LEVEE EVALUATION USING MASW: PRELIMINARY FINDINGS FROM THE CITRUS LAKEFRONT LEVEE, NEW ORLEANS, LOUISIANA

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Abstract

The utility of the multi-channel analysis of surface waves (MASW) seismic method for non-invasive assessment of earthen levees was evaluated for a section of the Citrus Lakefront Levee, New Orleans, Louisiana. This test was conducted after the New Orleans' area levee system had been stressed by Hurricane Katrina in 2005.

The MASW data were acquired in a seismically noisy, urban environment using an accelerated weight-drop seismic source and a towed seismic land streamer. Much of the seismic data were contaminated with higher-order mode guided-waves, requiring application of muting filtering techniques to improve interpretability of the dispersion curves. Comparison of shear-wave velocity sections with boring logs suggests the existence of four distinct horizontal layers within and beneath the levee: (1) the levee core, (2) the levee basal layer of fat clay, (3) a sublevel layer of silty sand, and (4) underlying Pleistocene deposits of sandy lean clay. Along the surveyed section of levee, lateral variations in shear-wave velocity are interpreted as changes in material rigidity, suggestive of construction or geologic heterogeneity, or possibly, that dynamic processes (such as differential settlement) are affecting discrete levee areas.

The results of this study suggest that the MASW method is a geophysical tool with significant potential for non-invasive characterization of vertical and horizontal variations in levee material shear strength. Additional work, however, is needed to fully understand and address the complex seismic wave propagation in levee structures.

Introduction

Levees have served for centuries as flood-control structures along surface-water systems such as rivers and lakes. Key for building a reliable levee are the construction of a strong, impervious levee base and core and understanding and consideration of the underlying geology. In practice, levees are constructed with locally available materials, which can vary in quality and suitability (e.g., silt-to-clay fraction). Over time, physical and hydrologic processes including seasonal water fluctuations, flood events, differential settlement, external and internal removal of levee matrix (piping), etc., can adversely affect levee structures, thereby increasing the chances for levee failure during high-water events.

Levee failures in New Orleans, Louisiana, during Hurricane Katrina in August 2005, illustrate the need to periodically assess, test, and monitor levees systems. Conventional levee assessments use invasive borings, which provide extremely useful and detailed information on levee properties proximal to the boring. However, borings are expensive and often sparse, with limited predictive utility in

heterogeneous environments. Non-invasive, rapid, and spatially continuous methods are needed to support and augment traditional assessment techniques. Such methods would increase public safety by improving the ability of engineers to design and monitor levee systems.

In contrast to borings, surface geophysical methods provide a non-invasive means of evaluating subsurface engineering materials and geologic structures by measuring and mapping specific subsurface physical properties. One physical property of particular relevance to levee assessment is shear modulus, which can be estimated from shear-wave velocity, Vs. Shear modulus, G, is a strong function of shear wave velocity, according to:

$$G \approx Vs^2 \rho, \tag{1}$$

where ρ is material density (Sheriff, 1994).

