Application of 2D ambient noise tomography to levee safety assessment in New Orleans

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Abstract

To develop noninvasive methods for levee inspection, we carry out shallow, active, and passive seismic investigations at three sites along levees in the New Orleans, Louisiana, USA, area: Industrial Canal, London Avenue Canal, and 17th Street Canal. These sites sustained damage from Hurricane Katrina in 2005 and have since been rebuilt. Recorded ambient noise data are processed using the common-midpoint spatial autocorrelation method. Dispersion curves obtained with active surface-wave methods and passive wave methods, which use both L-shaped and linear sensor arrays, show internally consistent similarities. Minimum frequencies range from 0.6 to 2 Hz and maximum frequencies range from 10 to 30 Hz. Nonlinear inversion of 2D S-wave velocity models generates velocity-depth cross sections that extend approximately 400–1000 m along levees and provide information to depths of 40–60 m. Resultant S-wave velocity (V_S) profiles are generally consistent with existing drilling logs and the results of laboratory tests. Beneath the London Avenue Canal wall, V_S values (130–170 m/s) likely correspond to saturated, unconsolidated sands, and a low-velocity (50–100 m/s) zone at depth to 15 m beneath the 17th Street Canal matches low-rigidity clays observed in geotechnical logs. Comparison to active surface-wave methods at the Industrial Canal site display similar results but highlight that while active methods have better resolution in the upper few meters, passive methods may be acquired more quickly.

Introduction

Conventional levee assessments use invasive borings that provide useful and detailed information of levees. However, borings are expensive and cannot provide continuous information along a levee in heterogeneous environments. Noninvasive, rapid, and spatially continuous investigation methods are needed to support traditional investigation techniques. Many researchers have tried to apply geophysical methods to levee investigations (e.g., Dunbar et al., 2007). Surface-wave methods (e.g., Ivanov et al., 2006) are often applied to such investigations, and although S-wave velocity (V_S) is not a direct measure of large-strain shear strength, it can correlate with shear strength and, by extension, levee safety (e.g., Imai and Tonouchi, 1982). The use of surface waves for near-surface V_S estimation has undergone significant development and increased use during the past decade.

Spectral analysis of surface waves (SASW) has been used for the determination of 1D V_S profiles to a depth of 100 m (Nazarian et al., 1983). Park et al. (1999a, 1999b) propose a multichannel analysis of surface waves (MASW) method, whereby practitioners transform the multichannel surface-wave waveform data from the time-distance domain into the phase velocity-frequency domain, which they then use to determine phase velocities. MASW is superior to SASW for recognition of dispersion curves and distinguishing the fundamental mode Rayleigh wave from other modes, such as higher modes and body waves. Xia et al. (1999) and Miller et al. (1999) apply MASW to shot gathers along a survey line and delineate pseudo 2D V_S sections. Hayashi and Suzuki (2004) adapt common-depth-point (CDP) analysis as used in 2D seismic reflection surveying to MASW, and utilize common-midpoint crosscorrelation (CMPCC) analysis to increase the lateral resolution of the surface-wave methods in heterogeneous environments.

During the past few decades, researchers have made considerable progress toward the development of passive surface-wave methods using ambient noise or microtremors. The methods are typically called microtremor array measurements (MAM) since 2D arrays are usually used for calculating phase velocity from ambient noise. Aki (1957) investigated ambient noise as surface waves and proposed a theory of spatial autocorrelation (SPAC). Okada (2004) developed a large-scale passive surface-wave method of MAM based on SPAC to estimate deep V_S structures.

Conventional passive surface-wave methods use a small number of sensors and only provide 1D velocity profiles. Hayashi et al. (2014) apply the concept of CMPCC to ambient noise data to propose the common-midpoint spatial autocorrelation method (CMP-SPAC). The method calculates local dispersion curves from ambient noise recorded by many sensors and provides 2D or 3D V_S structures. By comparison to active-source methods, natural low frequencies (< 2 Hz) may permit greater investigation depths and decrease data acquisition times. Another advantage of passive surface-wave methods is that traffic noise in urban areas can be used as signal, whereas in active-source surveys it can degrade data quality. Potentially, for large 2D and 3D investigations, passive methods may also be more effective — both active and passive methods would require more receivers, but active methods would require additional numbers of sources. As well, passive methods use the information obtained from receiver pairs, an amount of data that increases in proportion to the square of receiver numbers.

