Using MASW to Map Bedrock in Olathe, Kansas

Richard D. Miller
Jianghai Xia

Kansas Geological Survey
1930 Constant Avenue
Lawrence, Kansas 66047

Final Report to

Harding Lawson Associates
Lee's Summit, Missouri

Open-file Report No. 99-9 May 10, 1999

Using MASW to Map Bedrock in Olathe, Kansas

by

Richard D. Miller
Jianghai Xia
Choon Park
Julian Ivanov
Nathan Geier
David Laflen

of the

Kansas Geological Survey
1930 Constant Avenue
Lawrence, KS 66047-3726

Final Report to

Harding Lawson Associates
4121 NE Port Drive
Lee's Summit, MO 64064

Open-file Report No. 99-9

May 10, 1999

Using MASW to Map Bedrock in Olathe, Kansas

Summary

The shear wave velocity field, calculated using the Multi-channel 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 6 to 23 ft 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 fractures and/or an unmapped buried stream channel could be 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 introduced at or near the ground surface, determining the nature and location of anomalous bedrock was critical to hydrologic characterization of 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., approx 220,000 yd^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 only shear wave velocity data possesses significantly higher resolution than maps produced using drilling alone. There is less than 1 ft of difference in the depth-to-bedrock interpreted from surface wave data versus the depths determined through drilling. Geophones used for this study were equipped with steel baseplates. 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.

Localized anomalies were observed on lines 2 and 4 that are likely representative of anomalies in the bedrock. Anomalously low velocities observed on the western portion of the east-west lines is very abrupt and localized, suggesting a zone of either fractures, a relatively shear-sided channel, or a fault. Based on the seismic data alone it is not possible to determine

which of these scenarios is correct. Speculating from the character and apparent vertical extent of this feature, it is more likely a fault or fracture than a channel. The physical dimensions of this feature would require a channel to be over 20 ft deep and 30 ft wide with vertical side walls. A channel with these dimensions is possible, of course, but would not be expected in this setting.

The general topographic trend of the bedrock surface suggests a north dip with an apparent change in the material composition of the shallow bedrock at a localized low in the bedrock surface. Bedrock lows are present at the north end of lines 1 and 3. Based on the drop in shear wave velocities, these lows are also areas with either increased weathered bedrock near the contact between unconsolidated material and bedrock or the bedrock material changes slightly (i.e., limestone to shale or possibly the shale limestone thickens). Lines 2 and 4 possess a low velocity bedrock material near their eastern ends. It appears to transition from high velocity to low velocity very subtly on line 2 while on line 4 the feature is very abrupt and similar in character to the fault/fracture/channel interpreted on the western end of both these lines. Bedrock toward the eastern ends of lines 2 and 4 can be interpreted to be either flat or maybe slightly shallower than near the building on the west.

The depth-to-bedrock contour map produced using both drilling and seismic data is significantly more detailed and represents a closer approximation to the real bedrock surface than either drilling or seismic data could have produced alone. The match between drilling and seismic is excellent. Improved resolution on the surface of the bedrock provides insight into the texture of bedrock and permits identification and appraisal of short wavelength variations in the bedrock surface. The goals and objectives of this survey were met.

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 multi-trace 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 surface (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 330 ft 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 increasing 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 the area immediately outside along the southeast side of Building A ("New Building" on Figure 1). Within Building A industrial fluids were used during the manufacturing process. If these fluids were to escape from their containment vessels it would be imperative to have a detailed understanding of the bedrock surface so the most likely transport

