New Orleans Levee Strength Evaluations Using The MASW Method

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Final Report to

John Lane
Chief, Office of Ground Water, Branch of Geophysics
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11 Sherman Place, U-5015
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ABSTRACT

The objective of this work was to evaluate the applicability and feasibility of a set of seismic techniques to interrogate and map anomalous zones within and below New Orleans levees and evaluate their strength as it relates to failure potential.

Mapping the shear-wave velocity was a priority over estimating other physical properties because of its direct relationship to levee strength appraisals. Multichannel analysis of the surface-wave (MASW) method was the preferred geophysical method to make this measurement because of its reliability and efficiency.

The results obtained from applying the MASW method to estimate shear-wave velocity were successfully used to pinpoint two anomalous zones interpreted to have failure potential. MASW data were acquired in rapid and economical manner and processed to varying degree of accuracy depending on the complexity of surface-wave propagation patterns.

The MASW method has proven to be a potentially very efficient and effective tool for evaluating the strength of earthen structures. However, non-uniform site-specific surface-wave features can require significant processing and are the primary source of errors in absolute shear-wave velocity estimates.

INTRODUCTION

Communities have been building levees for centuries as a means of controlling rivers and high-water events. A key element for building a reliable levee is the construction of an impervious levee core. In practice, such a goal is usually not achieved due to the low quality of the locally mined core material. As a result, fines present in the clay/sand matrix of the levee can be washed out by water fluctuations, especially during high pool or floods, which can cause the levee to weaken enhancing the chances for failure. Traditional assessment of levees using borings is expensive and generally spatially sparse without sufficient information to pinpoint areas of failure potential.

Geophysical methods are non-invasive techniques designed to evaluate the near-surface geology by mapping technique specific physical properties of the subsurface. The estimation of the shear-wave velocities (V_s), which has been directly related to material strength, is of particular interest for any study of levees.

Advances in the use of surface-wave analysis to estimate shear-wave velocities have come with the development of the multi-channel analysis of surface waves (MASW) method (Park et al., 1999a; Xia et al., 1999a). The practical application of MASW has provided reliable correlations to drill data (Xia et al., 2000). Differences between MASW results and direct borehole measurements are generally around 15% or less (Xia et al., 2002a). Bedrock has been mapped at 1.5 to 7 m below land surface using MASW, with less than a 0.3 m mismatch with boring data (Miller et al., 1999a). Sinkholes and related subsidence features, identified in a residential area in western Florida, were obscured by suburban development and undetectable using other geophysical methods because of electrical and mechanical noise, reinforced concrete, and requirements for non-invasive testing (Miller et al., 1999c). Buried pits and trenches were located at an old refinery site in eastern Illinois through coincident analysis of phase and amplitude distortions on surface-wave data (Miller et al., 2000). Tunnels used for trafficking contraband across the US border were detected by analysis of surface-wave scatter from the tunnel (Ivanov et al., 2003).

The MASW method has also been used to characterize pavements (Park et al., 2001; Ryden et al., 2001), to study Poisson's ratio (Ivanov et al., 2000a), investigate sea-bottom sediment stiffness (Park et al., 2000; Ivanov et al., 2000b), detect dissolution features (Miller et al., 1999b), map fault zones (Ivanov et al., 2006), and measure S-wave velocity as a function of depth (Xia et al., 1999b). Research on the resolution and accuracy of the MASW method has included the effects of higher modes on the inversion of surface waves (Beaty et al., 2002; Xia et al., 2003), determination of near-surface quality factor (Q) by inverting attenuation coefficients of Rayleigh waves (Xia et al., 2002b), field repeatability (Beaty and Schmitt, 2003), and inverse (Rix, and Leipski, 1991) modeling. Because of its high reliability consistency in results in practice, the MASW method has proven more efficient than other methods for shear-wave velocity estimation (e.g., spectral analysis of surface waves [SASW], shear-wave refraction/tomography, etc.).

Recent field tests of improved seismic acquisition approaches have shown that receiver coupling suitable for accurate and repeatable recording of surface waves can be obtained by pressure contact to the earth surface, unlike body-wave surveying, in which coupling is optimized by invasive "planting" (Miller et al., 1999a). Marine streamer technology adapted to land provides rapid acquisition of 2D profiles on a wide range of

surfaces using pressure-coupled sources and receivers, ultimately requiring less labor than traditional body-wave reflection methods.

Surface-wave propagation (through the shallow layers of the earth) is influenced primarily by the V_s and layer geometry (Xia et al., 1999). Shorter wavelength components of the surface-wave sample the shallow parts of the geologic section and longer wave-length components sample the deeper parts of the earth. The greater the wavelength the greater the influence of the deeper volumes of the earth on surface-wave properties. As a result surface-wave propagation is dispersive, meaning different frequencies (i.e., wavelengths) propagate with different velocity. Because surface waves are dispersive, the dispersion curve, which relates frequency and phase velocity, can be inverted to estimate V_s as a function of depth. The MASW method uses the fundamental-mode dispersion curve estimations (Park et al., 1999) of surface-waves for each shot record, inverting (Xia et al., 1999) each dispersion curve to produce a 1D V_s vertical profile. Applying such a sequence repeatedly along a seismic line (much like 2D seismic reflection acquisition) allows display of the 1D profiles as a pseudo 2D V_s cross section beneath the transect. Subsurface shear-wave velocity anomalies are interpreted in the 2D contoured V_s field as changes in earth materials and/or geologic structure.

Survey Objectives

The survey objectives were to evaluate ability of the MASW seismic method to non-invasively interrogate the internal structure and fitness of levees and the near-surface geology immediately beneath the levees. Comparison of the MASW method with other geophysical methods was of particular interest to evaluate its relative capability to map materials within the upper 1-30 m and at the same time assess material strength, as a function of shear-wave velocity (V_s). This study included a calibration phase to allow identification of the levee "signature" and an exploration phase to evaluate the subsurface expression of the levee body and search out structural deficiencies with failure potential within and beneath the levees at two sites in New Orleans, Louisiana.