Authors often use the term “Ambient noise tomography” to refer to the passive surface-wave method analyzed with the CMP-SPAC method. This paper describes the CMP-SPAC method and introduces an application example of the ambient noise tomography along the levee in New Orleans, Louisiana, USA, to delineate 2D V_S structures beneath the levee

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Site of investigation

New Orleans is located in the Mississippi River Delta on the banks of the Mississippi River, approximately 105 miles (169 km) upriver from the Gulf of Mexico. Old districts in New Orleans such as the French Quarter are located on natural levees, the elevation of which is above sea level. The city expanded residential area by draining water from low-lying marshes resulting in the construction of many drainage canals through the city.

In 2005, Hurricane Katrina was responsible for the deaths of more than 1000 people. Most damage from the hurricane was caused by flooding, and a large area of New Orleans was covered by more than 2 m of water. During Hurricane Katrina, the levees along the aforementioned drainage canals collapsed at several places.

We carry out a geophysical investigation at three sites where levees once collapsed and caused serious floods (Figure 1) but are now repaired: Industrial Canal, London Avenue Canal, and 17th Street Canal. Except for the Industrial Canal where the flood wall collapsed as a result of over-topping, scouring, and erosion from the storm surge, the levee at the London Avenue canal and 17th Street Canal failed before water reached the top of the canal wall. Elevated pressures from the storm surge that mobilized a soft sand layer at the London Avenue Canal and weak lacustrine soils that failed in shear at the 17th Street Canal caused overlying levee walls to break (Dunbar and Britsch, 2008; Duncan et al., 2008). Our geophysical investigations serve to delineate the extent of the soft sand and clay layers beneath the levees. The geophysical methods include active and passive surface-wave methods. This paper summarizes data acquisition and analysis of surface-wave data in pseudo-2D continuous mode and 1D investigations.

2D continuous shallow investigation using ambient noise tomography

Measurements follow survey lines that range in length from approximately 450 to 1100 m along the toe of levees at three investigation sites. Twelve Geometrics "Atom" cableless seismic data acquisition units or seismographs with vertical-component, 2 Hz geophones record "ambient city noise" data. Each unit includes a GPS clock so all units can be synchronized over any distance without cables. Data acquisition uses a linear array of geophones spaced 5 m apart. We record ambient city noise over constant intervals of 10 minutes between which we move four geophones from the rear to the front of an advancing line (Figure 2). Data acquisition lasts two to three hours when using one to three people, covering line distances of approximately 450–1100 m. For comparison, at the Industrial Canal site where the passive-source technique was conducted by one person and covered approximately 1100 m, over the same approximately eight-hour work day the active-source acquisition employed two people to collect a line approximately half as long.

We process the ambient noise data via the CMP-SPAC method (Hayashi et al., 2015). (Figure 3). The processing procedure can be summarized into four steps:

Preprocessing. Approximately 10 minutes of ambient noise data for each recording interval are divided into several blocks, each block lasting approximately one minute. Time blocks that include nonstationary noises such as moving vehicles are rejected and removed from further processing.

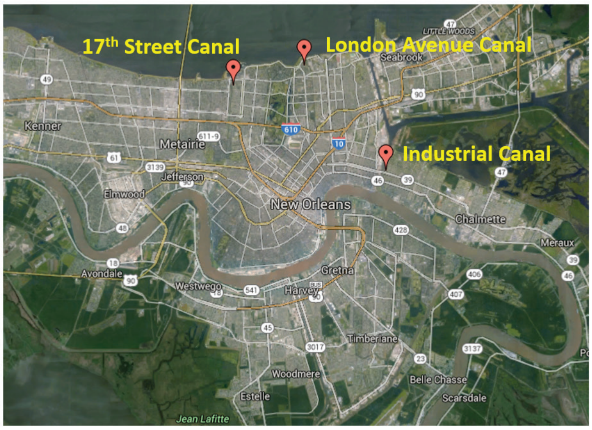

Figure 1. Three sites investigated in the greater New Orleans area are also locations where levees failed in the aftermath of Hurricane Katrina in 2005.

