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CONSTRUCTION OF 2-D VERTICAL SHEAR-WAVE VELOCITY FIELD BY THE MULTICHANNEL ANALYSIS OF SURFACE WAVE TECHNIQUE

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ABSTRACT

We present a method that utilizes the Multichannel Analysis of Surface Waves (MASW) technique and a standard common depth point (CDP) roll-along acquisition format similar to conventional petroleum exploration seismic data acquisition to construct a vertical section of the near-surface shear (S)-wave velocity field. A one-dimensional (1-D) S-wave velocity vs. depth plot is obtained by inverting phase velocities using the MASW technique. This 1-D profile appears to be most representative of the materials directly below the middle of a geophone spread. Multiple 1-D plots of S-wave velocity vs. depth are generated as the source and receivers roll along a survey line. A two-dimensional (2-D) vertical cross-section of S-wave velocity can be constructed by contouring grids produced by combining all the 1-D S-wave velocity profiles that are a function of the middle point of geophone spread (x) and depth (z). The combination of inverting the phase velocity for S-wave velocity and the standard CDP roll-along acquisition format makes this a very effective and time-efficient method of imaging two-dimensional S-wave velocity along a survey line. There are several advantages that make this method attractive in real world applications. 1. The method focuses on high-frequency (≥ 2 Hz) ground roll to provide a 2-D near-surface S-wave velocity map and to detect targets significantly shallower than feasible with other acoustic techniques. 2. That ground roll, which is acquired by the multi-channel acquisition method, has a high signal-to-noise ratio, allowing 2-D images to be obtained in extremely noisy environments. 3. The method uses the standard CDP roll-along acquisition format, which provides an efficient way to acquire large quantities of broadband surface wave data along a line. 4. The method utilizes the redundancy of the standard CDP roll-along acquisition format so that it not only provides a reliable way to verify inverted S-wave velocities, it also reduces the ambiguity of inverted S-wave velocities. 5. A 2-D display of S-wave velocity can be produced easily and quickly by contouring the inverted S-wave velocity to provide a map of the S-wave velocity field. 6. 2-D data processing techniques, such as regression analysis, could easily be applied to a vertical S-wave velocity section to enhance local anomalies (gas or oil fields, voids, tunnels, etc.). More than five thousand shots of MASW data have been acquired and processed producing more than forty vertical near-surface S-wave velocity sections since 1997. Four real world examples demonstrate the usage of the method.

INTRODUCTION

Shear (S)-wave velocity is one of the key parameters in construction engineering. As an example, Imai and Tonouchi (1982) studied compressional (P)- and S-wave velocities in an embankment, and also in alluvial, diluvial, and Tertiary layers, showing that S-wave velocities in such deposits correspond to the N-value (Craig, 1992), an index value of formation hardness used in soil mechanics and foundation engineering. Elastic properties of near-surface materials are of fundamental interest in ground-water, engineering, and environmental studies.

Surface waves are guided and dispersive. In the case of one layer on the top of a solid homogenous half-space, dispersion of the Rayleigh wave occurs when the wavelengths of the Rayleigh wave are in the range of 1 to 30 times the layer thickness (Stokoe et al., 1994). Longer wavelengths penetrate deeper than shorter wavelengths for a given mode, generally exhibit greater phase velocities, and are more sensitive to the elastic properties of the deeper layers (p. 30, Babuska and Cara, 1991). Shorter wavelengths are sensitive to the physical properties of surficial layers. For this reason, a particular mode of surface wave will possess a unique phase velocity for each unique wavelength, hence, leading to the dispersion of the seismic signal. Stokoe and Nazarian (1983) and Nazarian et al. (1983) presented a surface-wave method, called Spectral Analysis of Surface Waves (SASW), that analyzes the dispersion curve of ground roll to produce near-surface S-wave velocity profiles. The SASW method has been widely applied to many engineering projects (e.g., Sanchez-Salinero et al., 1987; Sheu et al., 1988; Stokoe et al., 1989; Gucunski and Woods, 1991; Hiltunen, 1991; Stokoe et al., 1994).

