Feasibility of Surface Waves to Delineate Fractures in the Winterset Limestone at the Johnson County, Kansas, Landfill

Summary

Fractures within consolidated rock layers can influence the transport and eventual fate of contaminants. Monitor well placement is critical to accurate estimations of fluid movement and composition in a fracture flow system. Hydrologic characterization of a site in Johnson County, Kansas, could be enhanced if any anomalous zones within the Winterset Limestone, reported to be between 100 and 150 ft below ground surface, could be located with sufficient confidence to allow drill investigation. Abrupt changes in shear wave velocity are expected at the boundary between unconsolidated fill materials and consolidated bedrock and within fractured or highly altered zones where otherwise competent rock is broken up with unconsolidated sediments and/or fluids filling the void spaced between cracks and blocks of rock. Abrupt and distinct changes in the shear wave velocity may also occur at the contacts between cyclic limestone and shale sequences at and below the bedrock surface at this site. This study will focus on the following goals and objective: 1) feasibility of a continuous non-invasive surface wave imaging technique in this very noisy industrial area, 2) vertical and horizontal resolution potential at this site, 3) potential of 2½-D profiling, 4) effects of surface vs. spike geophone coupling, 5) detect-ability of fractures/faults, 6) evaluation of effective depth of imaging, and 7) generation of a subsurface map of the shear wave velocity field. This study will be designed to both develop an accurate shallow subsurface image and study optimization and limitations of delineating lateral changes in shear wave velocity using surface waves.

Introduction

Surface waves have traditionally been viewed as noise on multichannel 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 (CDP) developed for petroleum applications (Mayne, 1962). 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., 1999; Park et al., 1999).

Surface wave imaging has shown great promise detecting shallow tunnels (Figure 1), bedrock surface (Figure 2), remnants of underground mining (Figure 3), and fracture systems/ karst (Figure 4). Extending this imaging technology to include lateral variations in lithology has required a unique approach incorporating SASW, MASW, and CDP methods. Integrating these techniques provides a 2-D continuous shear wave velocity profile of the subsurface. Signal enhancement resulting from determination of a dispersion curve using up to 60 closely spaced receiving channels and the calculation of a dispersion curve every 4 ft to 8 ft or so along the ground surface provides a unique, relatively continuous view of the shallow subsurface. This highly redundant method enhances the accuracy of the calculated shear wave velocity and minimizes the likelihood of irregularities associated with an occasional erratic dispersion curve corrupting the data analysis or interpretation.

The objective of this research program is to determine the feasibility of this new technology to delineate lateral variations in shear wave velocity within consolidated sediments. These variations should be detected as anomalously low velocity zones within otherwise relative uniform materials. This site study will be divided into three individual phases: 1) testing and evaluation, 2) imaging the inferred feature, and 3) sitewide mapping to delineate the three-dimensionality of the feature. The testing stage will involve forward modeling and on-site acoustic wavefield studies. This testing stage may require a short period (a day or two) away from the site to fully appraise the test data and to determine penetration depths, a generalized velocity model, and feasibility of distinguishing velocity changes within the Winterset Limestone. The second stage involves a small-scale attempt (two to four lines across the pad site) to detect the bedrock features of interest in areas with sufficient ground truth to allow evaluation of resolution and feasibility. This imaging stage will require some processing and may extend over a period of anywhere from a day to a week (depending on how much processing could be done on-site and how much would require time back in Lawrence). Extra time may be necessary to fully process and analyze the results of the survey so determinations can be made as to the extent this technique could map the features of interest. The third and final stage (if determined necessary or useful) will attempt to delineate the entire area of interest in a pseudo three-dimensional sense (2½-D). This stage will require the deployment of an extensive series of profile lines optimized (based on available drill data and the results of the second phase) to allow the areal trends and extent of any interpreted anomalous zones (fractures) in the Winterset Limestone to be mapped.

