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Improvements to the Near Surface Velocity Model of the Sacramento-San Joaquin Delta

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Improvements to the Near Surface Velocity Model of the Sacramento-San Joaquin Delta

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Abstract

Seismic surface wave surveys were performed at twelve sites in the Sacramento-San Joaquin Delta region, providing improved shear wave velocity (V_S) models of the near surface and V_{S30} measurements. A combined active and passive method utilizing MASW (Multichannel Analysis of Surface Waves) and MAM (Microtremor Array Method) provided depth penetration of 20 m to 40 m, depending on site. The method was able to detect velocity reversals and surficial layers as thin as 1 m. Velocity models derived from surface wave surveys were in good agreement with lithologic sequences from soil borehole logs. Measured peat velocities were extremely low, ranging from 42 m/s to 150 m/s. Velocities of a deeper sand unit ranged from 220 m/s to 370 m/s. Measured average V_S from the surface to a depth of 30 m (V_{S30}) ranged from 98 m/s to 257 m/s. Sites were assigned to NEHRP site classes D, E, and F. Assignments to class F were based on the presence of a near-surface peat layer up to 8 m thick. All sites have soft near-surface soils and are liable to experience large ground accelerations in the event of a strong earthquake. At four of the sites, additional surveys were performed using the two-station spatial autocorrelation (SPAC) method to provide depth penetration of approximately 2000 m. Velocity was determined to frequencies as low as 5 Hz, 1 Hz, and 0.3 Hz using MASW, MAM, and 2ST-SPAC, respectively. Tests indicate that near-surface seismic reflection data quality is good and that reflection profiling may be successfully conducted in the area using a relatively modest recording system.

Introduction

The goal of this study was to improve the near-surface shear-wave velocity (V_S) model of the Sacramento-San Joaquin Delta. V_S is directly related to the elastic rigidity of soil and rock, and is used to estimate the strength of ground shaking due to an earthquake. In this study, seismic surface wave methods were used to measure V_S at twelve sites. The primary products for each survey site are a 1D shear-wave velocity model and a V_{S30} measurement. The quality of the velocity models produced in this work was assessed through comparison with geotechnical logs from nearby boreholes.

The Sacramento-San Joaquin Delta consists of a network of river channels that originate in the Sierra Nevada and drain through the Carquinez Strait to San Francisco Bay. Because its outlet is constricted, deposits of peat and mud up to 10 m thick accumulated in the central Delta during the Holocene. These estuarine and floodplain deposits are underlain by eolian sands and Pleistocene alluvial fan deposits (Atwater and Belknap, 1980). The Delta is a major source of water for the State of California, is the site of agriculture, and provides habitat for a variety of species. During the past century, most the tidal wetlands constituting the Delta were converted to farmland by building levees around the perimeter of islands and draining the islands. Many of the islands have a thick peat layer, and have undergone several meters of subsidence during the past century as the peat has dried, oxidized, been carried away by wind, and undergone compaction (Mount and Twiss, 2005). The elevation of the ground surface of the island interiors is typically several meters below the height of the river outside the levees. The risk of flooding due to levee failure would be exacerbated by strong shaking due to an earthquake on a nearby

fault, such as the West Tracy fault or Midland fault (Figure 1). Levees built on sites with soft near-surface soils, especially peat, are liable to experience strong shaking in the event of a large earthquake. Levee vulnerability in the Delta to seismic shaking was evaluated by URS (2009), who classified the majority of the levees in the central Delta as high risk (Figure 2).