S-wave velocity can be derived from inverting the dispersive phase velocity of the surface (Rayleigh and/or Love) wave (Dorman and Ewing, 1962; Aki and Richards, 1980; Mari, 1984). Song et al. (1989) related the sensitivity of model parameters to several key earth properties by modeling and presented two real examples using surface waves to obtain S-wave velocities. Dispersion curves are inverted using least-squares techniques in SASW methods (Stokoe and Nazarian, 1983; Nazarian et al., 1983). Rix and Leipski (1991) examined the influence of the number of dispersion points, the maximum wavelength, and distribution of dispersion data with wavelength on the accuracy and resolution of S-wave velocity profiles.

Ground roll is a particular type of Rayleigh wave that travels along or near the ground surface and is usually characterized by relatively low velocity, low frequency, and high amplitude (p. 143, Sheriff, 1991). The Kansas Geological Survey conducted a three-phase research project to estimate near-surface S-wave velocity from ground roll:

1) acquisition of high frequency ($\geq$ 2 Hz) broad band ground roll,
2) creation of efficient and accurate algorithms organized in a basic data processing sequence designed to extract Rayleigh wave dispersion curves from ground roll, and
3) development of stable and efficient inversion algorithms to obtain near-surface S-wave velocity profiles.

The first two phases, acquisition of broad band ground roll and extraction of dispersion curves, are crucial to successfully estimate S-wave velocity through inversion. For phase 1, Park et al. (1996, 1999a) introduced the MASW method that successfully produces broad band ground roll by either a sweep or impulsive acoustic source. Phase 2 resulted in a presentation by Park et al. (1998) demonstrating a unique technique that can efficiently extract accurate Rayleigh wave phase velocities from ground roll. In phase 3, Xia et al. (1997 and 1999b) analyze the Jacobian matrix to show sensitivity of Rayleigh wave phase velocities in a layered earth model. S-wave velocities are the dominant influence on a dispersion curve in a high frequency range ($\geq$ 5 Hz) followed by layer thickness. An iterative solution technique to the weighted equation proved very effective in the high frequency range when using the Levenberg-Marquardt (L-M) (Levenberg, 1944 and Marquardt, 1963) and singular value decomposition techniques (Golub and Reinsch 1970). Convergence of the weighted solution is guaranteed through selection of the damping factor using the L-M method.

The Kansas Geological Survey, in cooperation with the Geological Survey of Canada, conducted a field test to determine the accuracy and consistency of estimating near-surface S-wave velocities calculated using the MASW method in the unconsolidated sediments of the Fraser River Delta, near Vancouver, B. C., Canada. In an attempt to evaluate the technique in a variety of near-surface conditions and through a wide range of velocities, S-wave velocity profiles calculated by the MASW method were statistically compared to S-wave velocity profiles measured in eight boreholes scattered around the Delta. An overall difference of approximately 15 percent was observed between these two uniquely determined sets of S-wave velocities from the eight well locations (Xia et al., in review).

In this paper, we present a method that combines the MASW method with the standard CDP roll-along acquisition format (Mayne, 1962). A combination of inverting phase velocity for S-wave velocity and the standard CDP roll-along acquisition format makes the method unique and useful in imaging two-dimensional S-wave velocities of a vertical subsurface. The method was successfully applied to map a bedrock surface at depth of 6 to 20 ft and identify potential fracture zones within bedrock at a site in Olathe, Kansas (Miller et al., in press) and to map a bedrock surface from 30 to 80 ft in Joplin Missouri (Xia et al., 1999a). The method was also used to image the subsurface dissolution features in Damascus, Alabama (Miller and Xia, 1999b) and a steam tunnel at the University of Kansas.

THE METHOD

The MASW method utilizes the property that the S-wave velocity is the dominant influence on Rayleigh wave for a layered earth model, which assures us to invert phase velocity for an S-wave velocity profile (1-D S-wave velocity function, Vs vs. depth). Because data are acquired in the standard CDP acquisition format similar to conventional petroleum exploration data acquisition, phase velocities of ground roll can be extracted from each shot gather so that numerous 1-D S-wave profiles along a survey line can generated. A two-dimensional vertical section of S-wave velocity is finally generated by any contour drawing software. The general procedure of the method is described in figure 1.