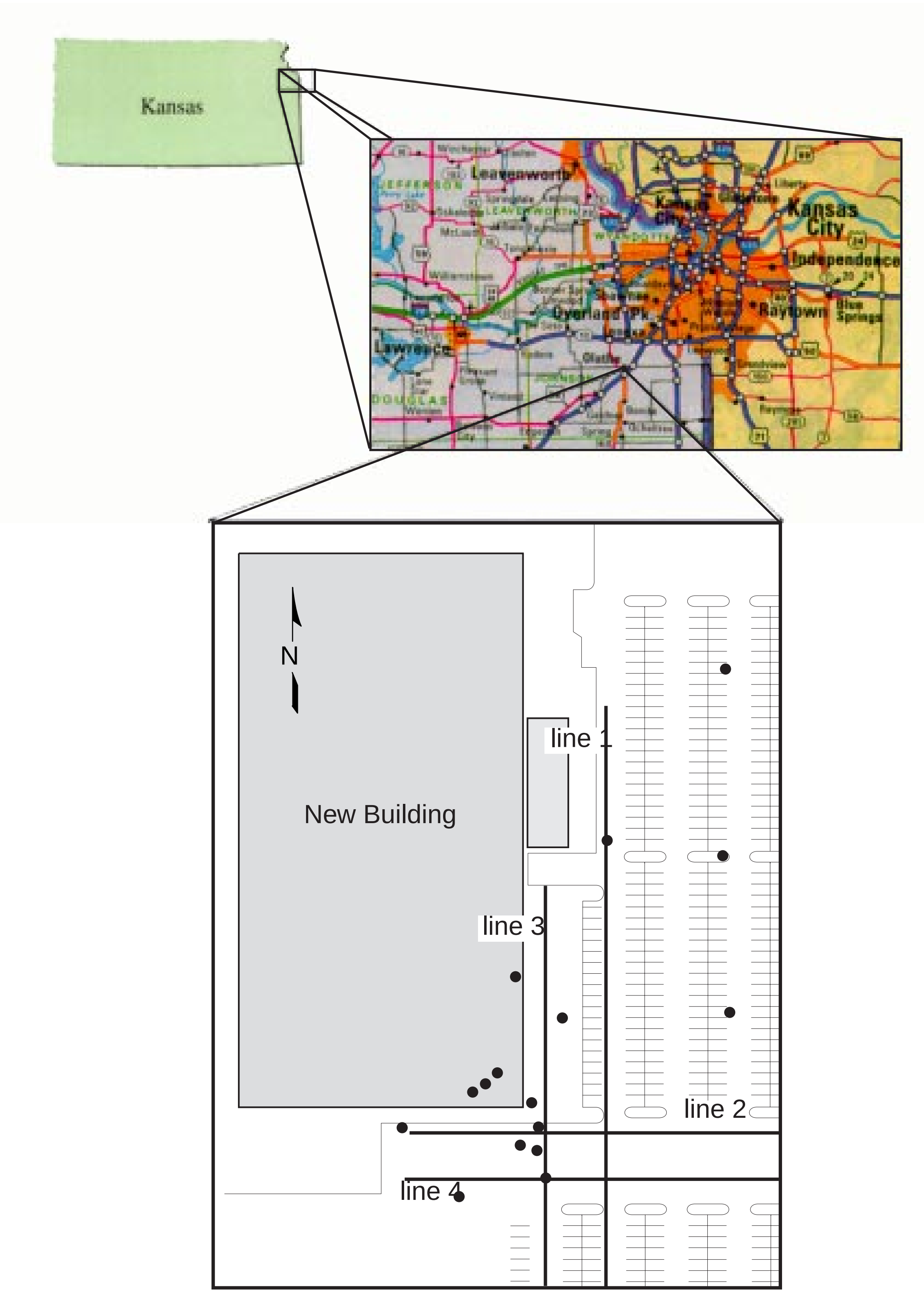


Figure 1. Site Map, Olathe, Kansas

and fate models could be used to contain and remove these fluids from the ground. This is a scenario not unlike thousands currently under investigation around the country. 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 2 ft to 33 ft 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 8 ft along the profile lines. The asphalt surface that covered most of the site complicated data acquisition. It was necessary to acquire some data with baseplates on the geophones (asphalt) and a portion with traditional spikes (grass). A 60-channel Geometrics StrataView seismograph was used to record and vertically stack four impacts from a 12 lb hammer on a 1 ft^2 plate. Single, 4.5 Hz Geospace GS-11D geophones spaced 2 ft apart along the profile lines were changed from flat plate to spike and back to flat plate as the surface condition dictated. The source-to-nearest-receiver offset was nominally 8 ft while each source station was separated by 4 ft. This recording geometry provided the optimum spread for examining earth materials between 3 and 50 ft 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 normally requiring at least 3.5-in 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 2 ft and 50 ft. These multi-channel records were analyzed with *SurfSeis*, a proprietary software package