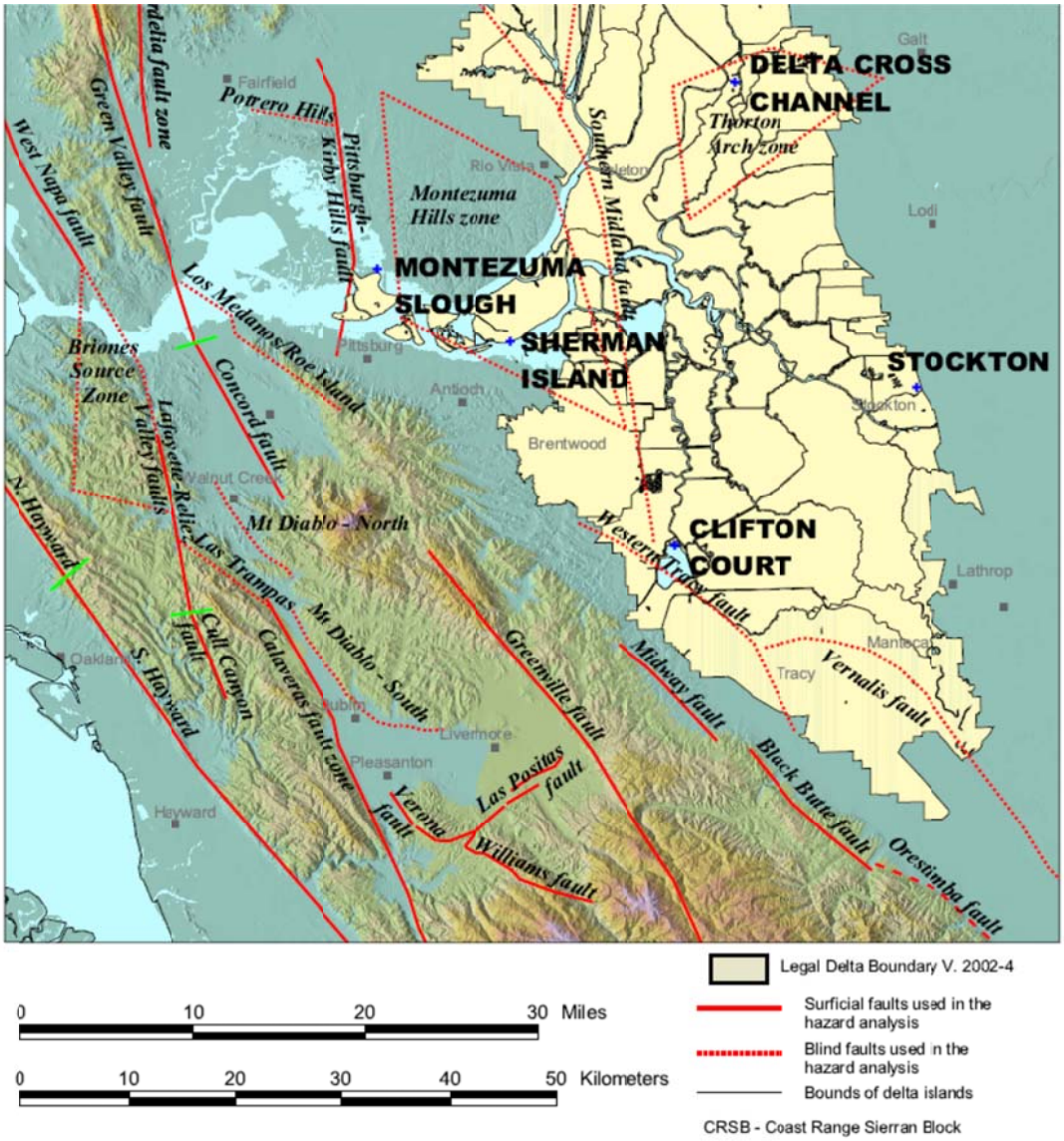

Figure 1. Map of active faults in the Delta region. Faults in the study area include the Western Tracy fault and Southern Midland fault (URS, 2009).