Levee strength and fitness is dependent on size, shape, and material composition of levee core, body, and underlying foundation. All these parameters vary for the levees

surrounding the city of New Orleans, making their relative strength and failure potential unknown.

Seismic investigations using the MASW method were conducted at two levee sites within the city of New Orleans. One was at the southwest part of the city along the Mississippi River and the other was at the northeast part of the city next to Lake Pontchartrain.

The efficiency of processing of data for the MASW method varied at the two sites with the surface wave exhibiting three different wave patterns. At the first half of the Mississippi levee site the MASW method was performed with ease and efficiency, acquiring confident shear-wave estimates. At the second half of the site the surface-wave energy was contaminated with higher modes and required significant analysis and processing effort to obtain confident V_s results. At the second site the MASW method did not provide the expected dispersion-curve patterns. Significant processing effort was expanded to optimize and evaluate the fundamental mode of the Rayleigh-wave under the apparently unusual setting. Dispersion curves were evaluated and inverted to produce a 2D V_s model. Presently it is unclear as to the affect of these higher modes on the accuracy of the resulting V_s and related strength estimates of the levee. However, even assuming a reasonable error, changes of dispersion curve trend along the line did not adversely alter the 2D V_s image to the point it is not useful for identifying weak spots and zones with failure potential within levees.

DATA COLLECTION AND PROCESSING

Seismic data were collected at two different levee sites using a 24-channel seismograph and a 24-channel towed seismic land-streamer housing 4.5-Hz pressure-coupled geophones spaced every 1.25 m (4.1 ft). The seismic source was a 90 kg trailer-mounted accelerated weight drop (AWD) source provided by Argonne National Laboratory. Approximately 300 m (985 ft) of seismic data were collected along the crest of a section of levee adjacent to the Mississippi River and south of the (USACE) facility. Another approximately 590 m (1940 ft) of seismic data were collected along the crest of a section of levee bordering Lake Pontchartrain along Crowder Avenue between borings B10C and B11C (Figure 1). Seismic noise from vehicular traffic near the two sections of levee had very little effect on the quality of the seismic data because the MASW method is relatively insensitive to most types of ambient noise.



Figure 1. Study areas and field site, New Orleans, Louisiana.

Mississippi Levee

MASW seismic data possessed two different dispersion-curve patterns at opposite ends of the Mississippi levee line. At the beginning of the line Surface-wave seismic energy (Figure 2a) had a strong fundamental-mode (Figure 2b) that could be efficiently estimated and inverted to V_s. Throughout the second half of the line (Locations 150 – 245 m) surface-wave seismic energy (Figure 3a) possessed a complicated pattern in the phase-velocity frequency domain (Figure 3b), which was later interpreted as fundamental and higher mode interfering with each other. Estimation of a wide frequency range for the fundamental mode of the surface-wave is essential for the MASW method. The fundamental mode for this part of the seismic data could be confidently estimated for a very narrow frequency range between about 4 to 10-12 Hz (Figure 3b). Estimation of fundamental mode at higher frequencies could easily have been misinterpreted due to numerical artifacts resulting from

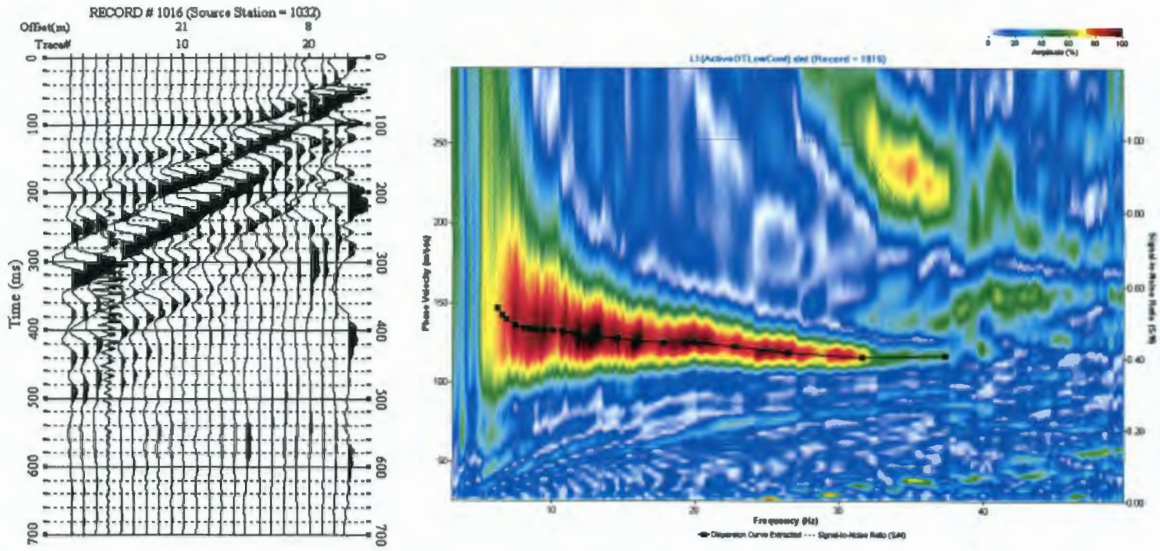


Figure 2. A seismic shot gather (a) and its corresponding phase-velocity – frequency image (b) from the first half of the Mississippi levee.

the higher-mode interference. The MASW method was applied across this narrow frequency range to acquire a brute 2D V_s estimate for the Mississippi levee line (Figure 4a). Such narrow dispersion curve frequency bands cannot provide enough data to confidently invert for the shear-wave properties of the levee. Higher frequency fundamental-mode dispersion-curve data were needed for that purpose. To overcome such harmful higher-mode energy interference, multichannel processing technique that mutes the interfering seismic waves in the shot records (offset-time [x-t] domain) can be used (Ivanov et. al., 2005). The mute filtering technique was preferred to another technique. This technique effectively filters dispersive events (i.e. higher modes) in the phase-velocity – frequency domain (Park et al., 2002). The later method requires that the dispersive event to be filtered (e.g., first higher mode) is clearly visible and consistent within and throughout the data set, which unfortunately was not the case for the levee data.