A multiple number of multi-channel records should first be collected in the standard CDP roll-along acquisition format. If a swept source is used, the recorded data should be converted into correlated format, which is equivalent to data with an impulsive source. Surface impact sources and receivers with a low response frequency, normally less than 8 Hz, should be chosen to acquire surface wave data. Data acquisition parameters, such as source-receiver offset, receiver spacing, etc., should be set to enhance ground roll signals (Park et al., 1999a).

Once the data collection is completed, phase velocities of the ground roll of each shot gather should be calculated. The frequency range and phase velocity range of the ground roll need to be determined by analyzing data along the entire line. These two ranges are very important constraints to correctly extract the dispersion curve from each shot gather. They not only help eliminate noises such as body wave, higher mode of Rayleigh waves, etc. during calculation of phase velocities (Park et al., 1999a), but also assist to define the thickness of the layer model.

Inversion should be performed on the phase velocity to generate an S-wave velocity vs. depth profile that should be located in the middle of the receiver spread (Miller and Xia 1999a). Initial models are a key factor for convergence of the inversion process. After processing more than five thousand shots of real data and countless modeling data, initial models defined by the algorithm (Xia et al., 1999b) are generally converged to models that are acceptable in geology and also fit the dispersion curve in a given error range. The number of layers is chosen between ten to twenty in most our experiences. The thickness of each layer varies based on the depth of interests. For example, for a geological problem with the depth of interests of 50 ft, we may choose a ten-layer model that possesses the first three layers with thickness of 3 ft each, the next three layers 6 ft each, the last three layers 10 ft each, and a half space. The inverted S-wave velocity profile for each shot gather is the result of horizontally averaging across the length of the geophone spread.

Gridding algorithms, such as kriging, minimum curvature, etc., may be used to generate a two-dimensional contour map of the S-wave velocity of a vertical section. With density information, a stiffness section can be generated simultaneously. Two-dimensional data processing techniques, such as regression analysis, could be easily applied to a vertical section of S-wave velocity to enhance local anomalies of S-wave velocity.

On a 2-D S-wave velocity map, the bedrock surface is usually associated with high S-wave velocity gradients, while fracture zones, voids, and buried landfill edges, etc. may be indicated by S-wave anomalies such as low velocity zones.

THE REAL WORLD EXAMPLES

Data shown in this section were collected by a Geometrics StrataView R60 seismograph. In the following four examples, data were processed by *SurfSeis*, a proprietary software package of the Kansas Geological Survey using the MASW method. Analysis of each shot gather required approximately 1 minute of processing time on a today's PC.

Mapping Bedrock in Olathe, Kansas

Data were acquired along two sets of parallel lines intersecting at right angles in February 1999. Data recorded and vertically stacked four impacts from a 12 lb. hammer on a 1 ft by 1 ft plate. Single, 4.5 Hz vertical component geophones were spaced 2 ft apart along the profile. The nearest source-geophone offset is 8 ft while source spacing is 4 ft. Complicating the acquisition was an asphalt surface covering most of the site. It was necessary to acquire data with base plate on the geophones (asphalt) and a portion (grass) with traditional spikes (Miller et al., in press).

The standard roll-along technique was used to acquire a total of 91 shots along line 2. Each shot gather possesses 48 traces and was suitable for sampling Rayleigh waves with a wavelength from 2 to 94 ft. The frequency range of Rayleigh waves is 20 to 60 Hz. The observed wavelength of Rayleigh waves is in the range of 9 to 50 ft. A ten-layer model with thickness of 1, 1.3, 2, 3.3, 3.7, 4.1, 4.6, 5, 5 ft, and a half space, respectively, was generated. Figure 2 shows the S-wave contour map. The weathered bedrock surface was interpreted along the 1,100 ft/s-contour line. An extreme drop in S-wave velocity beneath station 2050 was interpreted as a paleochannel that has been infilled with weathered bedrock. This feature is very close to the edge of the manufacturing facility. Drilling at station 2050 confirmed this channel. Another apparent channel feature on the east end of line (station 2185) is not drilled because it is away from the area of concern.