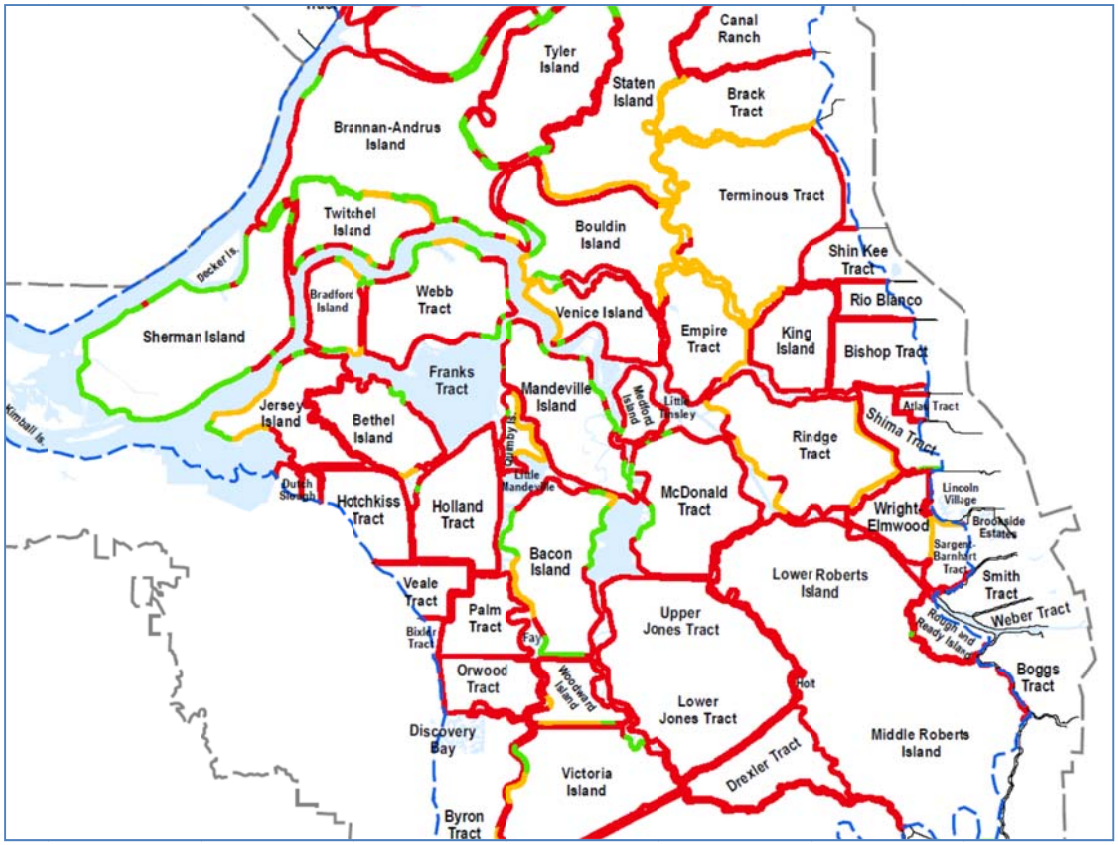

Figure 2. Levees of the San Joaquin-Sacramento Delta showing seismic vulnerability groups. Red = high, yellow = medium, green = low. (URS, 2009).

During the past few decades, several new methods have been developed for measuring shear-wave velocity. Borehole methods include P-S suspension logging (Ogura et al., 1989), which provides ~ 1 m vertical resolution. Downhole measurement of V_S using a surface source may be performed in conjunction with cone penetration testing (Holzer et al., 2005). Surface wave methods are non-invasive and less costly than borehole methods. The multichannel analysis of surface waves (MASW) method is suitable for measuring V_S to depths of about 30 m, depending on the site (Xia et al., 1999). MASW surveys are typically performed using a linear geophone array with an impulsive source such as a sledgehammer, but the same array and recording system may be used to record ambient noise and processed to obtain V_S using a similar method (Louie, 2001). For a comparison of several methods for the measurement of V_S, see Stephenson et al. (2005).

Previous work

Shear-wave velocity (V_S) and site amplification in the Delta were measured by Fletcher and Boatwright (2013), who utilized a network of broadband seismic stations. They used surface wave methods to determine V_S profiles from earthquake seismograms recorded at pairs of

stations. By examining H/V spectral ratios of ambient noise, they determined that levees have amplifications of 10-15 at 1-3 Hz. They provided cone penetration test (CPT) and soil borehole logs at some sites.

Site response and site effects for levees in the Delta were investigated by Kishida et al. (2009). Their work contains borehole V_S suspension logs from four sites in the Delta, with site maps showing borehole locations. An example log from Bacon Island is shown in Figure 3, which illustrates abrupt changes in velocity between peat and the sandy units above and below it. Borehole velocity logs of this type serve as a valuable independent measurement of shear-wave velocity that may be compared with results from surface wave methods (Stephenson et al., 2005).

