Seismic search for underground anomalies

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Summary

Methods are designed for detecting void related anomalies using surface wave energy on seismic shot gathers. First theoretical models are examined. Then methods for imaging the void-related anomalies are applied to real data. The data examples show good correlation between the models and the processed field data.

Introduction

Historically, detection of anomalies using seismic methods has relied heavily on wavefield interference and point source radiation phenomena (Rechtien et al., 1995; Miller and Steeples, 1991; Steeples and Miller, 1988; Cook, 1965; Fisher 1971; Watkins et al., 1967). This approach can be effective in some situations, but considering the wealth of information contained in the wavefield, it is at best a cursory use of the information available in the wavefield. Recent development of surface seismic techniques designed to provide a quantitative measure of key seismic properties for each 3-D cell of a specified earth volume from a single shot gather by analyzing individual components of the wavefield has shown great promise (Miller et al., 2001). This project proved an incremental step in the evaluation of the potential of these seismic imaging and sampling techniques for shallow tunnel detection. Geologic or anthropogenic underground anomalies have been successfully identified using various components of the seismic wavefield and empirical correlations, some of these include: bedrock karst feature in southern Alabama and eastern Kansas (Miller and Xia, 1999; Miller et al., 1999), faulted and/or mined out zones in southern Illinois, buried pipes at Lawrenceville, Illinois (Miller et al., 2000) and San Jose, California, and a tunnel at 35 ft below ground surface at Otay Mesa, California (Miller et al., 2002).

Surface waves traditionally have been viewed as noise on multichannel seismic data collected to image targets for shallow engineering, environmental, and groundwater purposes (Steeples and Miller, 1990). Recent advances in the use of surface waves for near-surface imaging have combined spectral analysis techniques (SASW), developed for civil engineering applications (Nazarian et al., 1983), with multitrace reflection technologies developed for near-surface (Schepers, 1975) and petroleum applications (Glover, 1959). The combination of these two uniquely different approaches to seismic imaging of the shallow subsurface permits noninvasive estimation of shear wave velocity and delineation of horizontal and vertical variations in near-surface material properties based on changes in these velocities (MASW) (Park et al., 1996; Xia et al., 1999; Park et al., 1999).

Extending this imaging technology to include lateral variations in lithology as well as tunnel and fracture detection, bedrock mapping, and subsidence/karst delineation has required a unique approach that incorporates SASW, MASW, and CDP methods. By integrating these techniques, 2-D continuous shear-wave velocity profiles of the subsurface can be generated. Estimating the dispersion curve from up to 60 closely spaced receiving channels located every 4 to 8 ft along the ground surface enhances the signal and results in a unique, relatively continuous view of shallow subsurface shear-wave velocity characteristics. This highly redundant method improves the accuracy of calculated shear-wave velocities (within 15% of measured, Xia et al., 2000) over other surface wave analysis techniques and minimizes the likelihood irregularities resulting from erratic dispersion curves will corrupt inversion results.

Model studies for underground anomalies

Abrupt, localized changes—either horizontally or vertically—in earth seismic velocities will alter the propagation pattern of seismic energy traveling through otherwise homogeneous earth materials. Perturbations in the propagation characteristics of seismic energy in the presence of such anomalous zones can be modeled to allow generalized differentiation of specific propagation characteristics, which are diagnostic of specific types of anomalies. Ground truth using real seismic measurements acquired over known target anomalies is also an important component in differentiating geologic noise from signal coming from a target anomaly. Using model-derived propagation characteristics in conjunction with calibrated ground truth seismic data, interpretation criteria can be established that allow high-confidence correlation between seismic observations on exploratory data and specific types of subsurface targets.

For the anomalies that were the target of this survey two different models scenarios and approaches were employed to better understand how the seismic energy would interact with them in this geologic setting. First, a model was developed for the case of an anomaly with minimal horizontal extent (few centimeters) but with a large vertical dimension (10s of meters) (Figure 1). This model was designed to determine if the seismic wavefield was sensitive to the void volume or the boundary between the void space and native earth.

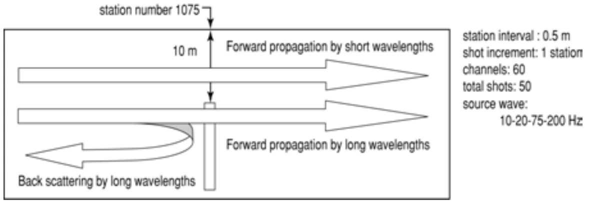

Figure 1. Model with arrows showing wave propagation and vertical void located at station 1075.

A second model portrays a void that is 1 m high and 5 m wide (Figure 2). This second model configuration was designed to evaluate the impact the horizontal size of the void has in altering the seismic wavefield.

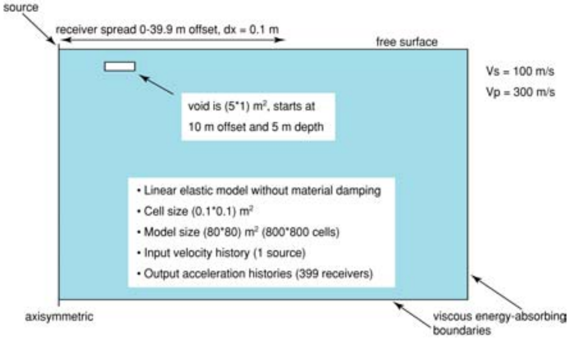

Figure 2. Void model using full elastic modeling routine.