Imaging a Steam Tunnel, Lawrence, Kansas

This data set was acquired in the Spring of 1997 to test a stacking technique of Rayleigh waves that is still under development. The data acquisition parameters are not optimal to the S-wave contour method discussed in this paper, especially the nearest source-receiver offset. If we recollect this data set, we may reduce the nearest source-receiver offset to 20 - 40 ft.

Data were acquired along a line perpendicular to a steam tunnel with an IVI minivib on the campus of the University of Kansas. A linear up-sweep ranges from 10 to 150 Hz and lasts 10 seconds. A group of three 10 Hz vertical component geophones wired in series were spaced 4 ft apart along the profile. The nearest source-geophone offset is 80 ft while source spacing is 4 ft. The standard roll-along technique was used to acquire total 76 shots along the line. Each shot gather possesses 30 traces and was suitable for sampling Rayleigh waves with wavelength from 4 to 116 ft. The observed frequency range of Rayleigh waves is 10 to 50 Hz. The observed wavelength of Rayleigh waves is in the range of 8 to 65 ft. A ten-layer model with a thickness of 3.3 ft for the first four layers and 6.6 ft for the last five layers, and a half space, respectively, was generated.

Figure 3 shows the S-wave contour map. The steam tunnel is beneath station 60. The contour map shows a strong S-wave anomaly around this station. A concrete walkway is parallel to the steam tunnel at station 40, which may explain an S-wave anomaly beneath that station.

Mapping Bedrock Surface, Joplin, Missouri

Data were acquired along two parallel lines in March 1997. Thirty-four groups of three 10 Hz vertical component geophones wired in series were spaced 4 ft apart. The nearest source-receiver offset was 40 ft. An IVI MiniVib was used as the energy source. A linear down-sweep with frequencies ranging from 100 to 10 Hz and lasting 10 seconds was generated for each shot station. A total of 186 shot gathers were collected on 4 ft spacing using the standard CDP roll-along acquisition format. Each shot gather possesses 34 traces and was suitable for sampling Rayleigh waves with wavelength from 4 to 132 ft. The observed frequency range of Rayleigh waves is 10 to 25 Hz. The observed wavelength of Rayleigh waves is in the range of 40 to 100 ft. A five-layer model with thickness of 18 ft for the first four layers on the top of a half space was generated. A five-layer model in the inversion process seems too simple. We did not try a ten-layer model because S-wave contour maps agree with the well data.

Figure 4 shows the S-wave velocity of line 2 that changes smoothly from one station to next station, suggesting stability in the inversion algorithm and reliability of the inverted results. Depth to the bedrock at the two well locations along the line is consistent with the high gradient portion of the contour plot. If the 1,700 ft/s-contour line is chosen as a possible bedrock surface, the difference between depths determined by well data and the S-wave velocity map is less than 10 percent in the two locations.

Mapping Dissolution Feature, Damascus, Alabama

A total of more than 2,500 shots of surface wave data were acquired along thirteen lines, eight lines in east-west direction, four in north-south direction, and one in northwest-southeast direction, in February 1999. For details, see Miller and Xia (1999b). Single 4.5 Hz vertical component geophones were spaced 4 ft apart. The nearest source-receiver offset was 40 ft. Three ground impacts from a rubber band accelerated weight drop were vertically stacked by a Geometrics StrataView R60 seismograph at each source location. Each shot gather possesses 48 traces and was suitable for sampling Rayleigh waves with wavelength from 4 to 188 ft. The observed frequency range of Rayleigh waves is 5 to 22 Hz. The observed wavelength of Rayleigh waves is in the range of 25 to 200 ft.