The objective of this study was to evaluate the utility of the multi-channel analysis of surface waves (MASW) method to differentiate and measure levee core properties and variability of the near-surface geology directly beneath a section of the Citrus Lakefront Levee along Lake Pontchartrain, New Orleans, Louisiana (Figure 1). Of particular interest was the ability of the MASW method to map horizontal and vertical changes in Vs and to use Vs changes to estimate material rigidity changes over the surveyed section.
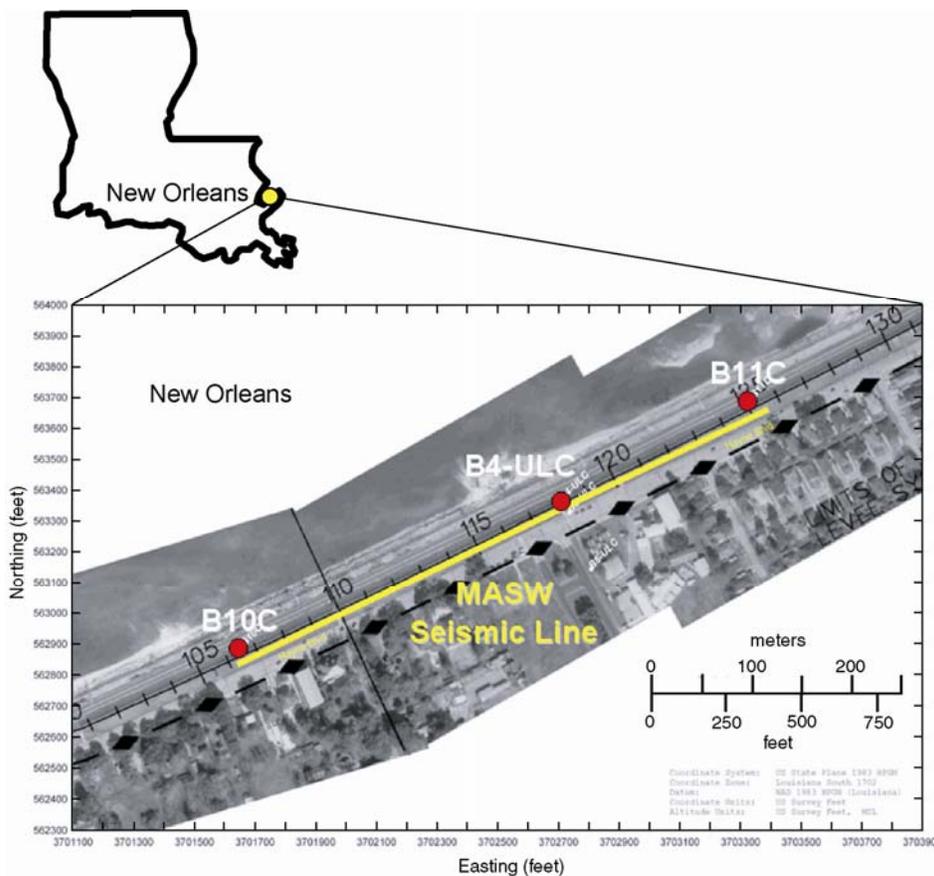
Figure 1: Site of the MASW survey line, Citrus Lakefront Levee, New Orleans, Louisiana. B10C, B4-ULC, and B11C are the locations of borings along the survey line.

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MASW Surface Wave Method

Surface waves typically are viewed as problematic noise in seismic data traditionally used for imaging shallow hydrogeologic, engineering, and geotechnical features (Steeples and Miller, 1990). MASW data analysis incorporates concepts from the spectral analysis of surface waves (SASW) method developed for civil-engineering applications (Nazarian et al., 1983) with multi-trace reflection methods developed for near-surface seismic (Schepers, 1975) and shot gather analysis for petroleum applications (Glover, 1959). Combination of these approaches into the MASW method permits non-invasive estimation of shear-wave velocity and delineation of horizontal and vertical variations in near-surface material properties (Park et al., 1999; Xia et al., 1999).

Subsurface layer geometry and V_S strongly influence the propagation of seismic surface waves through shallow earth layers (Xia et al., 1999), with V_S increasing as material shear strength (rigidity) increases (Equation 1). Surface-wave propagation is dispersive in layered media—different frequency components propagate at different phase velocities. Because shorter wavelength components of the surface wave sample shallow parts of the geologic section (relative to longer wavelength components, which sample deeper parts of the earth), the dispersive nature of surface-wave propagation can be used to infer material properties and structure of the subsurface.

An important advantage of the MASW method over body-wave seismic methods (such as refraction and reflection) is that the amplitude of surface-wave energy is normally several orders of magnitude greater than body-wave energy. Thus, pressure contact geophones (Miller et al., 1999) can be used to measure surface-wave energy instead of the planted, spiked geophones generally needed to collect body-wave data. Pressure coupling allows the use of towable "land streamers" for MASW surveys (Figure 2), permitting near-continuous data acquisition, thus greatly increasing the efficiency of data acquisition compared to traditional body-wave seismic methods.

Figure 2: (a) Accelerated weight-drop seismic source and land streamer used for the MASW survey, Citrus Lakefront Levee, New Orleans, Louisiana. (b) Close-up of 4.5-hertz vertical displacement geophone housed within the land streamer.