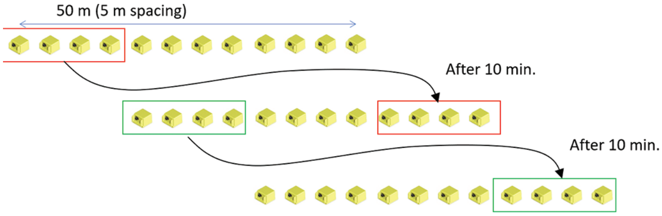

Figure 2. Schematic diagram of passive seismic acquisition for 10-minute intervals of time recording ambient city noise. Between recording intervals, the four rear units advanced to the front of the line of recording boxes (right side in this diagram).

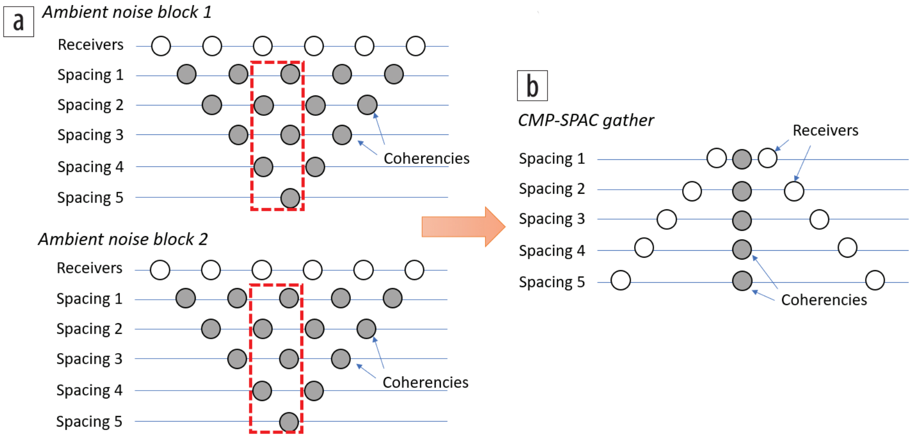

Figure 3. Concept of CMP-SPAC involves calculation of coherencies, CMP sorting, and stacking. (a) For each group of seismic acquisition units over a fixed time block (approximately 1 minute) coherencies are calculated between pairs of geophones and assigned a central common-midpoint location (dashed red box). (b) Coherencies from each time block that share a common midpoint (dashed red box) are then averaged.

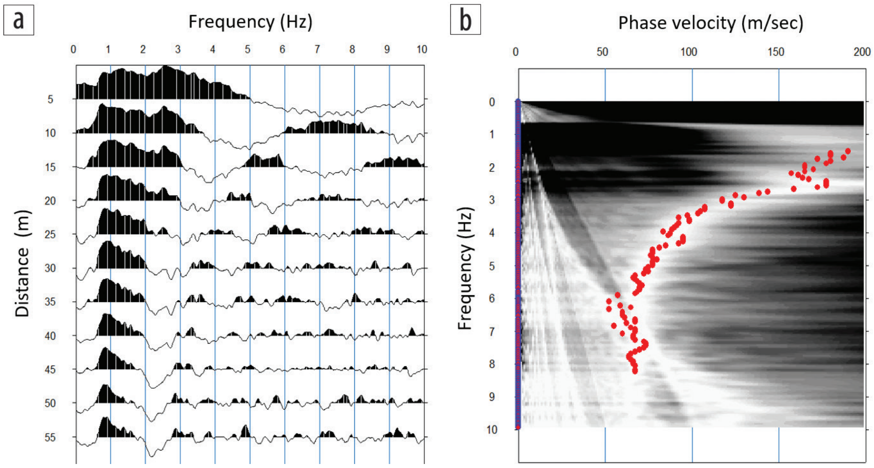

Figure 4. (a) Coherencies and (b) a phase velocity image in frequency domain obtained for the survey data collected at the 17th Street Canal site (Figure 1).