The study of a this Johnson County, Kansas, site will commence as soon as a mutually agreeable time can be set up between Deffenbaugh Industries (DI) and the Kansas Geological Survey (KGS). The three phases of this study will be distinguished by unique acquisition, processing, analysis, and decision milestones. Proceeding from one phase to another will require agreement by DI and KGS that the results are consistent with the ground truth and expectations. Deployment of the initial testing lines will depend on objectives and limitations expanded on during on-site discussions between representatives of DI and KGS. The actual procedures used to acquire and process these data will evolve as the technique develops, significant characteristics are determined, and the limitations are defined.

Current Procedure

The current operational procedure requires the generation and analysis of an extremely broadband acoustic signal. Lower frequency components are critical to deeper penetration and the imaging associated with deeper target while high frequency signals will be necessary for detecting smaller anomalies at shallower depths. The primary waveform of interest will be the Rayleigh wave. The dispersive nature of this wave can be related to the shear wave velocity structure of the subsurface. By calculating the dispersion curve (phase velocity as a function of frequency) and then inverting that curve, a shear wave velocity profile can be determined for the area directly beneath the acquisition spread. Acquiring data by progressively moving the source from one station to the next while maintaining a consistent number of receivers and source-to-receiver separation permits the generation of a two-dimensional profile showing the shear wave velocity structure as a function of depth and station location. This shear wave profile can then be analyzed to identify significant changes in shear wave velocity likely indicative of abrupt and large changes in material properties. Laterally non-uniform portions of the velocity profile can be seen most prominently when large variations are observed in the gradient of the velocity field.

Once anomalous velocity zones are detected, a grid of profiles can be laid out and data collected along each profile. This two-dimensional grid provides a 2½-dimensional fence diagram that readily allows interpretation of meandering or spatially extensive features (Figure 5).

Data will be recorded on a 60-channel Geometrics StrataView seismograph using single GeoSpace 4.5 Hz GS-11D geophones equally spaced along the profile line. Energy for this study will be provided by either a sledgehammer or accelerated weight drop source. The selection of source will be based on depth of interest, velocity structure, and frequency band transmitted by each source type.

Reduction of the raw shot gathers into 2-D velocity contours will be accomplished using experience-proven processing and analysis techniques. SurfSeis (a set of processing and display algorithms), developed by the KGS for this imaging technique, will be used in conjunction with a commercial contouring package to produce the interpretable displays. Interpretation will be based on correlating ground truth data (drilling, outcrop observations, trench studies, etc.) with unique features on the velocity field cross-sections. Once the shear wave characteristics of the features of interest can be confidently established it should be possible to locate areas with similar characteristics within the survey area that can be inferred to be of similar nature.

Final Products

The goal of this study will be to detect karst features prior to surface expression and to delineate a laterally discontinuous high velocity layer within the unconsolidated sediments. The results of this study will include a thorough analysis of the technique's feasibility to appraise these two unique geologic targets, an empirically based estimation of vertical and horizontal resolution potential, and an interpretation of the subsurface based on changes in the shear wave velocity field.

References

Mayne, W.H., 1962, Horizontal data stacking techniques: Supplement to *Geophysics*, v. 27, p. 927-938.

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, p. 38-45.

Park, C.B., R.D. Miller, and J. Xia, 1996, Multi-channel analysis of surface waves using Vibroseis [Exp. Abs.]: Soc. of Expl. Geophys., 66th Annual Meeting, Denver, Colorado, p. 68-71.

Park, C.B., R.D. Miller, and J. Xia, 1999, Multi-channel analysis of surface waves: *Geophysics*, v. 64, n. 3, p. 800-808.

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, Stan H. Ward, ed., *Volume 1: Review and Tutorial,* p. 1-30.

Xia, J., R.D. Miller, and C.B. Park, 1999, Estimation of near-surface shear-wave velocity by inversion of Rayleigh waves: *Geophysics*, v. 64, n. 3, p. 691-700.