The mute filtering technique is based on the established difference in the overall propagation velocity of different surface-wave modes. The higher the mode, the greater the overall velocity and the earlier the energy arrives within the shot record. As a result, different apparent velocity trends (consistent with the overall velocity of the different modes) can be recognized on the shot gather and separated (most often partially) via muting. The muting method is applied in two stages. Initially, the fundamental mode is interpreted within the

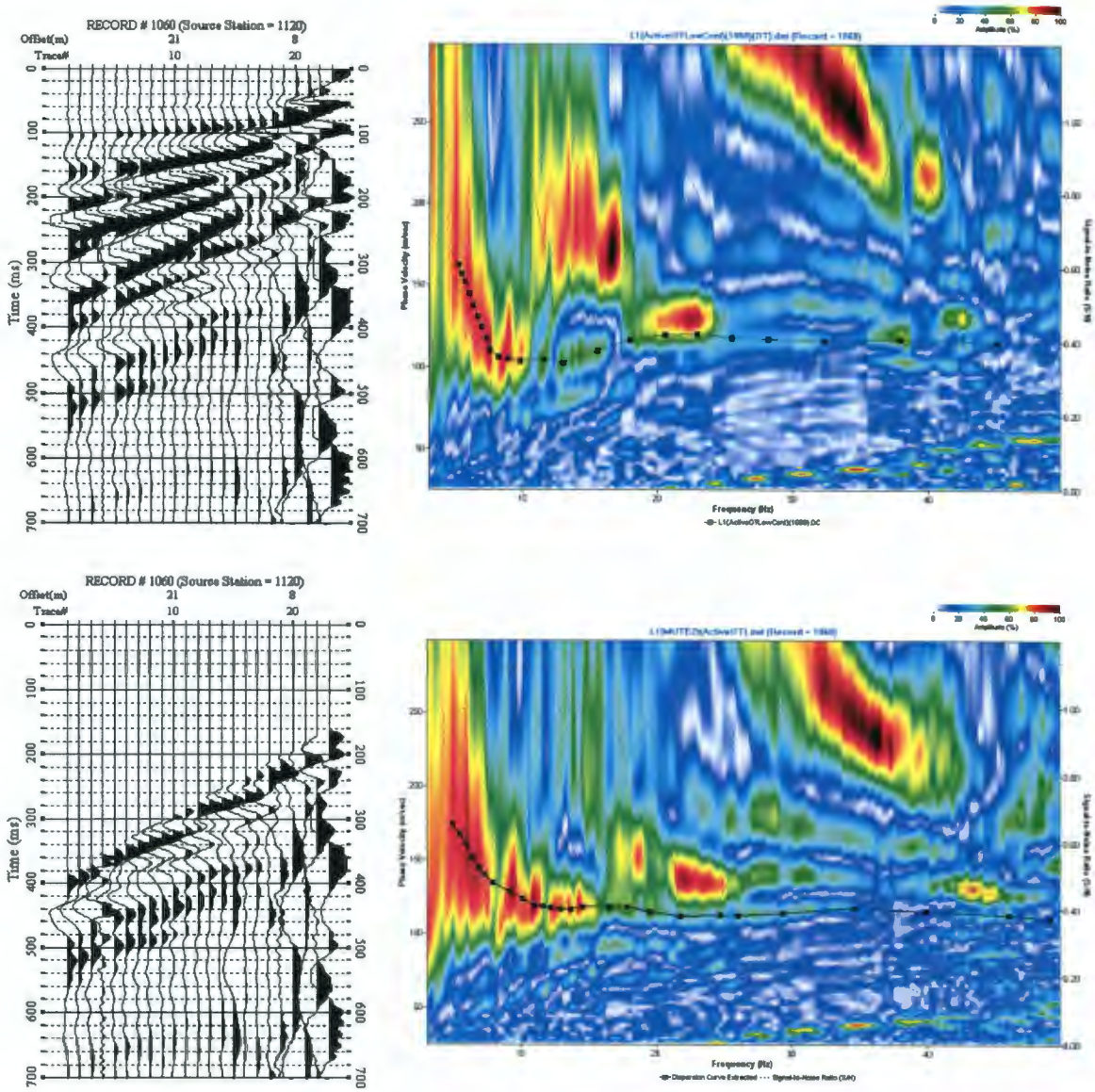


Figure 3. A seismic shot gather (a) and its corresponding phase-velocity – frequency image (b) from the second half of the Mississippi levee. The same seismic shot gather after muting (c) and its corresponding phase-velocity – frequency image (d).