Data Collection and Processing

MASW seismic data were acquired along an approximately 600-m section of the Citrus Lakefront Levee between borings B10C and B11C, bordering Lake Pontchartrain, New Orleans, Louisiana (Figure 1). Along this test section, the levee is about 20-m wide at the levee toe and about 5-m high at the crest.

The MASW data were acquired at a rate of about 100 m/hr using a 24-channel Geometrics[1] seismograph and a towed seismic land streamer housing 24 4.5-Hz vertical-displacement pressure-coupled geophones spaced every 1.25 m. The seismic source was a 90-kg trailer-mounted accelerated weight drop (AWD) source. One advantage of the MASW method relative to body-wave methods (such as refraction and reflection) at this site is its relative insensitivity to various sources of seismic noise (e.g., wind, pedestrian, or vehicular traffic), which limits or precludes the use of body-wave methods in noisy areas.

Surface-wave seismic data from the Citrus Lakefront Levee were processed and inverted using SurfSeis 2.0, a software package developed by the Kansas Geological Survey. For each shot gather, SurfSeis generates a phase-velocity versus frequency (*V-f*) plot and the user picks the dispersion curve for the fundamental Raleigh wave. The dispersion curves are inverted to obtain a series of layered-earth *Vs* models that are assembled into a *Vs* profile of the survey area (Figure 3).

The Citrus Lakefront Levee MASW data did not, in general, produce "typical" fundamental mode Rayleigh wave dispersion curves. Dispersion curves generated for adjacent shot points were often inconsistent, with *V-f* plots frequently displaying strong higher-order modes and other undesirable wave types (e.g. Lamb or plate waves). Although the MASW method is robust in the presence of seismic noise, the data did include noise caused by vehicular traffic along a busy road parallel to the levee, and it is possible that vehicle noise contributed to data inconsistency between shot points. However, similar observations of strong higher-order modes and other complex wave behavior by other studies using MASW to assess levees suggest levee geometry and construction design could be affecting seismic wave propagation within levee structures (e.g., Ivanov et al., 2005b, 2007). Although beyond the scope of this study, such observations suggest the need for additional work (e.g. full-waveform modeling) to better understand seismic wave propagation in levee structures.

For this study, non-fundamental mode Rayleigh wave energy was reduced by applying a muting filter developed by Ivanov et al. (2005a) to the shot gathers prior to generation of *V-f* plots and inversion of the dispersion curves. The layered-earth *Vs* models from the unfiltered and filtered data (Figures 3 and 4, respectively) generally show the same horizontal and vertical features, although the filtered data produced a *Vs* profile with greater continuity within layers and higher contrasts between regions of high and low *Vs* than the unfiltered data *Vs* profiles.