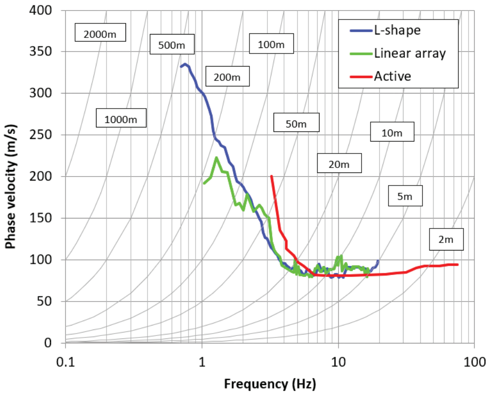

Figure 5. Dispersion curves obtained from two ambient-noise acquisition surveys (one uses a linear and the other an L-shaped geophone array) and a third, active-source, surface-wave survey at the Industrial Canal Site. For reference, concave curves trace reference wavelength (m) values.

Coherency. A fast Fourier transform applied to each time block transforms waveform data from the time domain into the frequency domain. Coherency is first calculated for each block, and then coherencies of all blocks are averaged together (Figure 3). Coherency (*COH*) is calculated according to equation 1:

$$COH(r,\omega)=\frac{CC(r,\omega)}{AC(x,y,\omega)AC(x+\Delta x,y+\Delta y,\omega)}, \tag{1}$$

where, x and y are the coordinates of the location of each recording unit, r is a distance between two geophones, ω is an angular frequency, and CC and AC are a crosscorrelation and autocorrelation of ambient noise recorded by two seismic acquisition units, respectively. In each measurement, the coherencies are calculated for every pair of geophones (Figure 3a). For example, 66 coherencies $(={}_{12}C_2)$ are calculated from an ambient noise time data block recorded by 12 geophones.

Common-midpoint spatial autocorrelation. A common-coherency gather collects calculations made from data collected at geophone pairs that share common midpoint locations. Averaging in the frequency domain can be performed only on coherencies that have the same spacing between their geophones. The differently spaced coherencies are sorted with respect to their spacing in each common midpoint into a named CMP-SPAC gather (Figure 3b).

Phase velocity. If the coherencies are averaged over many files (blocks) or over a long period of time, they can be considered equivalent to their spatial autocorrelation (SPAC) and can be expressed by a Bessel function as shown in equation 2.

$$\int_{\varphi=0}^{\varphi=2\pi} COH(r,\omega)=J_0\left(\frac{\omega}{c(\omega)}r\right), \tag{2}$$

where $c(\omega)$ is phase velocity of "microtremors," and J_0 is the first kind of Bessel function. A phase velocity can be determined at each frequency so that the difference between both sides of equation 2 is minimized. The resulting series of phase velocities defines a dispersion curve. In this study, CMP-SPAC gathers and associated dispersion curves are calculated with 10 m intervals (Figure 4).

Although the SPAC method has been applied previously to 2D spatial arrays of seismic sensors (e.g., Aki, 1957; Okada, 2004; Cho et al., 2013) a linear array can also achieve similar results. A comparison of dispersion curves derived from data collected both using the linear array (CMP-SPAC analysis) as well as the more classical L-shaped array (SPAC method) shows that both methods yield similar dispersion trends (Figure 5). The maximum wavelength obtained from the linear array (SPAC) is approximately 200 m and implies that V_S to a depth of 50 m can be estimated. Furthermore, for frequencies greater than approximatley 10 Hz, the results of the CMP-SPAC methodology are comparable to those derived from active-seismic methods collected using a sledgehammer source.

For the Industrial Canal site, dispersion curves (Figure 6) and final assembled cross sections (Figure 7a) both suggest that near the middle of the survey line (distances approximately 350–650 m) velocity values are relatively high (+ 150 m/s) and occur at relatively shallower depths (> 5 m) than along the rest of transect. This region (Figure 7a) lies immediately south of the section that failed during Hurricane Katrina in 2005 but that has since been repaired. Such lateral velocity changes in the shallow region in the section may be related to the rebuilding of the collapsed levee.

1D deep investigation using large L-shaped arrays

Large L-shaped arrays can be used both to investigate deeper targets and to evaluate the applicability of linear arrays (SPAC) while collecting ambient noise data. Clear coherencies and dispersion curves are also derived (Figures 8a and 8b), and their inversion results produce similar velocity-depth profiles as with the linear arrays. At the Industrial Canal site (Figure 8c), we vary the length of the array (15, 60, and 240 m) while keeping the same acquisition units but varying only the geophone spacing from 5 to 240 m.