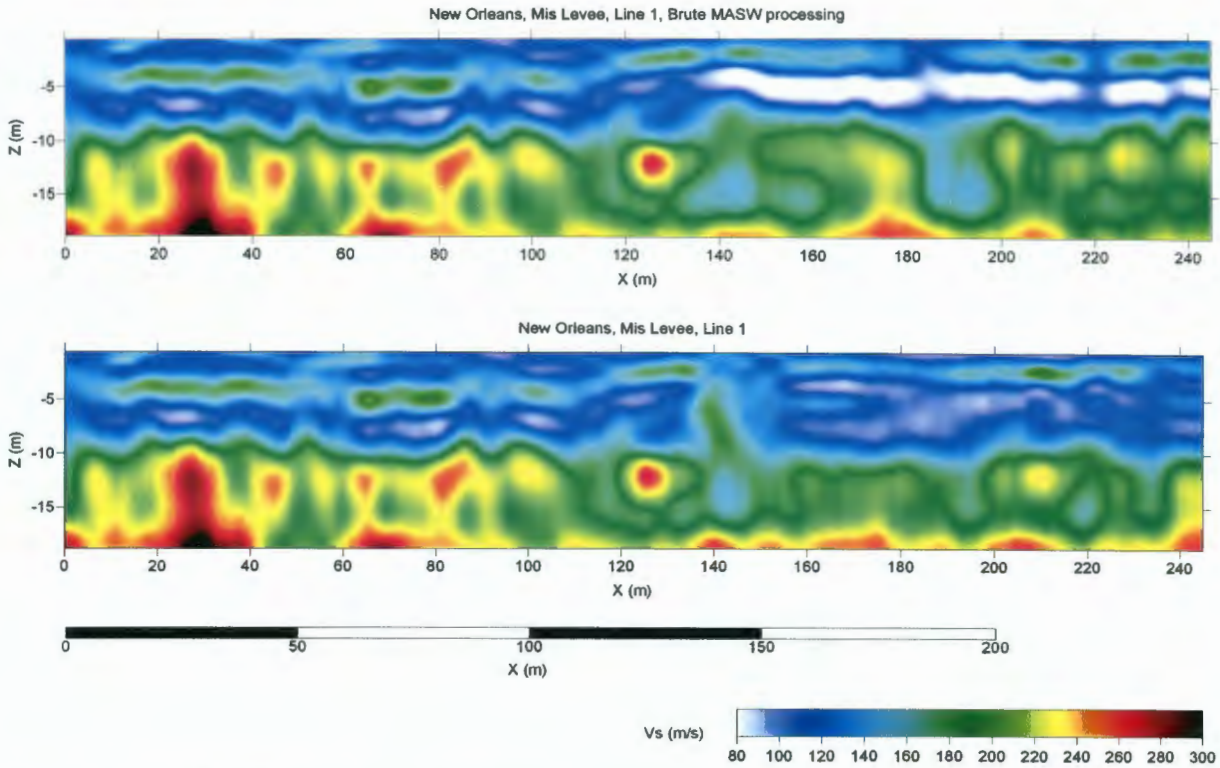


Figure 4. A MASW shear-wave-velocity (V_s) section from the Mississippi levee site, New Orleans, Louisiana.

available low frequency range. Then the shot records are muted to remove the observed higher-mode energy on the shot gathers. A new dispersion curve is estimated, now within a higher and wider frequency range that extends the initially observed dispersion curve trend. The two dispersion curves estimated during the two stages are then combined into one curve, ensuring that there is overlap continuity in frequency range.

Optimal muting parameters were evaluated to separate different apparent-velocity surface-wave trends from Mississippi-levee shot gather energy (Figure 3c). The resulting phase-velocity frequency domain images of the muted shot gathers had clearer surface-wave energy trends, allowing estimation of the fundamental mode of the Rayleigh wave was estimated (Figure 3d). A 2D V_s model was acquired (Figure 4b) after inverting all dispersion curves from line 1.

Lake Pontchartrain Levee

Seismic data from Lake Pontchartrain levee (Figure 5a) did not posses the "normal" (phase velocities decreasing with increase of frequencies) fundamental mode Rayleigh wave dispersive patterns when viewed in the phase-velocity frequency domain (Figure 5b). Various muting approaches were tested to evaluate their effectiveness. Muting non-fundamental mode Rayleigh waves on shot gathers (Figure 5c) resulted in reasonable dispersion curve trends only for only a very few of the phase-velocity frequency plots (Figure 5d). On most of the shot gathers (Figure 6a) the mute filtering (Figure 6c) enhanced multiple-higher modes in the phase-velocity frequency domain (Figure 6d). Those higher-mode patterns resembled plate wave (e.g., Lamb waves) dispersion curve trends. Further complicating interpretation, the dispersion curve patterns were often inconsistent from one shot to another. The MASW method was applied to estimate a brute 2D V_s estimate for the Lake Pontchartrain levee line from the available dispersion curve trends (Figure 7a). Because of the possibility for these dispersion curve trends to be representative of several interfering surface-wave modes, the estimated dispersion curves were inverted using an approximate "rule of thumb" approach (Figure 7b). For example, a phase-velocity value from the dispersion curve is assigned to a depth, equal half of its wavelength (phase-velocity vs. frequency). Although inaccurate the purpose of the approximate inversion approach was to evaluate its potential for detecting lateral shear-strength variations along the levee in a most prompt and economical fashion.

To obtain as accurate as possible 2D V_s image of the levee, various muting parameters were tested to help estimate and isolate fundamental mode dispersion-curve patterns. Best estimates of Rayleigh-wave fundamental-mode dispersion-curve patterns were inverted and a 2D V_s section was developed for the sampled section of the levee (Figure 7b). At the moment these inconsistent and unreliable representations are the best V_s evaluations for this data set and site. It is unclear how and to what extent deviations in the estimated dispersion curve trends from fundamental-mode dispersion-curve patterns (if there are such) affect the final V_s estimates. However, changes in the relative dispersion-curve trend along the levee are real and represent material and compositional variations within the levee.