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[1] Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.
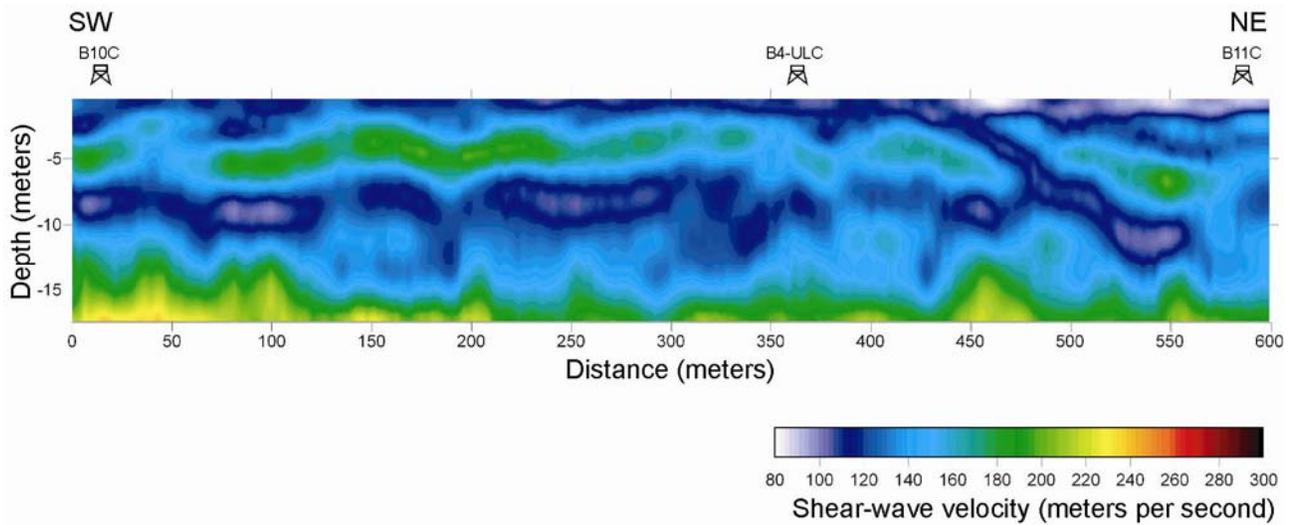
Figure 3: Layered-earth inversion shear-wave velocity profile obtained using unfiltered dispersion curves, Citrus Lakefront Levee, New Orleans, Louisiana. Annotations show the locations of borings along the profile (B10C, B4-ULC, and B11C).
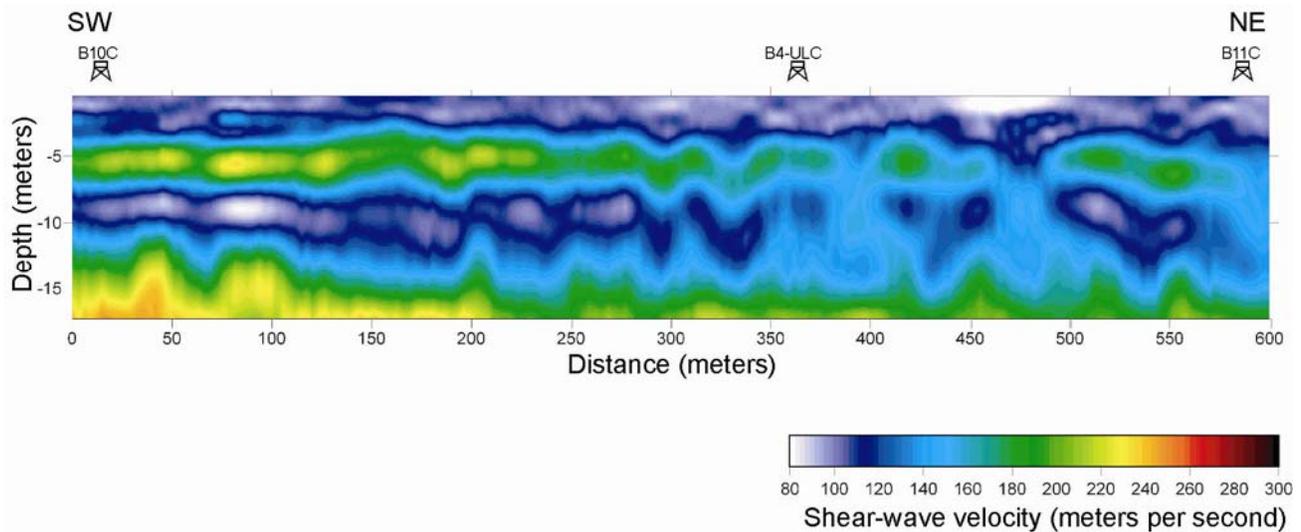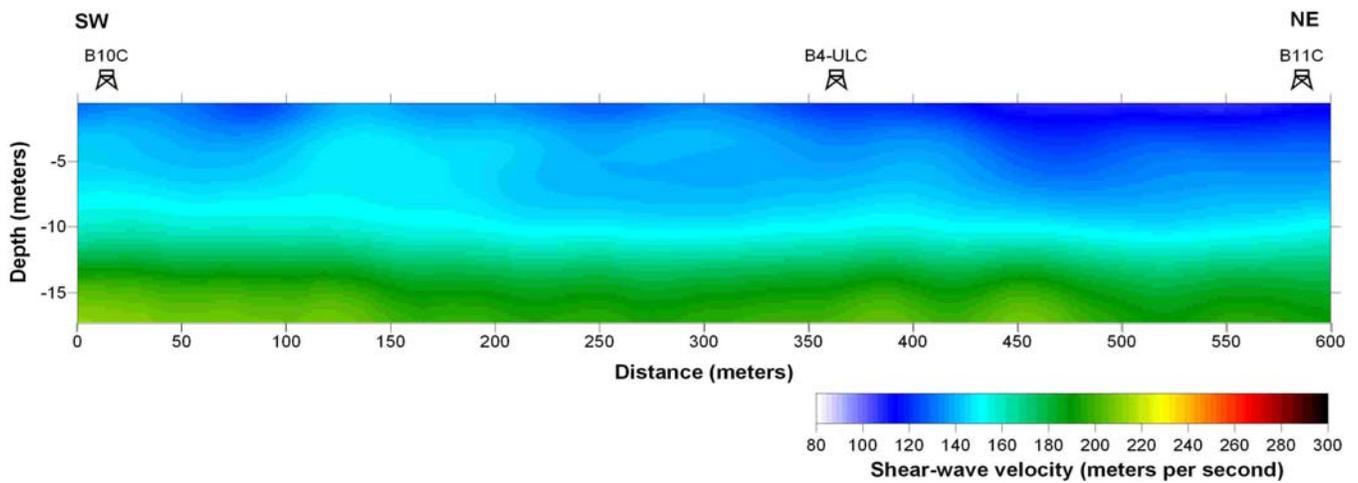