From a comparison of dispersion curves from all three canal sites (Figures 9a and 9b) (all derived using L-shaped arrays) we note how each successively wider L-shaped array captures information from greater depths from approximately 150 to 400 m. We especially highlight the relatively low S-wave velocities (70 m/s) at the 17th Street Canal site.

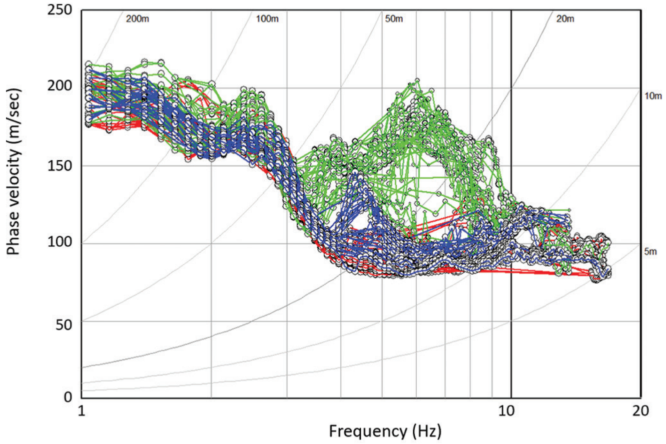

Figure 6. Dispersion curves drawn with colored lines and small, open circles calculated at 10 m-intervals from CMP-SPAC gathers at the Industrial Canal site, New Orleans. Red curves indicate CMP locations at the start of the survey line (N), green curves indicate the middle locations and blue mark the line end (S). Phase velocities are highest (150–200 m/s) in the frequency range between 4 and 10 Hz. For reference, concave curves trace wavelength (m) values.

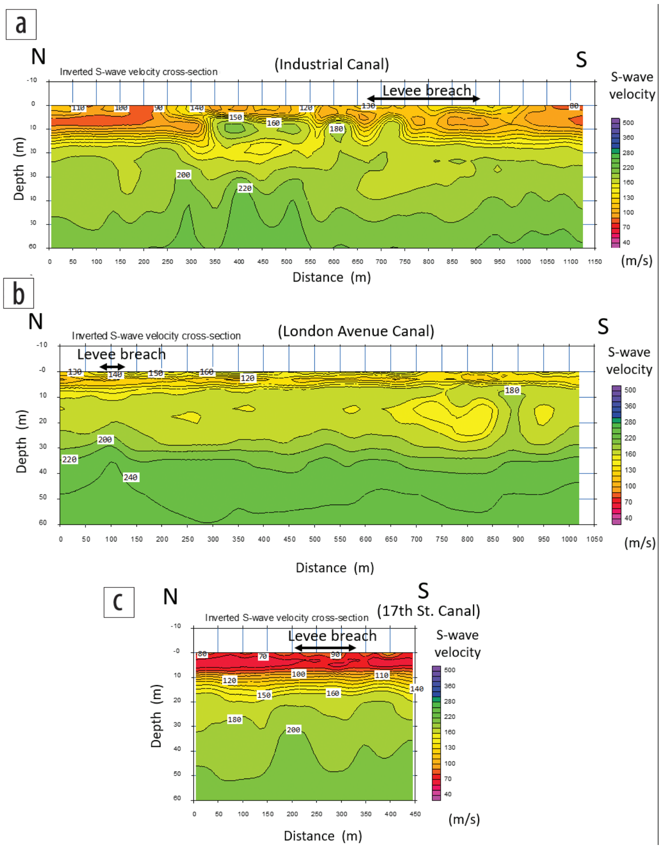

Figure 7. S-wave velocity cross section obtained by ambient noise array measurements along the (a) Industrial Canal, (b) London Avenue Canal, and (c) 17th Street Canal. Approximate extents of the levee breach (Dunbar and Britsch, 2008) are shown in the cross sections.