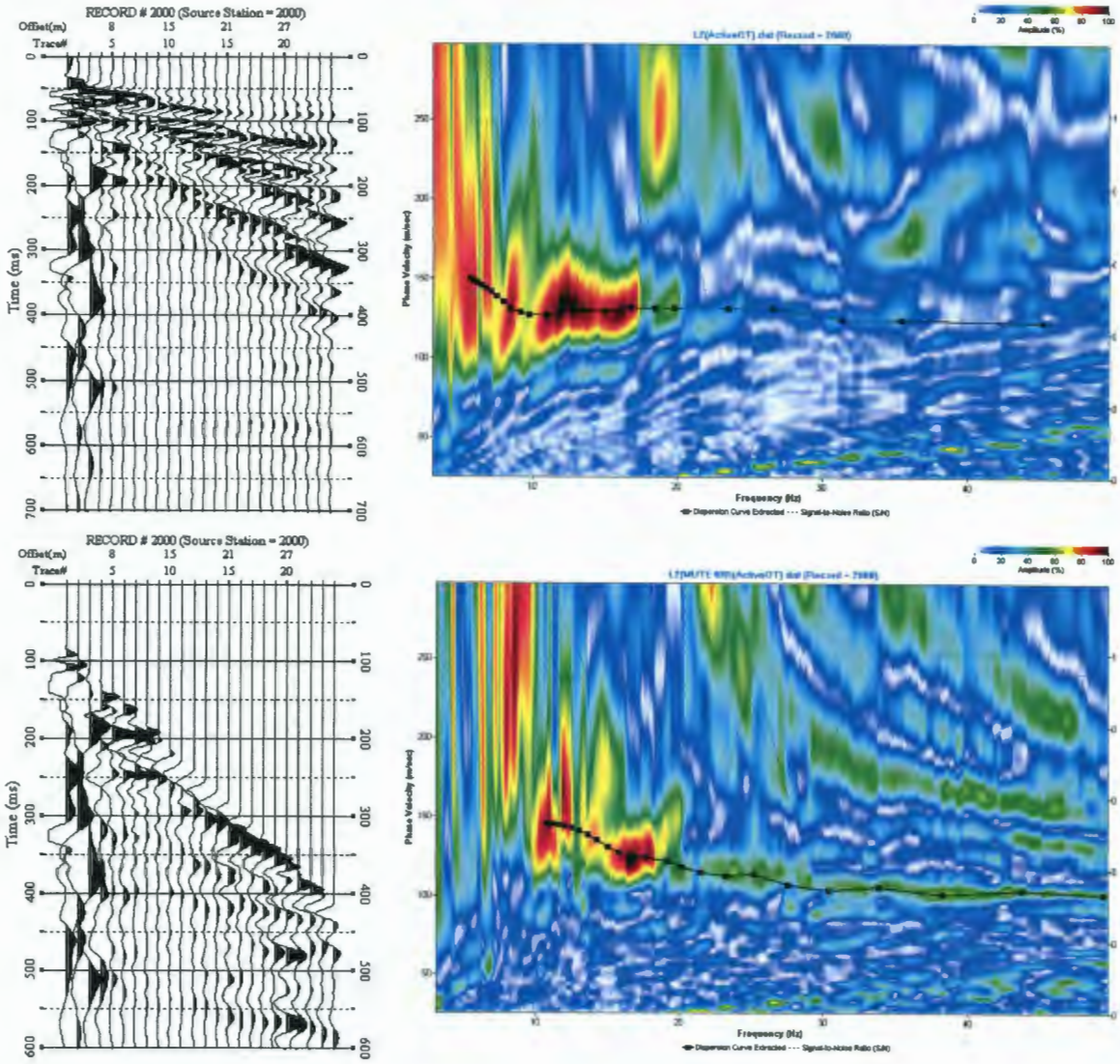


Figure 5. A seismic shot gather (a) and its corresponding phase-velocity – frequency ima
(b) from the lake Pontchartrain levee. The same seismic shot gather after mutin
(c) and its corresponding phase-velocity – frequency image (d).