A total of 224 shots were collected along line 1 using the standard CDP roll-along acquisition format. A fourteen-layer model with thicknesses of 5 ft for the first four layers, 7.5 ft for the next four layers, and 10 ft for the last five layers and a half space was created for the inversion of surface wave data along the entire line. Figure 5 shows the S-wave velocity contour map of line 1 that was generated independent of drill data. The 1,200 ft/s-contour line is interpreted as a top of weathered limestone surface. Two striking low velocity zones can be identified. One is between station 1030 to station 1080 from 40 to 100 ft of depth. The other is between station 1230 and station 1320 from 40 to about 100 ft. These two zones are most likely related to a fracture system or void area as indicated by pulldown in the 1,200 ft/s-contour line.

DISCUSSIONS

This method possesses several advantages in mapping subsurface geology. It provides a unique way to image two-dimensional near-surface S-wave velocity because the method focuses on high-frequency ground roll. It can be used to detect targets significantly shallower than feasible with seismic reflection techniques. Since ground roll has a high signal-to-noise ratio and the multi-channel acquisition method is used, two-dimensional images can be obtained in noise environments that have been a major factor in inhibiting the routine use of conventional body-wave seismic methods in cultural areas.

Because the method uses the standard CDP roll-along acquisition format, it provides an efficient way to acquire broadband ground roll data along a line. And also because the method utilizes the redundancy of the standard CDP roll-along acquisition format, it not only provides a reliable way to verify the inverted S-wave velocity, but reduces ambiguity of the inverted S-wave velocity as well.

A two-dimensional display of S-wave velocity can easily and quickly be done by contouring the inverted S-wave velocities. It provides an efficient way to map S-wave velocity in a vertical section. The two-dimensional display of S-wave velocity reduces nonuniqueness of inverted S-wave velocity and the potential for mis-interpretation based on one-dimensional S-wave velocity vs. depth plot. Two-dimensional data processing techniques, such as regression analysis, could be easily applied to a vertical section of S-wave velocity to enhance local anomalies of S-wave velocity (gas or oil fields, voids, tunnels, etc.).

There are also some limitations on this method. The inversion is based on the layered earth model (Xia et al., 1999b). The method could only provide qualitative understanding on the horizontal and vertical resolution, especially on the horizontal resolution in an area where S-wave velocity varies significantly laterally. Quantitative measurements of the horizontal and vertical resolution need to be studied. Empirical formulas to calculate the horizontal and vertical resolution may be obtained through detailed modeling analysis.

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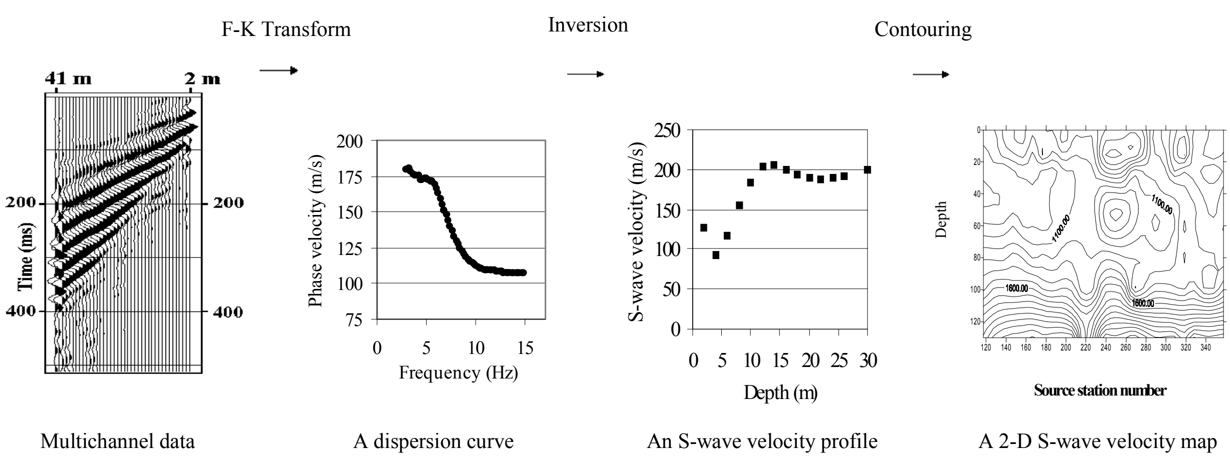