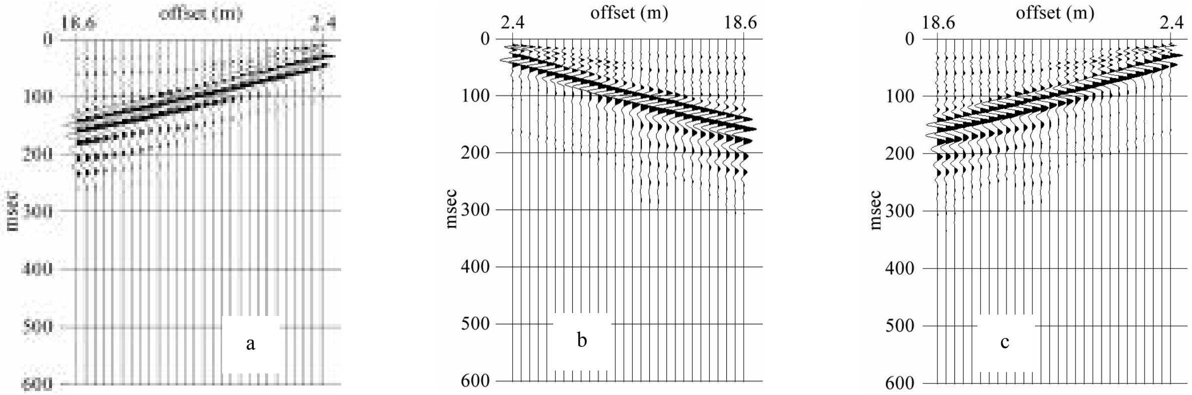


Figure 2. Shot gathers of geophones with spikes (a), baseplates (b), or baseplates with weights (c).

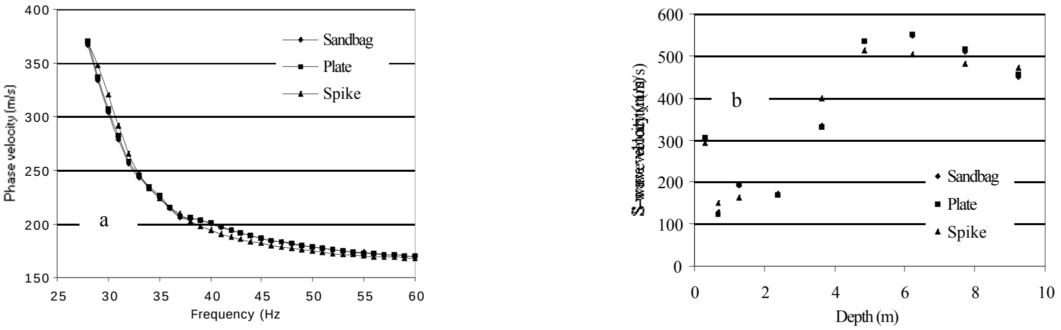


Figure 3. Dispersion curves (a) extracted from Figure 2 and inverted S-wave velocities (b) based on the dispersion curves.

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 that will be significant to the hydrologic characteristics of this site. Drill data acquired prior to the seismic survey were used to optimize the recording parameters and confirm the interpretation of bedrock on shear wave velocity field contour maps. The bedrock surface was selected based on gradient of the contours, correlation to boreholes drilled prior to the seismic survey, and reasonable velocity value.

Line 1 was the longest profile and was acquired completely on the asphalt parking lot immediately east of Building A. Data quality were consistent, with dispersive ground roll possessing an optimum bandwidth for investigation of near-surface materials between about 4 and 30 ft below ground surface. The shear wave velocity profile of line 1 (Figure 4) represents a relatively smooth bedrock surface with a localized low around station 1160. Topographic variations of bedrock on this line are from about 10 to around 15 ft below ground surface. A sub-bedrock surface anomaly manifests itself as a localized bedrock high starting at about 15 ft of depth beneath station 1070. This feature represents an area of the bedrock or possibly sub-bedrock with a high average shear wave velocity (harder) than the surrounding rock. Contrasting the south and north halves of this profile, the bedrock material on the south appears “harder” (i.e., higher shear wave velocity) than that on the north. This could be related to a different material or to a large fracture zone. A change of over 40% in the shear wave velocity between the two ends of this line represents a significant change in the average “stiffness” of the bedrock materials.

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 5). An extreme drop in shear wave velocity beneath station 2050 can be interpreted as either a paleochannel infilled with weathered material or a fracture/fault zone. A localized low beneath station 2040 is quite pronounced and represents the topographically lowest bedrock surface along this line. Directly above station 2050 is a drop in the shear wave velocity between the surface and about 5 ft or so. This is directly related to the sewer line buried along the eastern side of the building. Also of interest is the apparent channel feature on the east end of the line. This feature is away from the area of concern but does strongly resemble a bedrock channel infilled with lower velocity material prior to deposition of the unconsolidated material present across this site above bedrock.