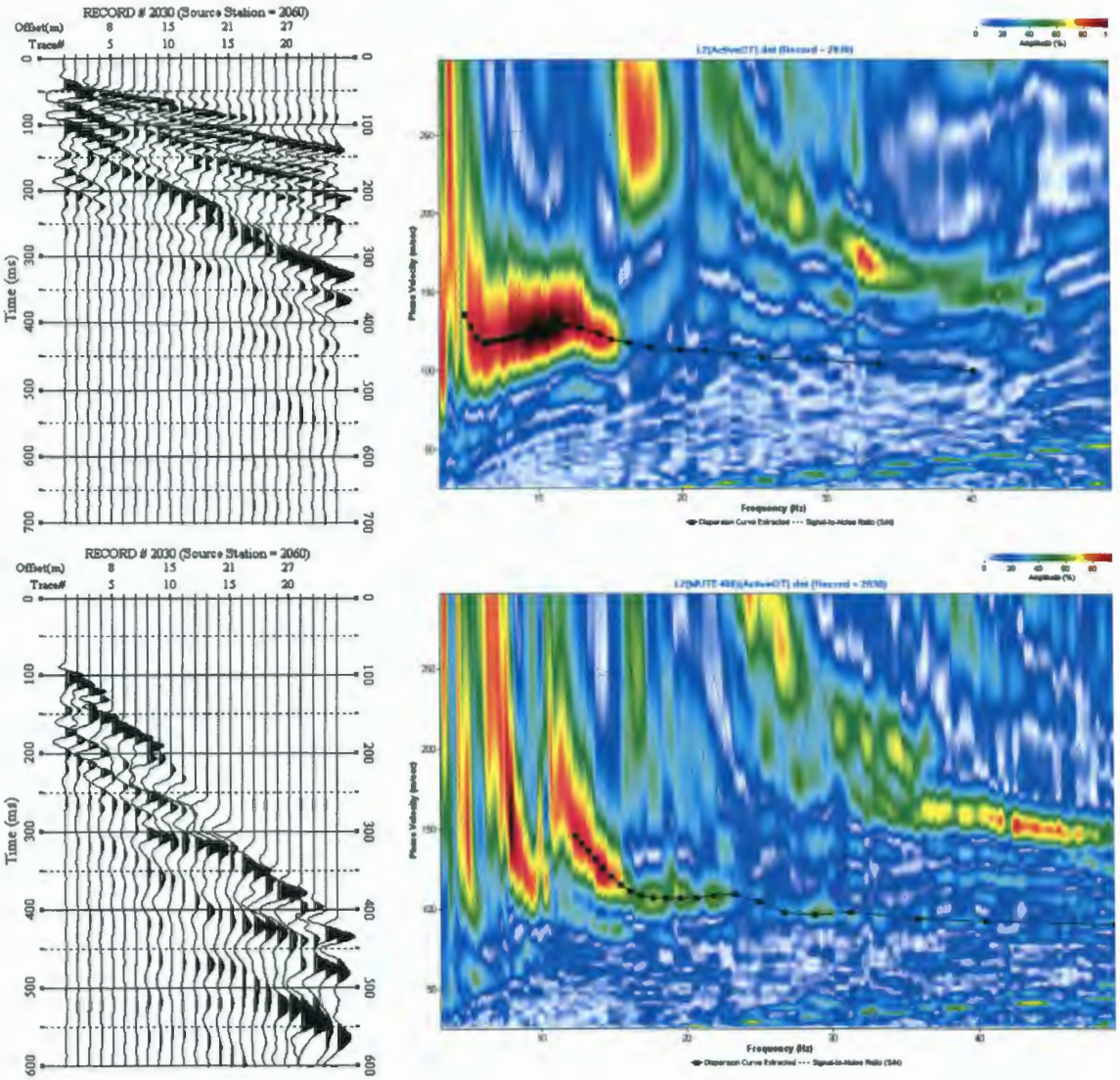


Figure 6. A seismic shot gather (a) and its corresponding phase-velocity – frequency in (b) from the lake Pontchartrain levee. The same seismic shot gather after muti (c) and its corresponding phase-velocity – frequency image (d).

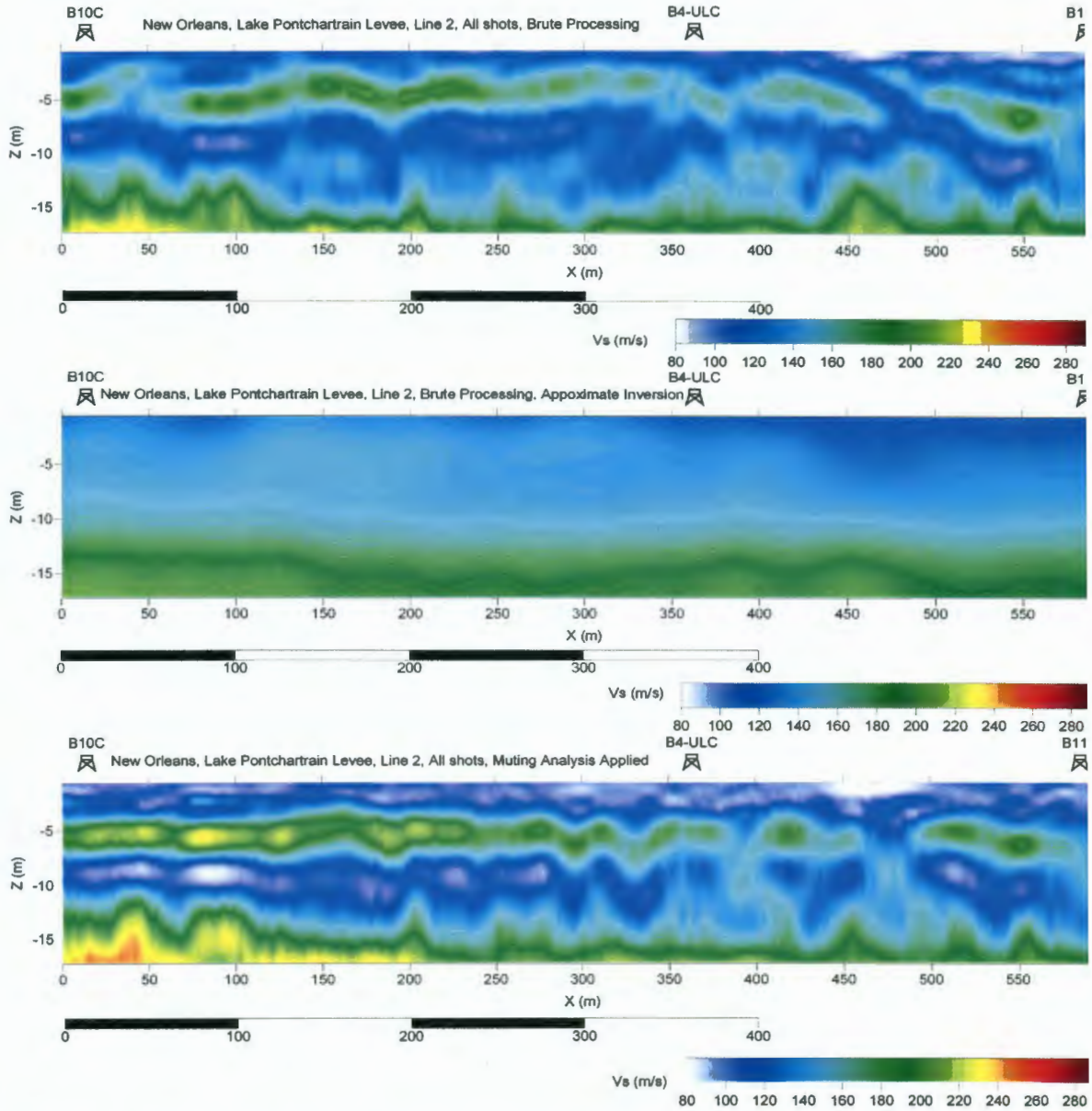


Figure 7. An MASW shear-wave-velocity (Vs) sections at the lake Pontchartrain levee sit New Orleans, Louisiana a) using brute dispersion curve analysis, b) approximat inversion of the brute dispersion curve estimates, c) after filtering possible highe mode energy.