The first case might be geologically analogous to a fault zone or an extremely thin tunnel (Figure 1). Looking at surface wave energy only for this model, the presence of the anomaly is quite distinguishable on shot gather simulations over the anomaly when comparing to shot gather simulations with only uniform earth beneath the receiver spreads (Figure 3).

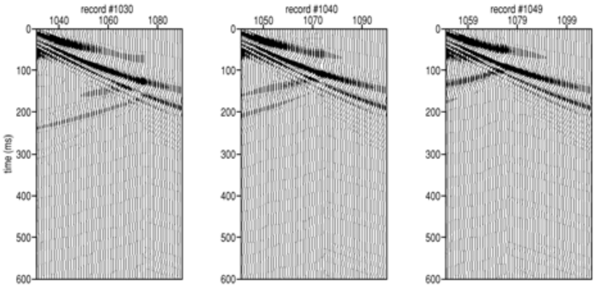

Figure 3. Selected model shot gathers as the source and receiver move across void.

As the simulated source and receiver spread advance across the model anomaly, changes in the arrival pattern of the surface wave energy are very evident. The width of the anomaly is obviously not as critical to the seismic response as the interface between native material and void space. Using the seismic wave pattern observed here it is possible to design a specialized processing flow that enhances energy that has scattered or reflected back after coming in contact with the interface between native materials and void space (Figure 4).

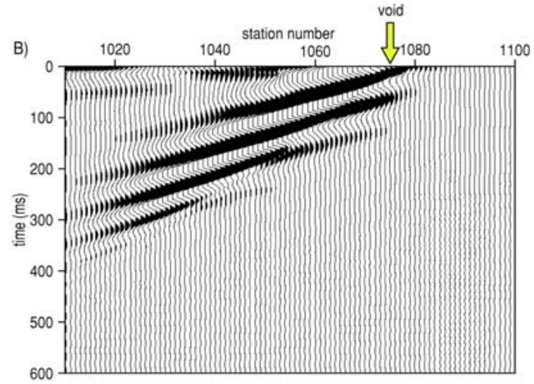

Figure 4. Void appearance after processing; void station =1075. Processing to LMO sloping events consistent with dispersion curve after horizontal f-k filtering applied.

An important observation associated with this particular model of a thin, tall void is the effect that the depth to the top of the anomaly has on the seismic response. As the depth to the top of the void is increased the wave pattern remains constant, with only changes in frequency content and amplitude appearing to be depth dependent. This observation is consistent with the nature of the surface wave, where longer wavelengths penetrate deeper into the geologic section. Since this model represents native undisturbed material as homogeneous, the surface wave energy should not have any dispersive characteristics. The apparent dispersive characteristics of the backscattered or reflected surface wave seem to remain relatively consistent irrespective of depth to the top of the anomaly.

Studying the effect a vertically small void has on the seismic wavefield produces some very intriguing observations (Figure 2). Surface wave energy passing through the model volume produces a seismogram with several very low amplitude events with apparent reverse phase velocities (Figure 5).

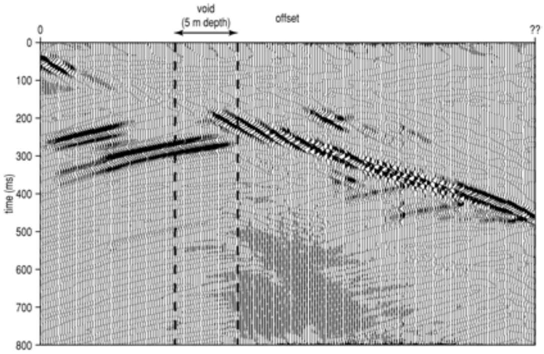

Figure 5. Shot gather form model shown in Figure 2 after f-k filtering of forward propagation to emphasize the backscattering from the void.

Energy traveling back toward the source appears to originate from both walls of the model void. To enhance this apparent backscattered energy an f-k filter is applied to remove as much forward propagation surface wave as possible (Figure 5). Using this enhancement technique, two dominant reverse-traveling components of the surface wavefield become the highest amplitude events on the seismogram. Upon closer inspection it becomes evident that these events originate at the point in time when the surface wave passes through the contacts between the native material and void area. This suggests the surface wave energy is not particularly sensitive to the size of the void so much as the characteristics of the contacts between void and native material.

