Using MASW to map bedrock in Olathe, Kansas

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Summary

The shear wave velocity field, calculated using the Multichannel Analysis of Surface Waves (MASW) method (Park et al., 1999; Xia et al., in press) was used to map the bedrock surface at depths of 2 to 7 m and identify potential fracture zones within bedrock at a site in Olathe, Kansas. Preliminary analysis of this site's hydrologic characteristics, based primarily on borehole data, suggested that fractures and/or an unmapped buried stream channel was influencing fluid movement along the drill-defined bedrock surface. Since topographic variations on the surface of bedrock can influence the transport and eventual fate of contaminants released at or near the ground surface, determining the nature and location of anomalous bedrock was critical to establishing the environmental risk at this site. High velocity gradients within the shear wave velocity field were used as diagnostic of the bedrock surface, while localized lateral decreases in the shear wave velocity below the bedrock surface were considered characteristic of fracture zones or erosional channels. Calculating the shear wave velocity field from surface wave arrivals can generally be accomplished with a high degree of accuracy regardless of cultural noise. The insensitivity of MASW to cultural obstacles and noise was demonstrated at this site (e.g., a 185,000 m^2 asphalt parking lot, electrical and mechanical noise from nearby industrial facilities, traffic noise from the adjacent highway, exploratory drilling on the asphalt parking lot, and aircraft noise). The depth-to-bedrock map produced using shear wave velocity data only possesses significantly higher resolution with less than 0.3 m in difference observed between the interpreted bedrock depth from surface wave data and from drill confirmed bedrock. Advantages of mapping the bedrock surface with the shear wave velocity field calculated from surface waves include the insensitivity of MASW to velocity inversions, ease of generating and propagating surface wave energy in comparison to body wave energy, and its sensitivity to lateral changes in velocity.

Introduction

Surface waves have traditionally been viewed as noise on multi-channel 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 multitrace reflection technologies originally developed for petroleum applications (Glover, 1959). Combining these two uniquely different 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., 1997; Xia et al., 1998; Park et al., 1999; Xia et al., in press).

Surface wave analysis has shown great promise detecting shallow tunnels (Park et al., 1998), bedrock surfaces (Xia et al., 1998), remnants of underground mines, and fracture systems. Extending this technology from detection to imaging required incorporating MASW with concepts from the CDP (Mayne, 1962) method. Integrating these two methodologies resulted in the generation of a laterally continuous 2-D cross-section of the shear wave velocity field. This cross-section contains information about horizontal and vertical continuity and physical properties of materials as shallow as a few decimeters down to depths of over 100 m in some settings. Areas with subsidence potential may possess unique characteristics evident in the shear wave velocity field. If the shear wave velocity of earth materials changes when the strain on those materials becomes "large," forcing the ratio of stress to strain to change, it is reasonable to suggest roof rock immediately above mine or dissolution voids may experience elevated shear wave velocities detectable with surface waves. The sensitivity of surface waves to shear wave velocity, compressional wave velocity, density, and layering in the half space they travel in is key to exploiting them as a site characterization tool.

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 are generated relative to body waves. The high amplitude nature of surface waves makes working in areas with elevated levels of mechanic/acoustic noise possible. Only a layer over half space is necessary for surface waves to propagate. This method does not require any kind of a contrast (i.e., acoustic impedance or conductivity) or increase in velocity with depth. Of course, things such as the conductivity of the soils, electrical noise sources, conductive structures, and buried utilities—all significant problems for electrical or EM methods—have no impact at all on the generation and propagation of surface waves. This flexibility permits shear wave velocity profiling in many areas where other geophysical methods are difficult to use.

This study focused on an area immediately outside a manufacturing building where industrial fluids were used as part of the production process. It is a scenario not unlike thousands currently under investigation. Two sets of parallel profile lines were located as close to the building as possible and in proximity to borings used to define bedrock and/or monitor groundwater (Figure 1). The profiles were designed to image bedrock and near-surface materials between about 0.5 m and 10 m below ground surface. An improved bedrock surface map and delineation of any potential contaminant pathway on or into bedrock were the primary objective of this survey.

