SASW method. In *Geophysical Characterization of Sites,* R. D. Woods, ed., pp. 15-25. Oxford and IBH Publishing Co., New Delhi.