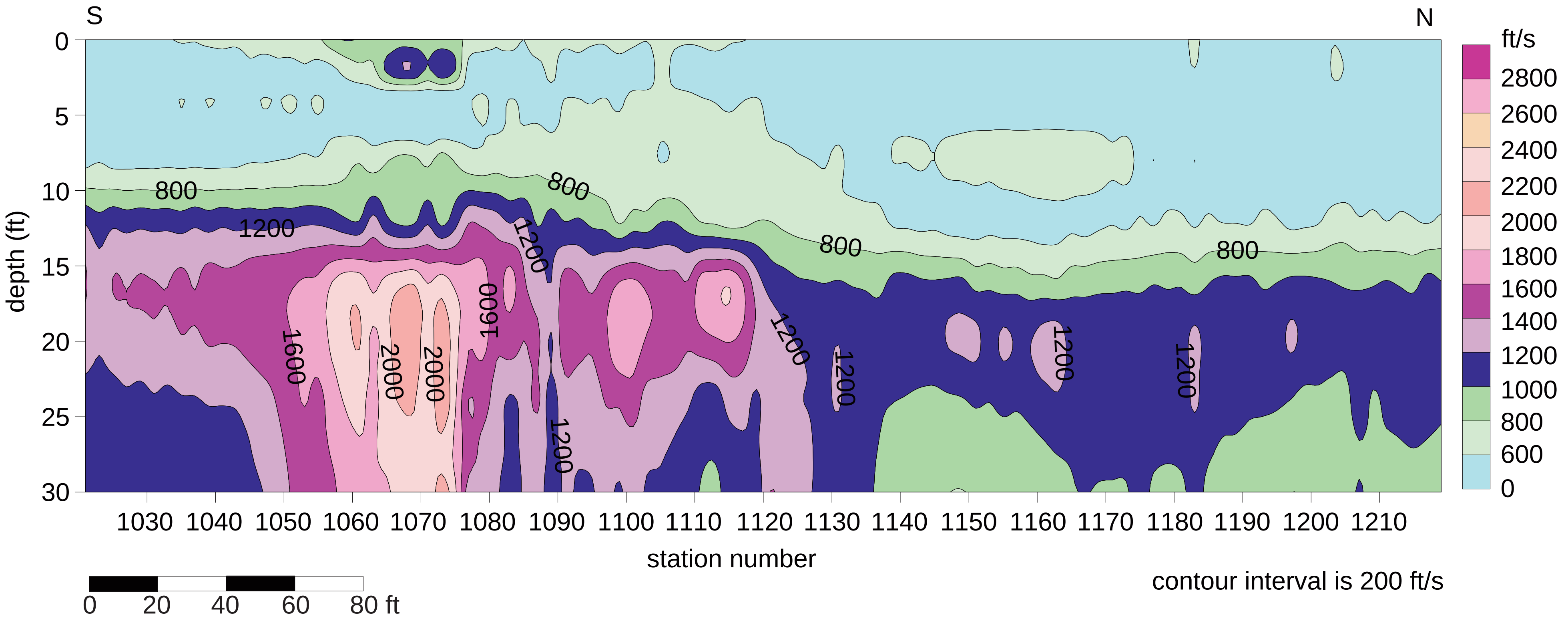


Figure 4. S-wave velocity contours along line 1 at Olathe, Kansas, site.