Figure 4: Layered-earth inversion shear-wave velocity profile obtained using filtered dispersion curves, Citrus Lakefront Levee, New Orleans, Louisiana. Annotations show the locations of borings along the profile (B10C, B4-ULC, and B11C).

In addition to layered-earth inversion, a "quick-look" approximate data inversion approach was used (Figure 5). The approximate inversion approach assigns the phase-velocity value from the dispersion curve to a depth equal to between one-half and one third of Rayleigh wave wavelength (Gazetas, 1992) according to:

$$\lambda = \frac{V}{f} \quad , \tag{2}$$

where λ is wavelength. The approximate inversion approach is fast, straight-forward, and generally provides estimates that are consistent with velocity trends (Calderón-Macias and Luke, 2007), although it is recognized that the resulting phase velocity and depth estimates are rough, and regular inversion (Xia et al., 1999) is recommended for layered systems (Gazetas, 1992). Because the approximate inversion approach generates a smoothly varying *Vs* model as a function of depth, it tends to smear discrete anomalies and/or small-scale spatial changes in heterogeneous environments. However, the approximate inversion approach does provide an efficient means to rapidly assess general subsurface conditions and identify lateral shear-strength variations along levee structures, and is the best approach when guided-wave patterns are dominant (K. Hayashi, Oyo Corporation, oral commun., 2007). For this study, the one-half-wavelength depth ratio was selected because this value resulted in an approximate inversion (Figure 5) that best matched those from the regular layered-earth inversion (Figures 3 and 4).

Figure 5: "Smooth" shear-wave velocity profile obtained using the approximate inversion method, Citrus Lakefront Levee, New Orleans, Louisiana. Annotations show the locations of borings along the profile (B10C, B4-ULC, and B11C).

Results

The MASW results were correlated with lithologic and geotechnical information provided by the U.S. Army Corps of Engineers (USACE) from borings B10C, B4-ULC, and B11C (USACE, 1976) (Figure 1). MASW V_S estimates correlate with observed lithologic changes and *Vs* estimates proximal to the borings are consistent with measured shear-strength depth trends (e.g., Figure 6). Vertical and horizontal variations in shear-wave properties beneath the surveyed levee are interpreted as changes in material rigidity both with depth and along the levee crest.

Vertical Shear-Wave Velocity Structure

The two-dimensional layered-earth V_S profiles (Figures 3 and 4) delineate four distinct and spatially persistent layers (Figure 7) within and beneath the Citrus Lakefront Levee. The materials within the levee core (layer 1, 0 to about 4-m below ground surface (bgs)) have V_S of about 80 to 140 m/s. The next layer (layer 2, about 4 to 7 m bgs) has V_S values of 170 to 230 m/s, and is interpreted as the base of the levee. It is consistent with a layer of fat clay observed on the boring logs. Layer 2 overlies a lower velocity layer (layer 3, about 7 to 13 m bgs) that has V_S values of about 80 to 140 m/s. Layer 3 correlates with a sand and silt layer identified in the boring logs. The bottom of the V_S sections is bounded by layer 4 (deeper than about 13 m bgs), a high-velocity layer with shear-wave velocities of 170 to 230 m/s and interpreted as the top of Pleistocene deposits, which consist of silty-sand and "lean" clay.