RESULTS

Mississippi Levee

The 2D V_s image from the Mississippi levee (Figure 4b) reveals two patterns indicative of different structural/composition makeup. The first half of the seismic line (Figure 4b, X= 0 to 110 m) suggests a highly rigid levee core (180-200 m/s) at depths from 3 to 5 m with a 3 m low-velocity zone (80-100 m/s) immediately below (5 m to 8 m), which probably represents the uppermost least compacted sediments on which the levee was built. Stiffer "bedrock" sediments (250 m/s) are interpreted below 9 m. The high-velocity levee core (140-180 m/s) at the second half of the seismic line (X=120 to 245 m) is at shallower depths (1 to 3 m) followed by a thicker (about 6 m) low-velocity zone (80-100 m/s) than observed on the first half of the profile. Hints of a little stiffer, higher velocity layer (130 m/s) at 5 m depth beneath locations 155-180 m and 220-245 m are likely representative of the base of the levee along this part of the line. Depth to the stiffer bedrock sediments remains about 9 m beneath the second half of the profile but bedrock velocities appear to decrease to 210-230 m/s. The low-velocity anomaly at 180-200 m between 3 to 10 m depths is interpreted as a candidate weak zone with piping potential during high-water conditions. A high-velocity anomaly (190 m/s) at 140-150 m from 0 to 10 m depth appears to be a physical divide that separates the two parts of the levee. This separation or divide is interpreted to be a depositional feature related to the delta sedimentation but it could also be a fault zone if supported by additional data. Thus, we also speculate that the higher velocities within this zone may be the result of efforts during construction to strengthen the fractured area caused by the faulting. Regardless of the nature this divide, the overall layered earth structure on each side of this zone appears to be different.

Lake Pontchartrain Levee

Seismic line locations were tied to GPS coordinates and the location of borings B10C, B4-ULC, and B11C. Soil and geologic data from 1976 (Figure 8) describe a 1 m thick fat clay layer at the top of the section followed by a at least 5-6 m of sand with no change in geology between the borings. It is speculative and risky to make direct correlations between geologic units and intervals in the V_s section because measured physical properties do not always correlate directly with geologic units.

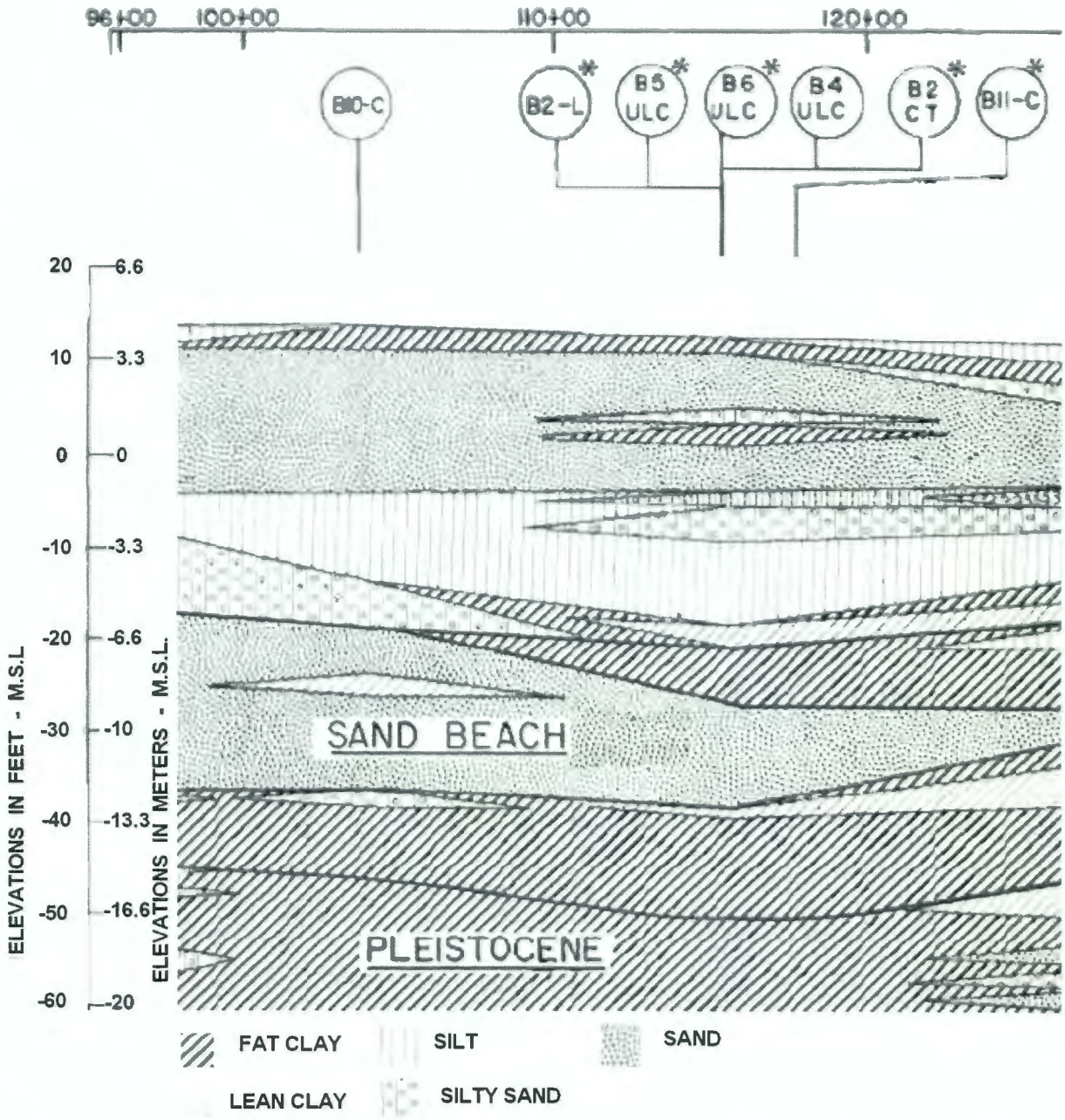


Figure 8. Portion from soil and geologic profile, U.S. Army Engineer District, New Orleans, Corps of Engineers, File No H-2-26533, Plate 55.