Data Acquisition

Data were acquired along two sets of parallel lines intersecting at right angles. Standard roll-along techniques provided shot gathers with a consistent spread geometry every 2.5 m along the profile lines. Complicating the acquisition was an asphalt surface covering most of the site. It was necessary to acquire some data with baseplates on the geophones (on asphalt) and a portion with traditional spikes (on grass). A 60-channel Geometrics StrataView seismograph was used to record and vertically stack four impacts from a 5.3 kg hammer on a 0.9 m^2 plate. Single, 4.5 Hz Geospace GS-11D geophones spaced 0.6 m apart along the profile lines were changed from flat plate to spike and back to flat plate as the surface conditions dictated. The source-to-nearest-receiver offset was nominally 2.5 m while each source station was separated by 1.2 m. This recording geometry provided the optimum spread for examining earth materials between 1 and 15 m of depth.

Recording data on an asphalt surface generally comes with inherent coupling problems and high frequency trapped waves. Receiver-ground coupling is critical for body wave surveys and normally requires at least 9 cm spikes to maximize frequency response and body wave recording. Receiver coupling for surfaces wave recording appears to require only ground contact with little improvement in response apparent when geophone coupling is improved by “planting” the phones with spikes or weighting the plated phones (Figure 2).

Data Processing

Shot gathers nominally consisted of 48 traces and were within the optimum window for surface waves wavelengths appropriate for subsurface sampling the interval between 0.5 m and 15 m. These multi-channel records were analyzed with SurfSeis, a proprietary software package of the Kansas Geological Survey, using the MASW method. Analysis of each shot gather resulted in the generation of one dispersion curve for each shot gather (Figure 3). Care was taken to insure the spectral properties of the time/offset data (shot gathers) were consistent with the maximum and minimum frequency/phase velocity value contained in the dispersion curve. Each dispersion curve was individually inverted into a depth/shear wave velocity trace. Since a shot gather was recorded for each shot station and a shear wave velocity trace calculated for each station location, a single 2-D contour plot of the shear wave velocity field can be produced by gathering all the velocity traces into sequential order according to receiver station.

Interpretation

The 2-D cross-sections have several striking characteristics, with the ones most significant to the hydrologic characteristics of this site confirmed by drilling. The bedrock surface was selected based on gradient of the contours, correlation to boreholes drilled prior to the seismic survey, and reasonable velocity value. For line 2, there are two features that are quite evident and are likely affecting movement of fluids on the surface of the bedrock (Figure 4). An extreme drop in shear wave velocity beneath station 2050 was interpreted as a paleochannel which has been infilled with weathered bedrock (a thin shale layer underlain by a thick limestone layer is the bedrock complex across much of this site). This channel feature is very close to the edge of the manufacturing facility. Drilling at station 2050 confirmed this channel and its apparent depth below the ground surface. Coring into this feature produced clay until refusal where the surrounding bedrock was shale. Also of interest is the apparent channel feature on the east end of the line. This feature is away from the area of concern and therefore was not drilled. It does, however, strongly resemble a bedrock channel cut into the limestone beneath the shale and then infilled with shale or weathered shale.

The shear wave velocity profile of line 3 is extremely busy but provides not only an excellent match to the 4 boreholes in close proximity to this line but some insight into the very irregular nature of the bedrock surface (Figure 5). This extreme irregularity was something that could not be determined by borehole data alone. Data resolution is an issue that must be addressed with this data. It is unlikely the bedrock surface has quite the extreme pinnacle topography suggested by this section. However, considering the vertical exaggeration of 4:1, outcrop studies have noted blocks of bedrock material scattered beneath weathered material at spacings consistent with the highs observed on this section.

Resolution of the bedrock surface map improves significantly when the shear wave velocity data are incorporated with drill data (Figure 6). Depth to bedrock and contours of the bedrock surface based on drill data alone has effectively defined the gross configuration of bedrock at this site. However, due to the sporadic locations and non-uniform spacing it is difficult to extend or define subtle bedrock features at this site. The bedrock contour map produced using only shear wave data lacks control off line. It is difficult to correlate features or extend features identified by the seismic survey out of the 2-D plan. Incorporating the drill data and shear wave data produces a greatly improved and much more accurate representation of the bedrock surface when compared to either by itself. The addition of as little as two more seismic lines would dramatically improve the 3-D aspects of the bedrock contours.