Field procedures/Data acquisition

Data were acquired for the 2-D full wavefield surveys at the three border sites visited during this campaign using state-of-the-art near-surface imaging equipment and techniques. Four Geometrics StrataView R60 seismographs were interfaced to a Geometrics StrataVisor NZC to allow the flexibility necessary to record from 1- to 240-channel configurations, each with 24-bit resolution. Because of the broad spectral requirements of full wavefield measurements it was necessary to use a low frequency source and matched low natural frequency receivers. Receivers were deployed in both a conventional spike-coupled format and a towed spread. In the spike-coupled format all receivers were Geospace GS-11D 4.5 Hz vertical geophones. For the towed array both Geospace GS-11D 4.5-Hz vertical geophones and Geospace GS-11 14-Hz horizontal geophones were towed in a continuous pressure coupled streamer. Receiver stations were spaced 1.2 m apart with the source impact points separated by 2.5 m. Three ground impacts from a rubberband accelerated weight drop (RAWD) were vertically stacked in the seismograph at each shot station.

Processing focusing on void seismic characteristics

Processing concentrated on data recorded from 30 vertical receiver stations optimally offset from the source by a range of distances determined during preliminary testing at the known tunnel site with confirmation of the selected range of offsets at each site. All processing was centered around wavefield anomalies caused by small voids in otherwise relatively uniform earth materials less than 100 ft below the ground surface. Traditional approaches to surface wave processing were used to estimate dispersion characteristics and to designate the acquisition geometries and operational procedures.

Analysis of dispersion curves (frequency vs. phase velocity) and shot gathers (scattered energy, non-linearity of wave propagation, and frequency vs. source offset) provided a variety of different approaches to enhancing the empirical and model-derived seismic characteristics of voids. Data were analyzed and processed using beta versions of both SurfSeis and WinSeis Turbo (proprietary software packages from the Kansas Geological Survey facilitating use of MASW as well as general seismic data processing). These data were run through a large and diverse set of processing routines with the most notable listed below:

- offset-dependent estimations of dispersion curves,
- inversion of dispersion curves to establish velocity depth dependencies,
- linear moveout as a function of phase velocity in the f-k domain,
- filtering in the f-k domain of all energy consistent with normal surface wave propagation in a homogeneous earth in both shot and receiver domain,
- common receiver stacking after linear move-out (LMO) and receiver gathers for different offsets,
- digital filtering pre- and post-LMO and receiver stack

Interpreting voids

As is the case with all geophysical methods, no single data set can provide a unique answer or solution. All seismic data is non-unique. Therefore, to best provide a defensible, confident interpretation it is important to first construct numerical models and synthetic seismic data based on best estimates of target characteristics and second, if possible, to acquire data at a site with similar geology and a known feature closely resembling in depth and size the survey's target feature. By establishing a "seismic template" in this fashion (Figure 5 and Figure 4), pattern recognition and associated assignment of candidate features with confidence ratings can be effectively done.

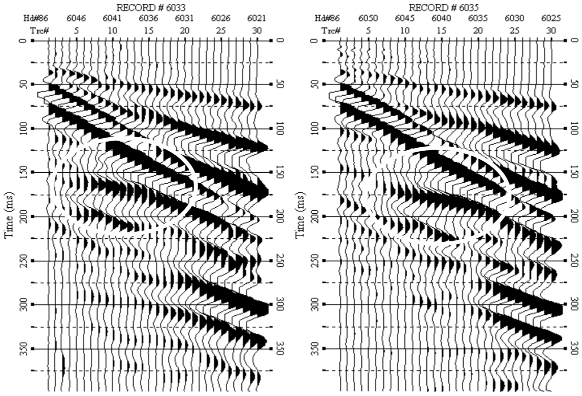

Figure 6. Shot gathers from line 6 showing void-suspect wave patterns.

Shot gathers were used as a diagnostic tool for directly detecting abrupt changes in an otherwise uniform earth (Figure 6). As can be seen on shot gathers there is a pronounced scatter consistent with the model data (Figure 5) and with a scatter feature on void-processed line 6 beneath about station 6040 (Figure 7), which is similar to the appearance of the void-model after the specialized void processing (Figure 4).

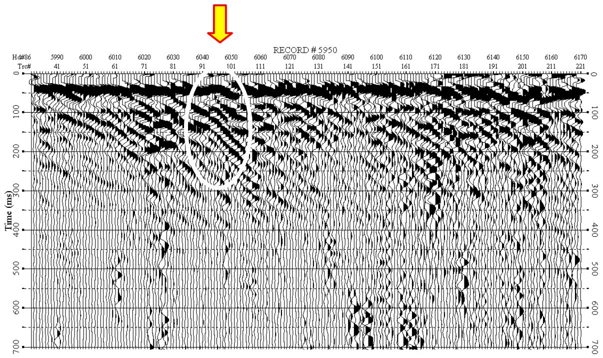

Figure 7. Line 6, on asphalt street, after f-k filtering of shot gathers and void processing. Location of the void-suspect wave patterns observed on the shot gathers.

The unique curvature of these scatter features is particularly candidate for voids, as it is diagnostic of abrupt changes in velocity. Shot gathers were used in conjunction with processed records to establish confidence in observed scatter events on stacked sections.

Discussion

Comparison of the acquired results with the theoretical model shows close resemblance. Still, ground truth is critical. If invasive confirmation is the next step, enhanced processing and modeling of the specific anomaly to be confirmed could greatly reduce the number of boreholes necessary to confirm or refute these interpretations.

Acknowledgments

The authors would like to thank Mary Brohammer for assistance in manuscript preparation and submission.

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