The acquired 2D V_s results (Figure 7b) show a 2.5 m thick high-velocity layer (170-230 m/s) at 4.5 to 7 m depth, which is interpreted here to be the base of the levee. Based on the geologic data (1976) and the material stiffness expectations, we speculate this layer is dominated by the fat clay. This layer of fat clay is sandwiched between two low-velocity

layers (80-140 m/s), one within the levee and the other, probably dominated by sand and silt, below. Another high-velocity layer with similar velocity characteristics (170-230 m/s) is likely representative of silty sand and "lean" clay layers can be observed near the bottom of the section. The first part of the line (0-220 m along the line) is characterized by relatively higher velocities at the levee base and bottom layer, which appears to thin from at the beginning of the line. A transition zone follows (220-280 m along the line), in which the high-velocity layers decrease in velocity. Across the next zone, the layer considered to be the base of the levee (4.5 to 7 m depth) possesses shape irregularities (280-380 m along the line), with low-velocity (120 m/s) discontinuities at 380-400 m and 460-490 m. Within the same location range along the line, the low-velocity layer below the base has patches of increased velocity up to 175 m/s (from the original 80-120 m/s range). We speculate these discontinuous locations are representative of missing clay particles that have washed out of the fat clay and reside in the fine sand below. Consequently, the shear-wave velocities decrease in the base layer and increase in the fine sand. The levee velocities above the discontinuities at 440-490 m along the line are the lowest (80 m/s) and suggest weakness within the levee body. Identification of such a zone is one of the primary goals of the survey. This zone should be of interest into further geotechnical evaluations searching for areas with failure potential and corresponding remedies.

The MASW V_s estimates correlate well with geotechnical shear-strength data trends, collected at boring B4-ULC (Figure 9), which was drilled at the toe of the levee about 9 m from the levee crest. This anomalous zone coincides in size and location with a high-velocity and low-resistivity anomaly observed during refraction tomography and electrical resistivity surveys (ANL).

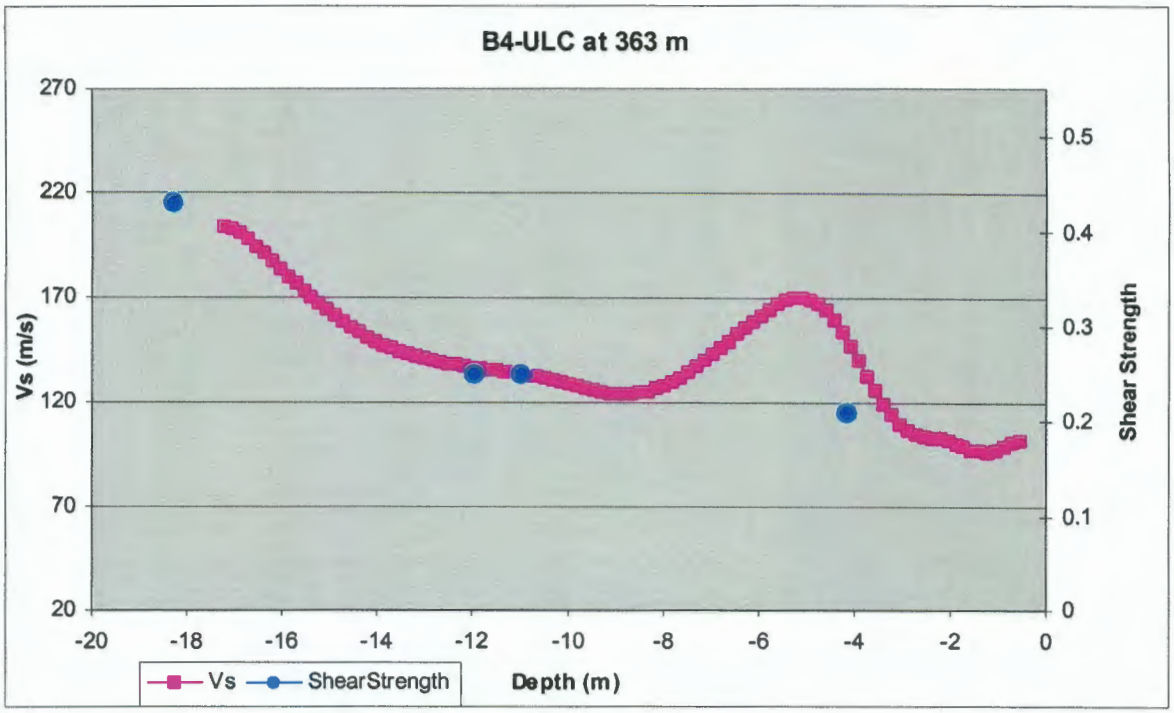


Figure 9. An MASW shear-wave-velocity (Vs) 1-D profile compared with shear-strength measurements at boring B4-ULC at the lake Pontchartrain levee site, New Orleans, Louisiana.

DISCUSSION

MASW data was collected in a fast and economical manner and processed with varying degrees of efficiency and accuracy dependent on the complexity of surface-wave propagation patterns. The MASW method could be a very efficient and effective tool to evaluate levee strength. Site-specific surface-wave features may require significant processing effort and may affect the absolute shear-wave velocity estimates. Success at these sites was based on the application higher mode filtering techniques for the accurate estimation of the fundamental mode of the surface wave.

The brute processing provided misleading results for the second half of the Mississippi River levee line. Its results for the Lake Pontchartrain line, lacking high accuracy, were sufficient to identify the discontinuities within the base layer. The approximate inversion results also mapped laterally these locations as velocity lows at the top part of the section. These results are encouraging for further testing of the brute-and-approximate-inversion approach, which could become a rough but quick and efficient way to pinpoint suspect areas

within levees. The MASW survey achieved its goals of identifying zones with structural deficiencies and failure potential. Further geotechnical investigation is required to study these locations for designing remedies. Although providing varying degree of efficiency and confidence in the final V_s values, the MASW method should be regarded as a tool with significant potential for mapping zones prone to failure and strength assessment of levees.

This study has enlarged the range of applications of the MASW method and has shown the efficiency of using the land streamer approach for broadband surface-wave data acquisition.

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