The "smooth" shear-wave velocity profile estimated from the approximate inversion method (Figure 5) shows a general increase of *Vs* with depth. *Vs* values at the top and bottom of the "smooth" profile are consistent with *Vs* values of layers 1 and 4, respectively, although the range of *Vs* values in the "smooth" profile is less than in the layered-earth models. The distinct high-velocity layer 2 and low-velocity layer 3 seen in the layered MASW inversions (Figures 3 and 4) are not resolved in the "smooth" model.

Horizontal Shear-Wave Velocity Structure

Horizontal variations in *Vs* along the surveyed levee section are observed in the MASW inversions (Figures 3 and 4). Relative velocities within the interpreted basal layer of the levee (about 15 m bgs) across the first third of the line (0 to 220 m horizontal distance along the profile), are higher than those observed along the rest of the line. A transition region, from 220 to 350 m, characterized by a decrease in velocity contrast between layers and a general decrease in velocity, is interpreted as a reduction in overall material rigidity. Across the end of the surveyed line (350 to 600 m), discrete, low-velocity discontinuities and irregularities in the shape and spatial continuity of layers 1-3 are observed (Figure 7). Shear-wave velocities in layer 1 at around 460 m along the line are the lowest (80 m/s) along the tested section, and could indicate a discrete zone of weakness within the levee body. Below the areas of low-velocity in layers 1 and 2 are areas of *increased* velocity (about 140 m/s) in layer 3. We postulate that observed variations in shear-wave velocities could be the result of one or more factors including construction or geologic heterogeneity, differential settlement or movement resulting in an anomalous stress regime (compression inside and extension outside the subsidence zone), and/or a redistribution of fines within discrete sections of the levee. Whatever the cause, the anomalous zones could be targets of future geotechnical evaluations.