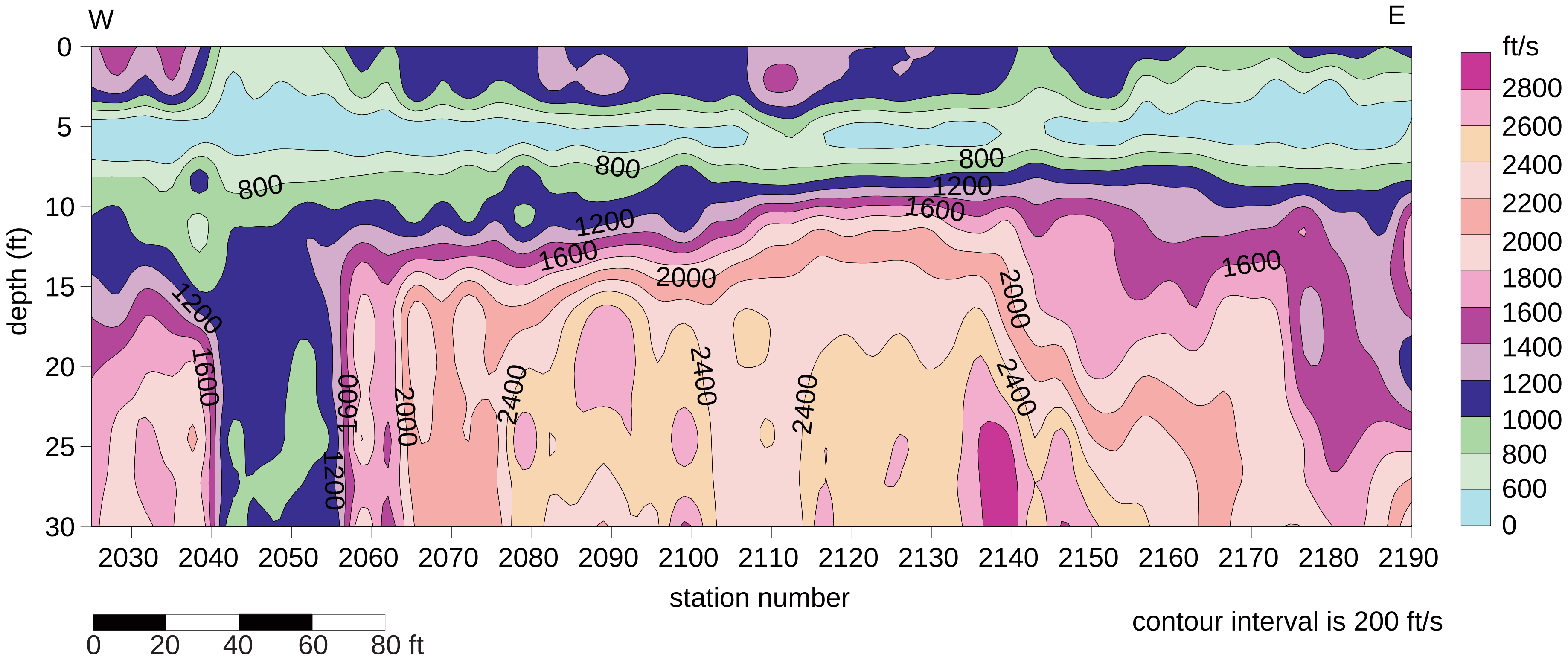


Figure 5. S-wave velocity contours along line 2 at Olathe, Kansas, site.

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 texture and very irregular nature of the bedrock surface (Figure 6). These short wavelength undulations in the bedrock surface were features that could not be determined with borehole data alone. It is unlikely the bedrock surface has quite this severe a pinnacle type topography but it can be characterized as hydrologically complex due in part to the multitude of localized highs and lows in the bedrock surface. An apparent high separates the low observed on the south from the low on the north. This feature could be acting as a hydrologic barrier, separating fluid introduced south of station 3140 from any entering the subsurface north of station 3120. The deepest bedrock observed on any of the surface wave profiles can be observed on the northern end of line 3 with an estimated depth to bedrock of around 25 ft near the loading dock area of Building A.

Two features on line 4 are quite striking and likely represent breeches in the bedrock surface (Figure 7). Beneath station 4080 is a feature that can be directly correlated to a similar feature on line 2. Velocity contrasts associated with this channel-fault/fracture, its physical dimensions, and relative location of this feature are consistent with line 2. As well, the observed low velocity zone down to about 5 ft above this feature is interpreted to be the footprint of the sewer located along the eastern side of Building A. Probably the most hydrologically significant feature as it relates to transport and fate in close proximity to the southeast corner of Building A is the “V” shaped channel below station 4075. This feature is observable on line 2 with nearly identical geometry. This feature will influence how fluid moves on bedrock, acting as a barrier and conduit. Bedrock seems to get closer to the ground surface toward the eastern end of line 4. This observation is also consistent with the interpretation of line 2. The anomalous feature located beneath station 4140 on line 4 is difficult to directly correlate to line 2. If this fracture/fault-channel feature rapidly widens, with a southwest-northeast trend it might be present on line 2 in the form of a wider channel-looking feature with a much more subdued velocity gradient. Line 4 possesses several features that need to be considered in a transport and fate model for this site.