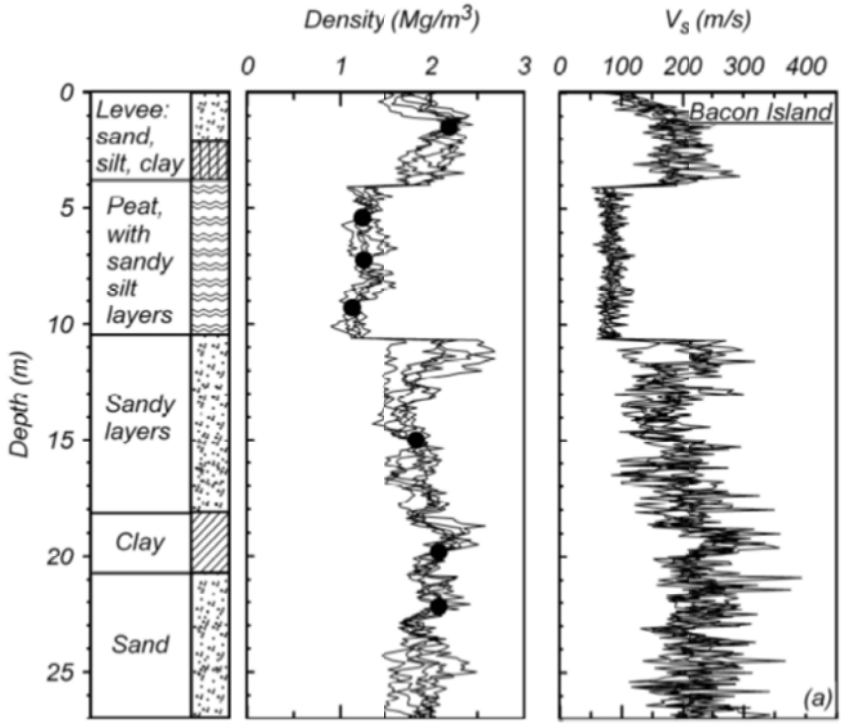

Figure 3. Lithology, density, and V_S logs from Bacon Island (URS, 2009). Note the extremely low values of V_S of the peat layer, and the abrupt change in velocity at the bottom of the peat layer.

The strength of ground shaking for an earthquake of a given size varies greatly according to site conditions. Site response in the San Francisco Bay area has been shown to vary greatly depending on surface materials, leading to amplifications of several times for sediments like alluvium and Bay mud (Borcherdt, 1970; Borcherdt and Gibbs, 1976). The NEHRP site classification scheme incorporates shear wave velocity, and provides a physical basis for assessing seismic hazard and designing seismically resistant structures (Table 1).

Table 1. NEHRP site classes (BSSC, 2000)

Site Class	Material	Velocity (m/s)
A	Hard rock	$V_{S30} > 1500$
B	Rock	$760 < V_{S30} \leq 1500$
C	Very dense soil and soft rock	$360 < V_{S30} \leq 760$
D	Stiff soil	$180 \leq V_{S30} \leq 360$
E	Soil	$V_{S30} < 180$
F	Soils requiring site-specific evaluations	

Site class F includes liquefiable soils, peats more than 3 m thick, and certain types of clays vulnerable to failure under seismic loading.

V_{S30} , as defined by BSSC (2001), is the average shear-wave velocity over the upper 30 m,

$$V_{S30} = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} \frac{d_i}{V_{Si}}} \quad ,$$

where d_i = thickness of the ith layer, $V_{Si} = V_S$ of the ith layer, n = number of layers, and

$\sum_{i=1}^{n} d_i$ = 30 m.

Site Locations

Site locations were selected to provide relatively uniform spatial coverage of the central Delta and to sample a range of different geologic conditions. Where possible, locations of stations used in previous studies or networks were reoccupied. New sites were located in areas where borehole logs were available. Sites were located at a total of twelve locations (Figure 4): Sherman Island (SIA), Bethel Island (SRB), Holland Marina (HOL), Sandmound Boulevard (SMB), Empire Tract (EMR-E, EMR-N, EMR-S) , Webb Tract (WEB-N, WEB-S), Bacon Island (BAC-N, BAC-S), and Clifton Court Forebay (CC). Four sites were at or near the locations used by Fletcher and Boatwright (2013): SRB, HOL, SMB, and EMR.