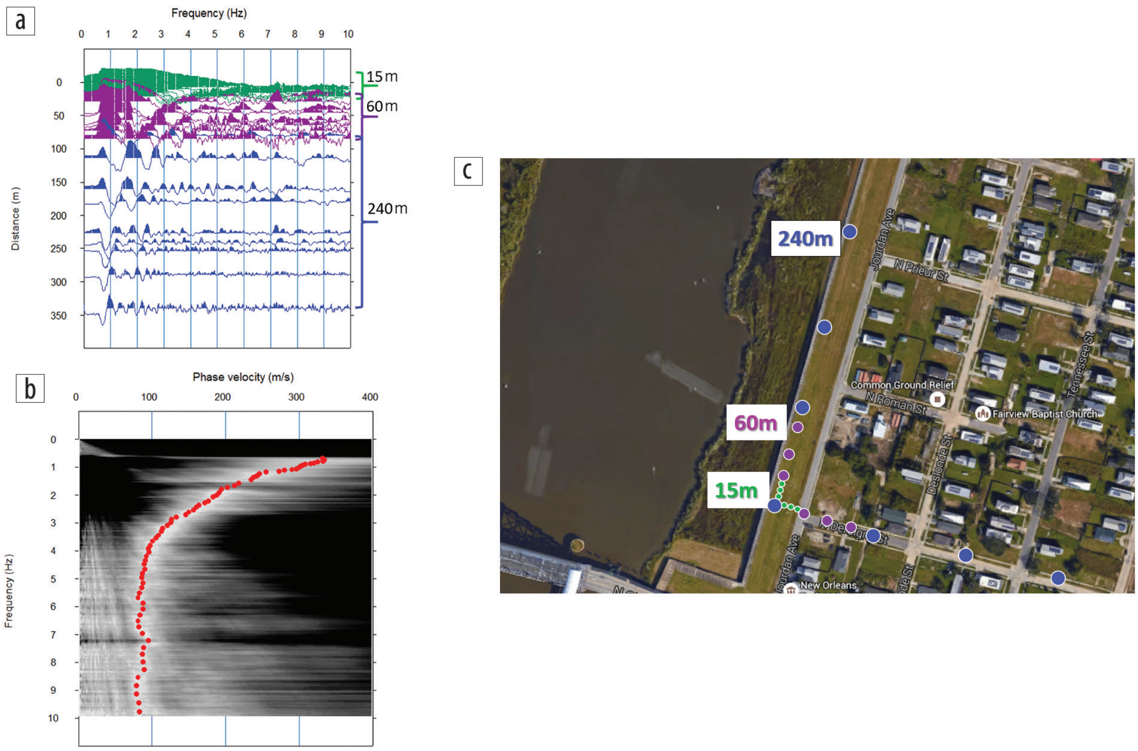

Figure 8. (a) Coherencies and (b) phase velocity image in frequency domain calculated using spatial autocorrelation using ambient noise recorded using the L-shaped arrays of three lengths: (green-1 5m), medium (purple-60 m) and large (blue-240 m) from the Industrial Canal site. (c) c: Three differently sized L-shaped arrays (15-green circles, 60-purple and 240 m-blue circles) at the Industrial Canal site.

Comparison of velocity-depth profiles with existing drilling information: 17th Street and London Avenue Canal sites

As mentioned earlier, piping due to a soft sand layer and shear failure due to weak lacustrine soils caused levee collapse at the London Avenue Canal and the 17th Street Canal, respectively (Dunbar and Britsch, 2008). Unusually low and shallow velocities, possibly indicative of weak soils, can be interpreted from both dispersion curves (Figure 9a) and their corresponding inverted velocity-depth profiles (Figures 7b, 7c and 9b). We highlight the low (70–100 m/s) values seen in dispersion results for the London Avenue and 17th Street Canal sites over small wavelengths of 5–20 m. We use complementary subsurface geotechnical engineering data at the London Avenue Canal and the 17th Street Canal to assign a soil type to the low velocity (Figure 10). V_S values corresponding to a sand layer beneath the London Avenue Canal site (approximately 130 m/s) and the clay layer beneath the 17th Street Canal site (approximately 70 m/s) respectively imply that these layers are very soft and may pose geotechnical concerns in relation to the levee collapse, as highlighted by Dunbar and Britsch (2008).