The *Vs* profile produced by the "smooth" approximate inversion method (Figure 5) shows less horizontal variation than seen in the layered inversion (Figure 7). However, the "smooth" profile does show high velocities in the Pleistocene layer on the southwest end of the line (left side) and particularly low velocities in the upper 7-8 m of the levee on the northeast (right) end of the line, which are consistent with trends in the layered-earth MASW *Vs* profiles.
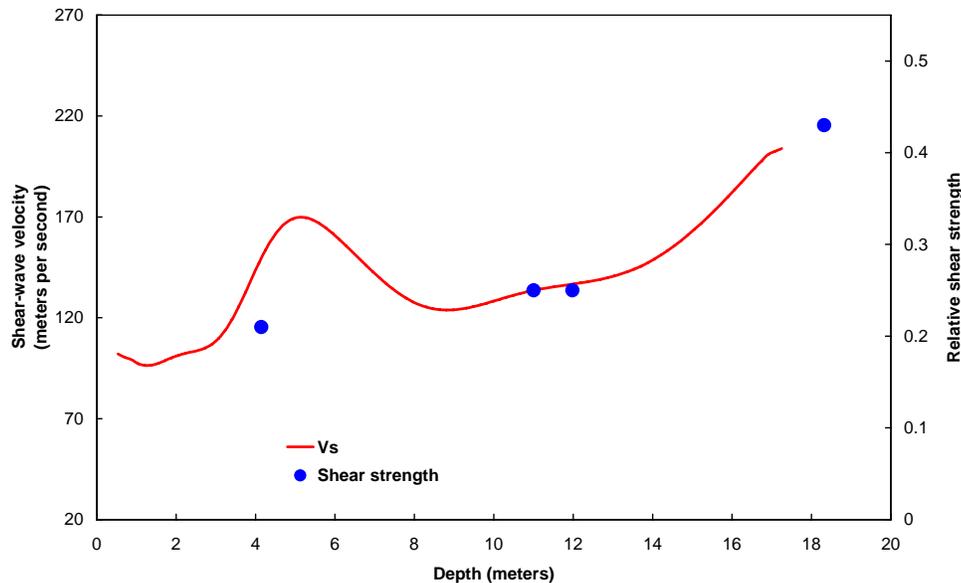
Figure 6: One-dimensional MASW shear-wave velocity model adjacent to boring B4-ULC, compared to boring shear-strength measurements, Citrus Lakefront Levee, New Orleans, Louisiana.
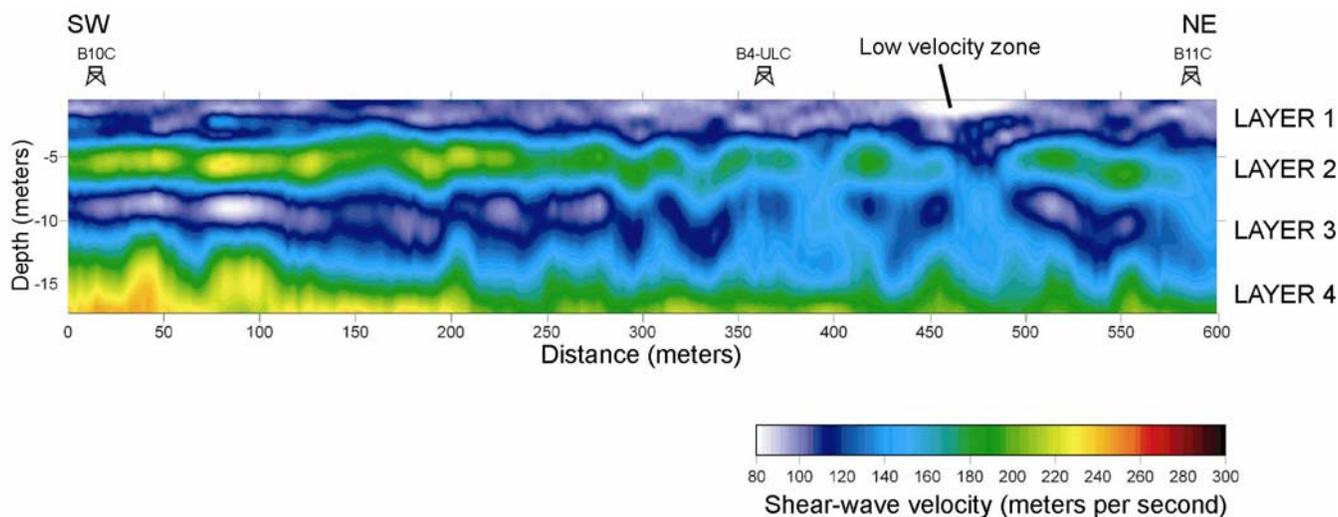
Figure 7: Interpreted layered-earth inversion shear-wave velocity profile obtained using filtered dispersion curves (Figure 4), Citrus Lakefront Levee, New Orleans, Louisiana. Annotations show the locations of borings along the profile (B10C, B4-ULC, and B11C).

Conclusions

For this study, we evaluated the effectiveness of the MASW seismic method to estimate the characteristics and variability of a section of earthen levee and underlying native materials along the Citrus Lakefront Levee on the shores of Lake Pontchartrain, New Orleans, Louisiana.

The MASW data were acquired in a seismically noisy environment using a weight-drop source and a towed, seismic land streamer. The details of the data processing depended upon the complexity of the observed surface-wave propagation patterns. Much of the data required use of higher-order mode filtering techniques to allow robust estimation and interpretation of the dispersion curves.

The layered-earth inversion *Vs* profiles delineate four distinct horizontal layers beneath the surface that correlate with lithologic changes (levee core, fat clay levee base, layer of silty sand, and contact with Pleistocene deposits) in the boring logs. Based on the *Vs* cross sections, *Vs* and material rigidity are interpreted to generally decrease between borings B10C and B11C, with several discrete anomalously low *Vs* zones that could be indicative of natural geologic heterogeneity or dynamic processes (e.g., settling) affecting the levee structure.

The results of this study demonstrate that the MASW method should be regarded as a tool with significant potential for non-invasive characterization of the vertical and horizontal variations in levee shear strength. Strong higher-order modes and other complex non-Rayleigh-type waves evident in data from this study and several others where seismic methods have been used to assess levees suggest levee geometry and/or structure could uniquely affect seismic wave propagation. Additional work (e.g., full wave-form modeling), is needed to assess the full effect of levee geometries and structures on surface-wave propagation.

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