Figure 1. A diagram of construction of 2-D S-wave velocity map by the MASW method. Multichannel raw field data are acquired in the CDP roll-along format. Rayleigh wave phase velocities are extracted from the field data in the F-K domain. The phase velocities are inverted for a shear-wave velocity profile (V_s vs. depth). Finally, a 2-D S-wave velocity map is generated by any contour software.

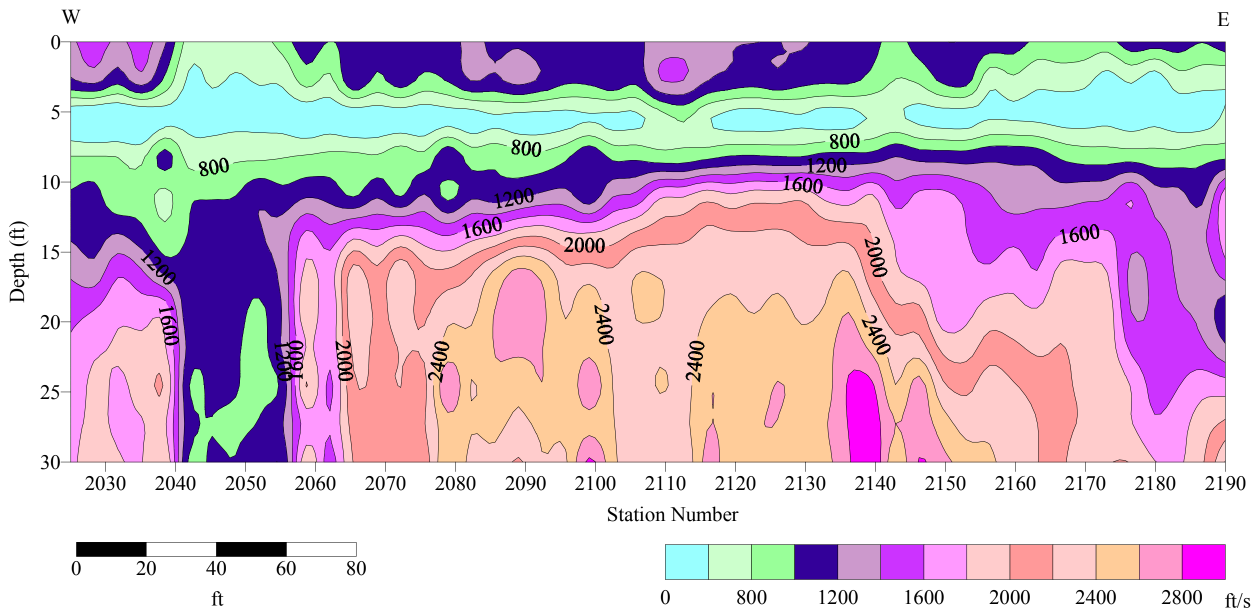

Figure 2. A 2-D S-wave velocity map of line 2 of Olathe, Kansas. A weathered bedrock surface is interpreted along the 1,100 ft/s-contour line. A fracture zone is interpreted and confirmed by drilling data around station 2050.