Conclusions

Depth to bedrock interpreted from shear wave velocity cross-sections correlates extremely well with the drill-determined bedrock surface. Incorporation of the drilling and the shear wave velocity field provided a much improved (resolution) visualization of the real bedrock surface. Improvements in data acquisition and processing currently being tested would permit the previously described survey to be completed in less than one day by two people.

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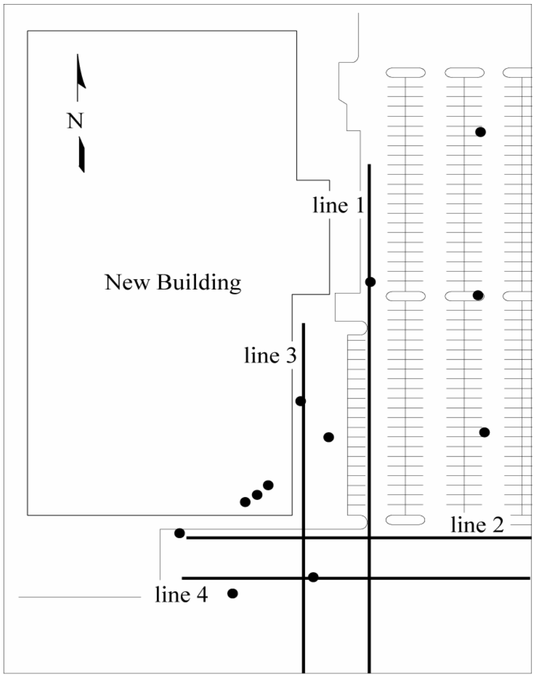

Fig. 1. Site map.

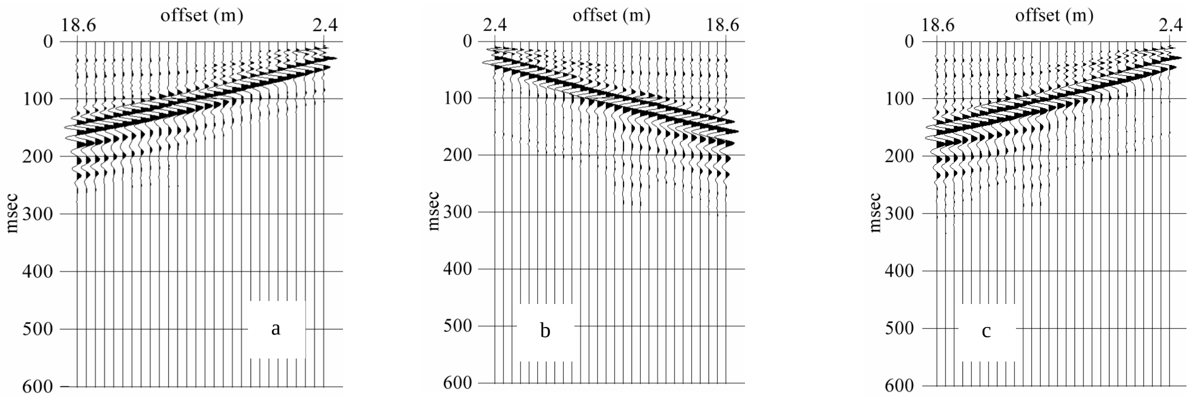

Fig. 2. Shot gathers of geophones with spikes (a), baseplates (b), or baseplates with sandbags (c).

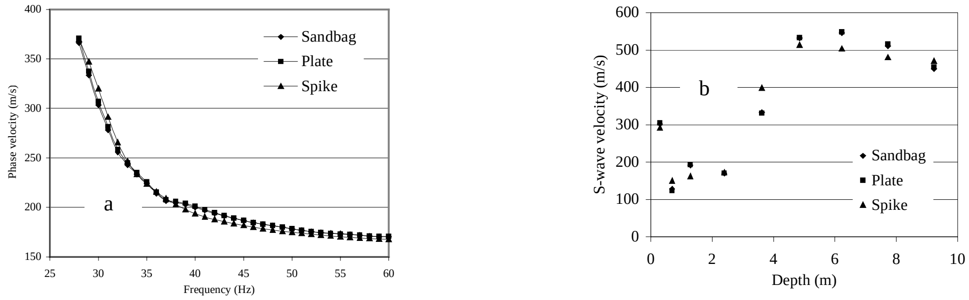

Fig. 3. Dispersion curves (a) extracted from Figure 2 and inverted S-wave velocities (b) based on the dispersion curves.