Data resolution is an issue that must be addressed with this data. It is unlikely the bedrock surface on line 3 possesses 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

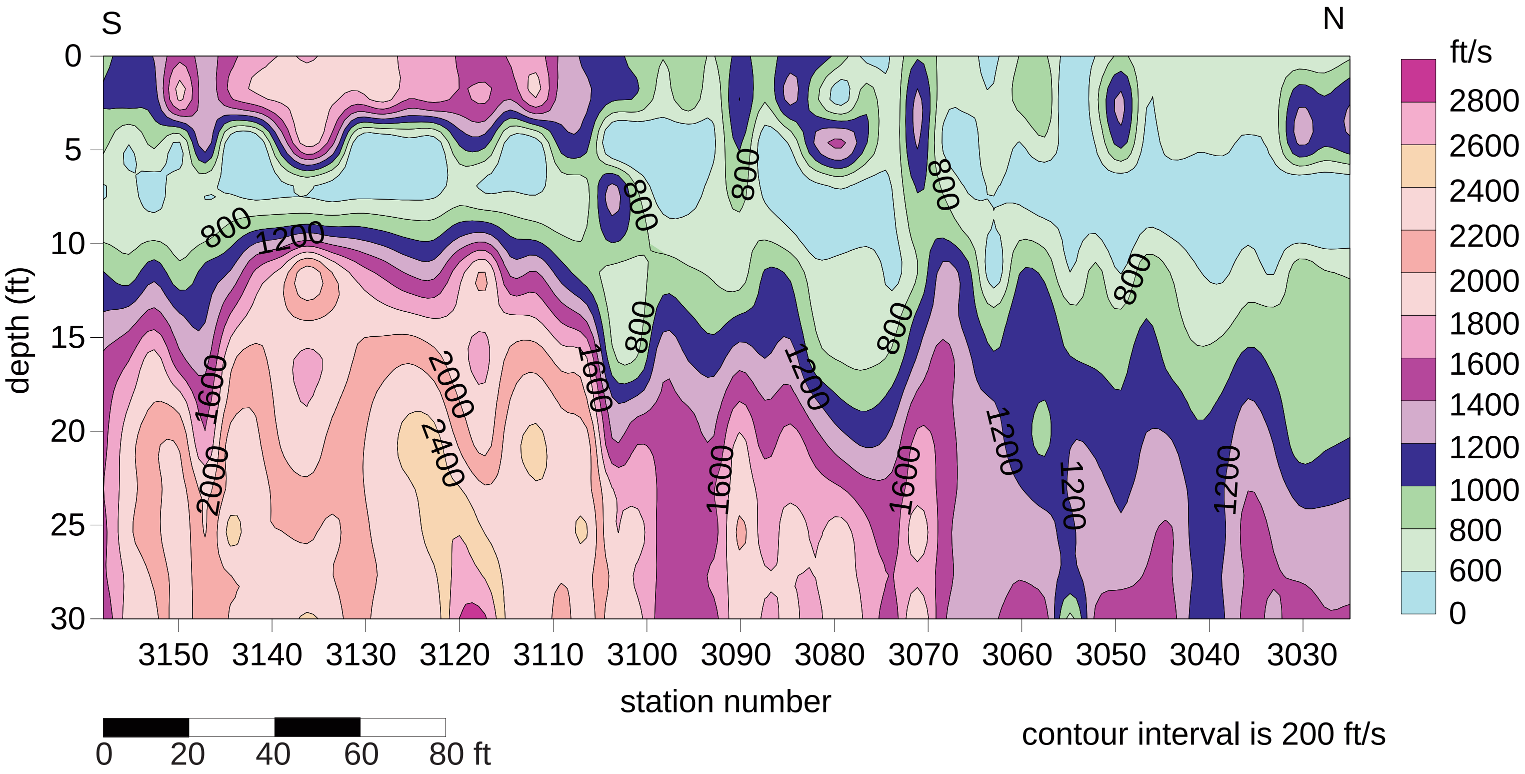


Figure 6. S-wave velocity countours along line 3 at Olathe, Kansas, site.