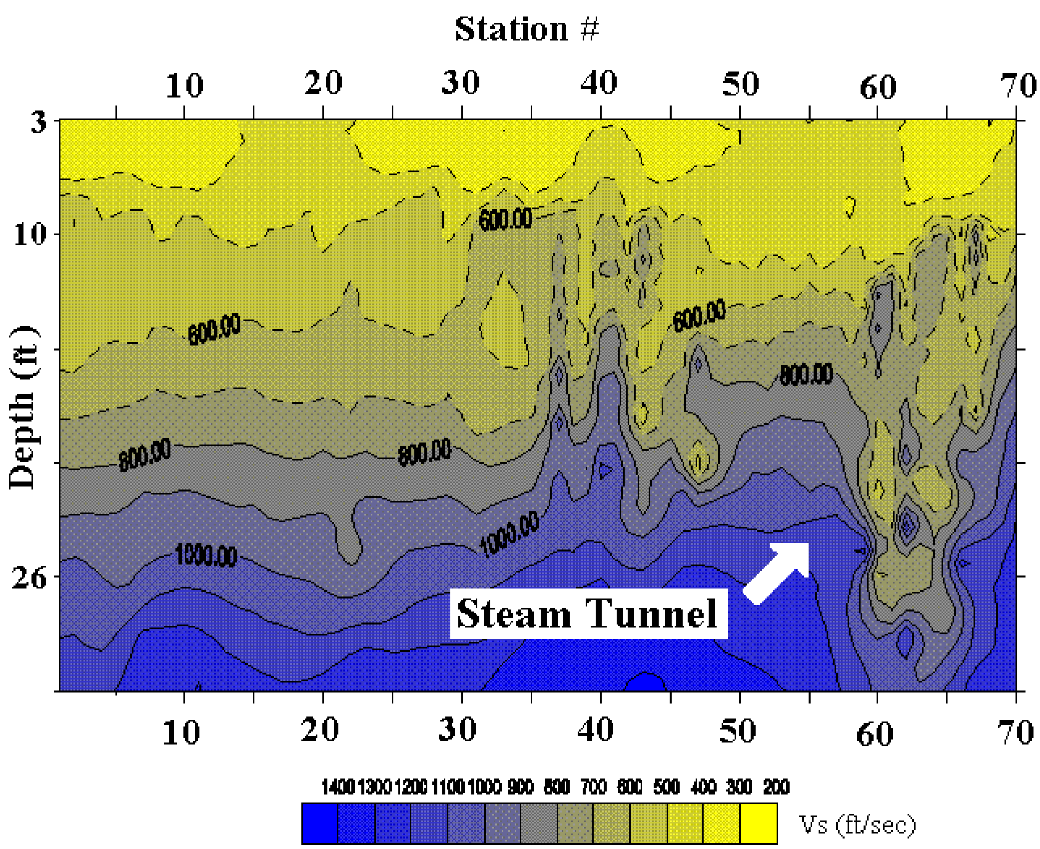

Figure 3. A vertical section of S-wave velocity on the top of a steam tunnel on the campus of the University of Kansas. Station spacing is 4 ft.