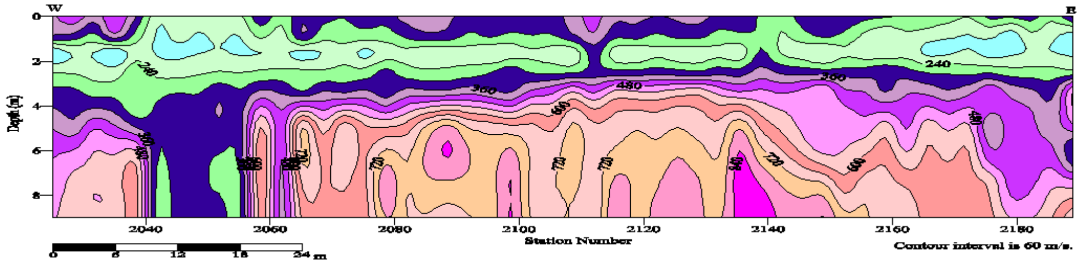

Fig. 4. S-wave velocity of line 2. The bedrock is interpreted by the contour line of 330 m/s.

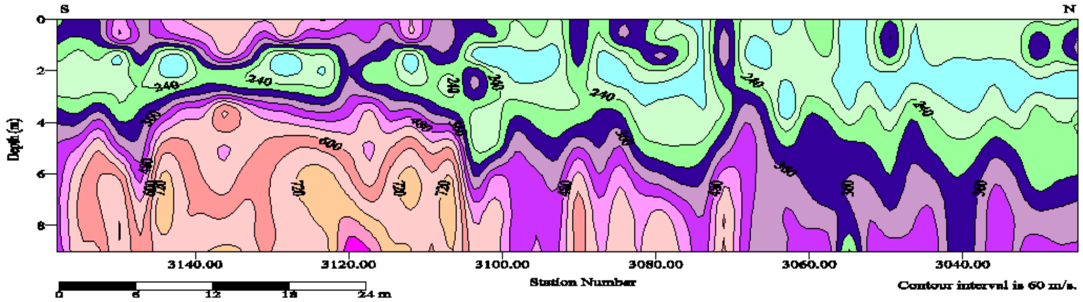

Fig. 5. S-wave velocity of line 3. The bedrock is interpreted by the contour line of 330 m/s.

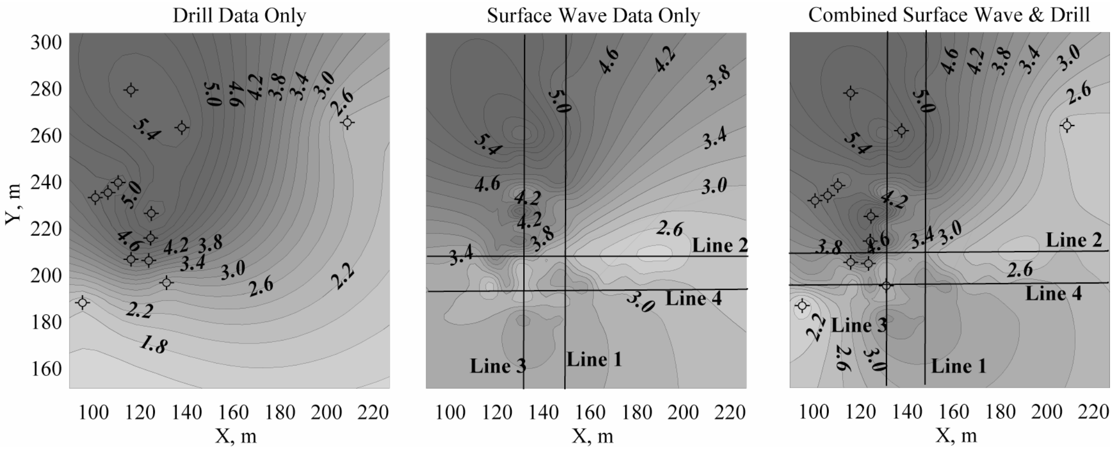

Fig. 6. Maps of depth to bedrock. The bedrock surface map improves when the shear-wave velocity data are incorporated with drill data.