Conclusions

We show that V_S structures along the levees collapsed by Hurricane Katrina can be derived using ambient noise tomography. The results show that cableless seismic acquisition units and a linear array of geophones can simply and quickly estimate the V_S cross sections to a depth of 50 m. The resultant V_S structures are generally consistent with soil profiles estimated from drilling information. TLE

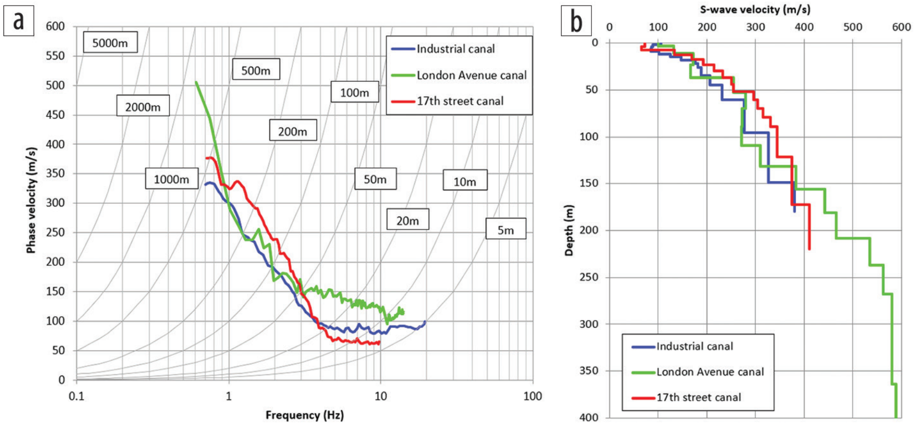

Figure 9. (a) Dispersion curves and deep S-wave velocity profiles at three Canal sites and their (b) inverted velocity-depth curves. Note the particularly low velocity estimates for the 17th Street Canal site (red line), between 4 and 10 Hz. For reference, straight colored lines trace wavelength (m) values.

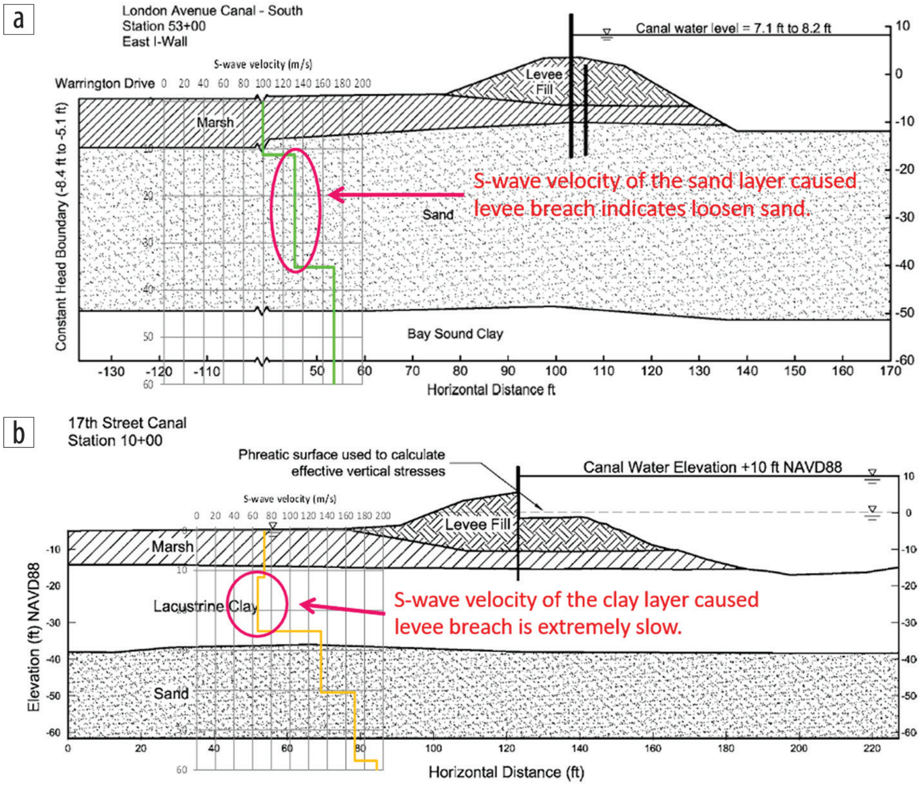

Figure 10. Comparison of soil profiles and inverted S-wave velocity profiles derived from ambient noise tomography at (a) London Avenue Canal and (b) 17th Street Canal. The underlying geotechnical models (Duncan et al., 2008), predate the 2005 failure.

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