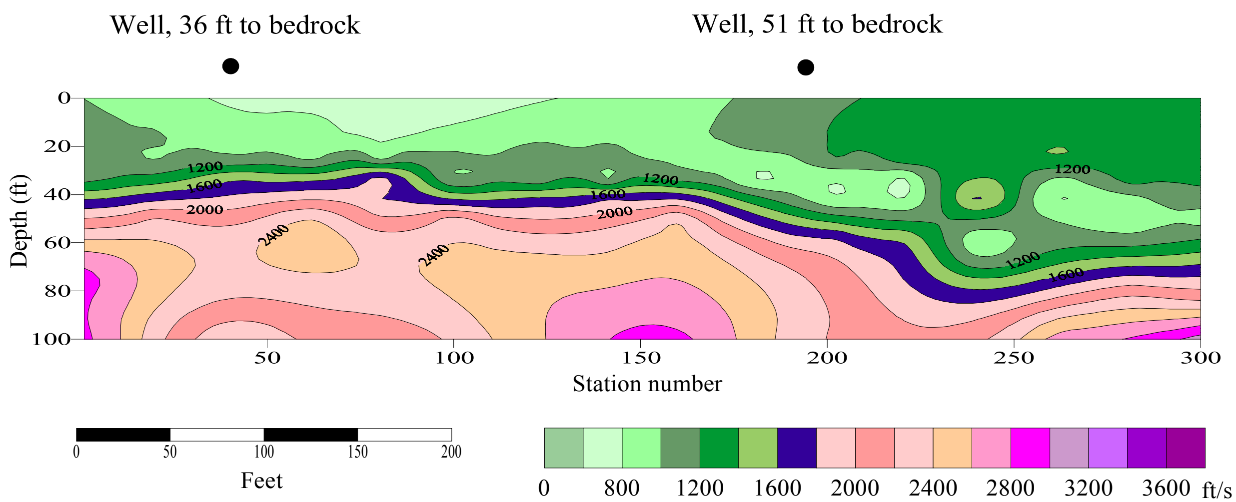

Figure 4. A 2-D S-wave velocity map of line 2 of Joplin project. The bedrock surface is interpreted along the 1,700 ft/s-contour line. Two wells along the line confirm the interpretation.

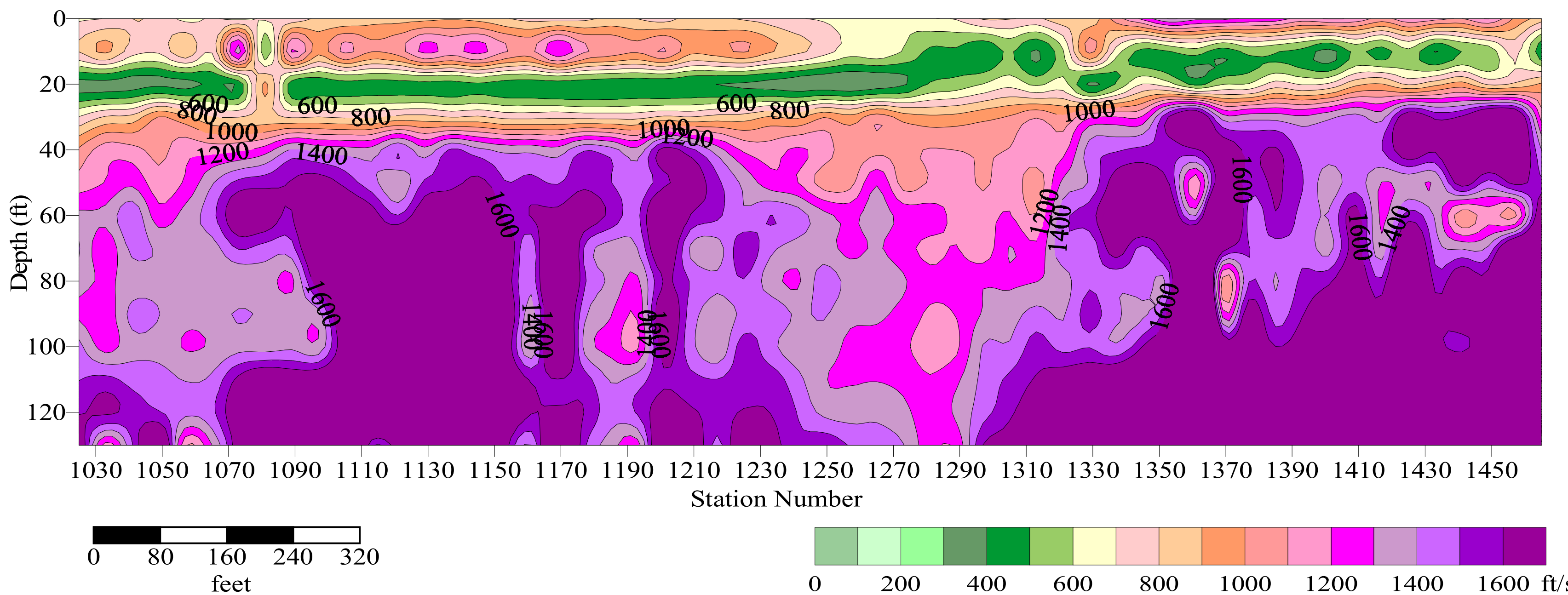

Figure 5. A 2-D S-wave velocity map of line 1 of the Damascus project. Two distinguished S-wave velocity lows are around station 1050 and 1270 from 40 to 100 ft depth. The weathered limestone surface is interpreted along the 1,200 ft/s-contour line.