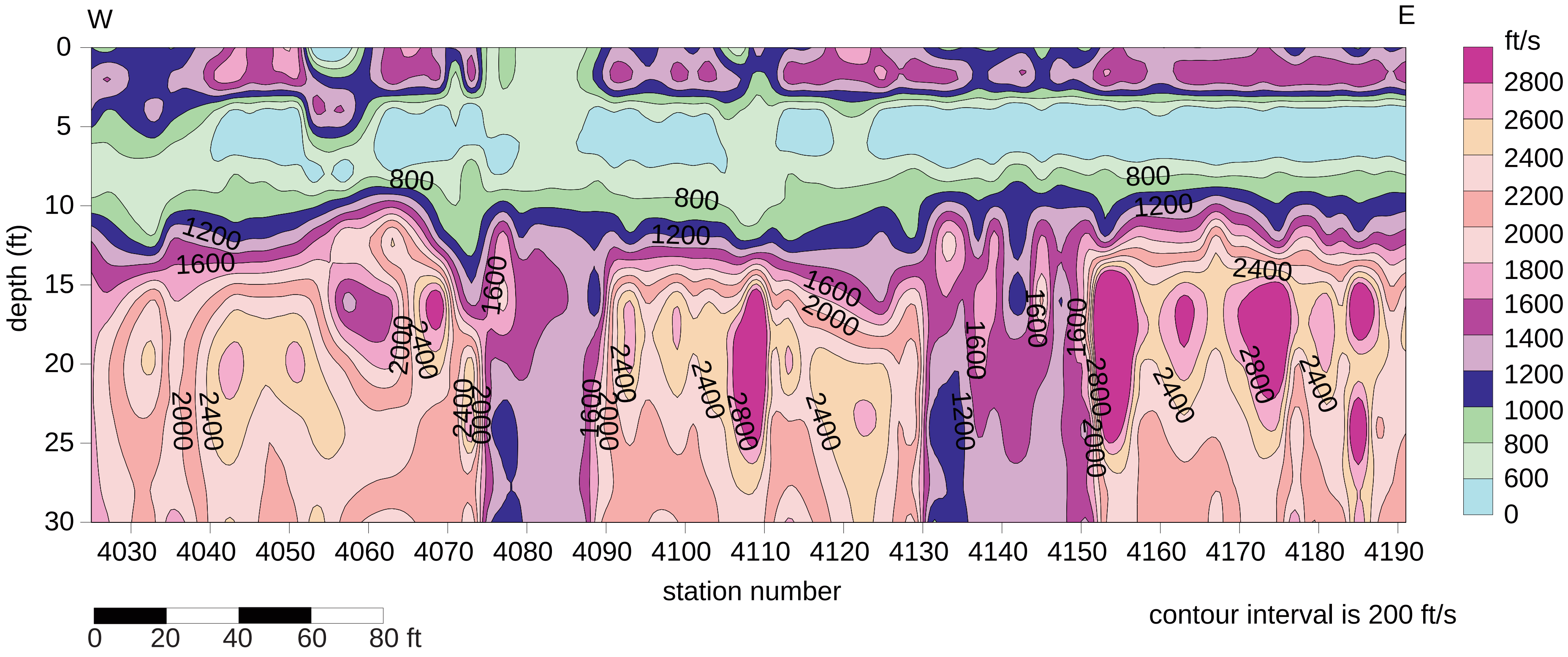


Figure 7. S-wave velocity contours along line 4 at Olathe, Kansas, site.

observed on this section. It must be kept in mind that surface wave imaging techniques involve the inversion of a wave that has sampled an area as wide as it is deep. Therefore, structures observed on shear wave cross-sections are likely smoothed version of what really exists in the subsurface.

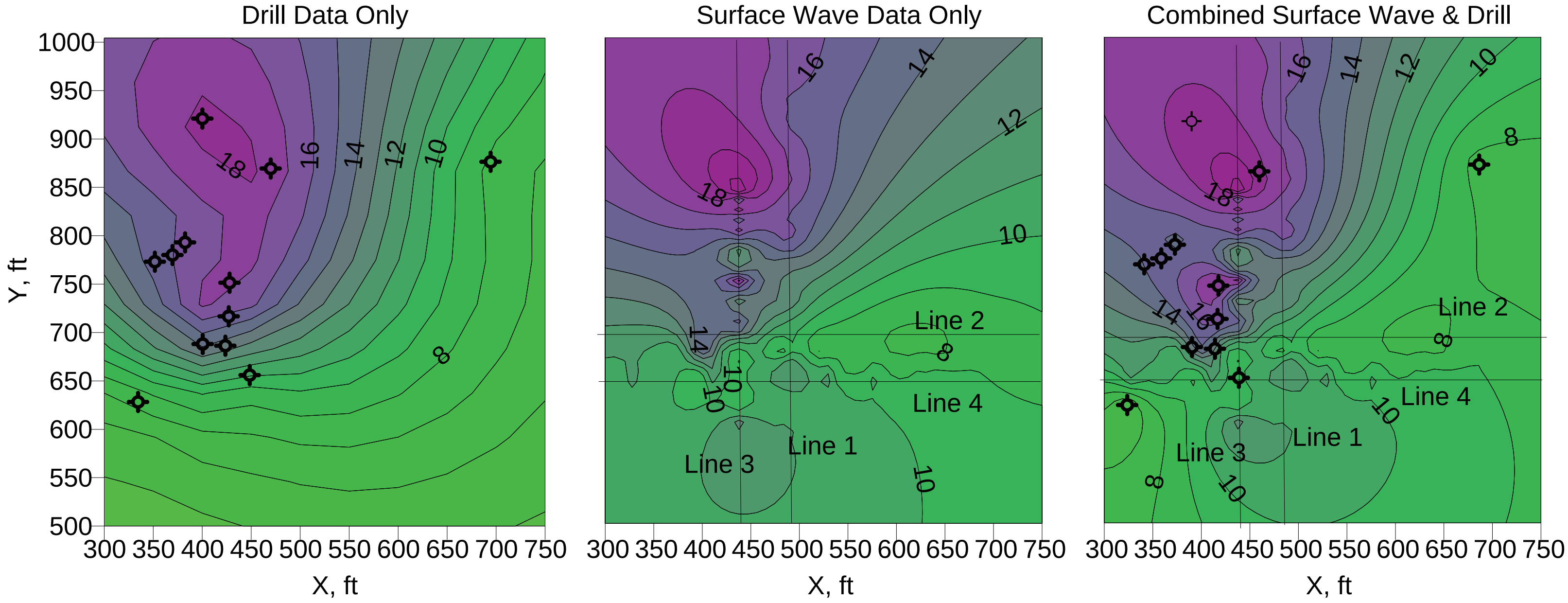
Resolution of the bedrock surface map improves significantly when the shear wave velocity data are incorporated with drill data (Figure 8). Depth to bedrock contours based on drill data alone effectively defined the gross configuration of bedrock at this site. However, due to the sporadic locations and non-uniform spacing of drill holes it is difficult to extend or define subtle bedrock features at this site. The bedrock contour map produced using only shear wave data lacks off-line control. It is difficult to correlate features or extend features identified by the seismic survey out of the 2-D plan of the profiles when this much variation is observed. Incorporating the drill data and shear wave data produces a greatly improved and much more accurate representation of the depth-to-bedrock from the ground 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. It would be beneficial if two more profiles were acquired immediately east of line 1 to better define and extend the bedrock lows observed on lines 1 and 3. One more east-west line immediately south of line 4 would also go a long way toward improving the delineation of the two channel-fracture/fault features interpreted on lines 2 and 4.

Acknowledgments

Assistance in document preparation was given by Mary Brohammer and Amy Stillwell.



(a) (b) (c)

Figure 8. Depth to bedrock contour map based on drilling alone (a), seismic data alone (b), and a combination of both drilling and seismic data (c).

References

Glover, R.H. 1959, Techniques used in interpreting seismic data in Kansas: in Symposium on Geophysics in Kansas, ed. W.H. Hambleton. Kansas Geological Survey Bulletin 137, p. 225-240.

Mayne, W.H., 1962, Horizontal data stacking techniques: Supplement to Geophysics, p. 927-937.

Nazarian, S., K.H. Stokoe II, and W.R. Hudson, 1983, Use of spectral analysis of surface waves method for determination of moduli and thicknesses of pavement systems, Transportation Research Record No. 930, 38-45.

Park, C.B., R.D. Miller, and J. Xia, 1996, Multi-channel analysis of surface waves using Vibroseis (MASWV) [Exp. Abs.]: Soc. Expl. Geophys., p. 68-71.

Park, C.B., R.D. Miller, and J. Xia, 1998, Ground roll as a tool to image near-surface anomaly [Exp. Abs.]: Soc. Explor. Geophys., p. 874-877.

Park, C.B., R.D. Miller, and J. Xia, 1999, Multi-channel analysis of surface waves (MASW): Geophysics, May-June (forthcoming).

Steeples, D.W., and R.D. Miller, 1990, Seismic-reflection methods applied to engineering, environmental, and groundwater problems: Soc. Explor. Geophys. Investigations in Geophysics no. 5, S.H. Ward, ed., Vol. 1: Review and Tutorial, p. 1-30.

Xia, J., R.D. Miller, and C.B. Park, 1997, Estimation of shear wave velocity in a compressible Gibson half-space by inverting Rayleigh wave phase velocity: Technical Program with Biographies, SEG, 67th Annual Meeting, Dallas, TX, 1927-1920.

Xia, J., R.D. Miller, and C.B. Park, 1998, Construction of vertical seismic section of near-surface shear-wave velocity from groundroll [Exp. Abs.]: Soc. Explor. Geophys./AEGE/CPS, Beijing, p. 29-33.

Xia, J., R.D. Miller, and C.B. Park, in press, Estimation of near-surface shear-wave velocity by inversion of Rayleigh wave: *Geophysics*.