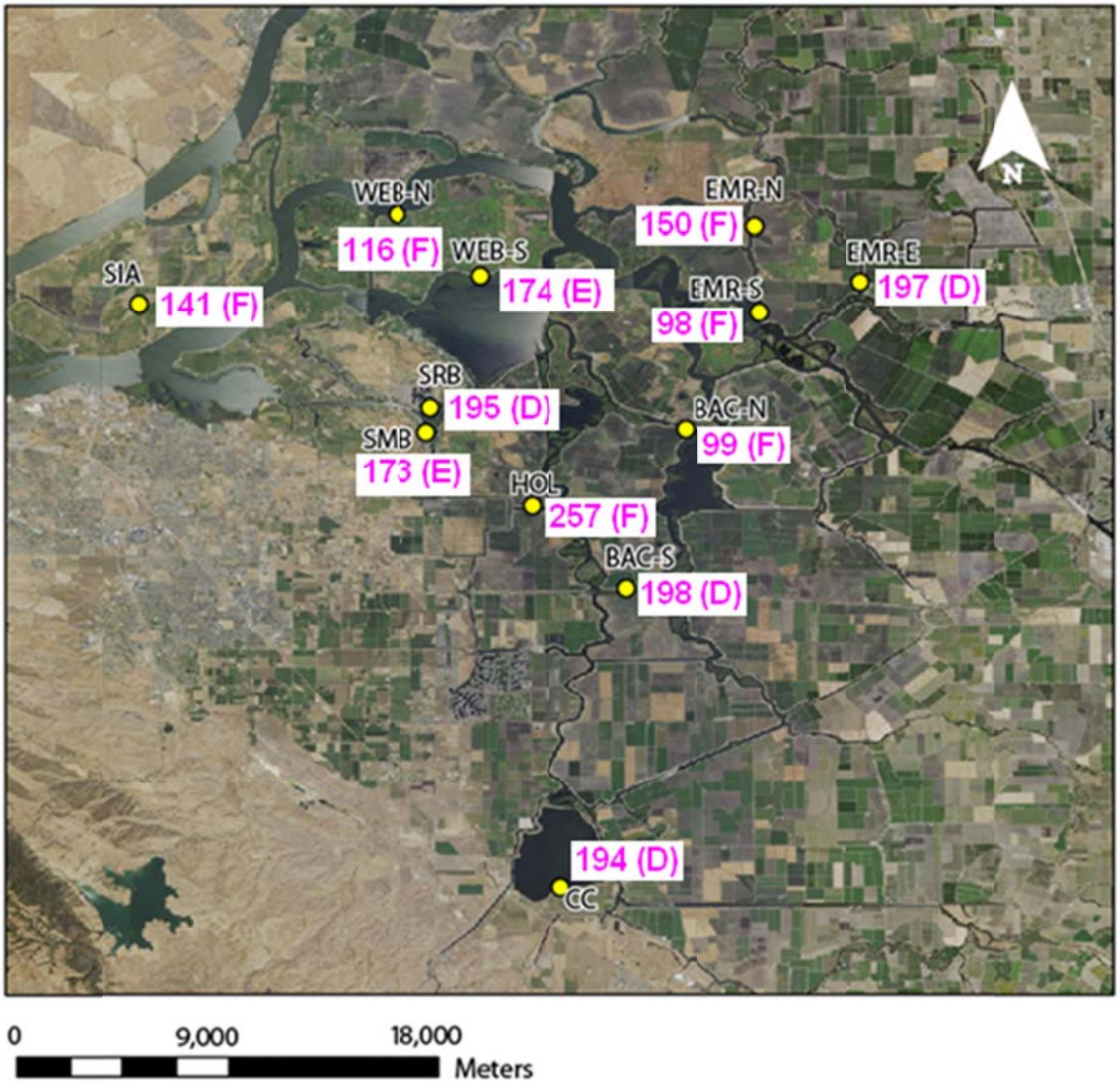

Figure 4. Site map of the Sacramento-San Joaquin Delta with V_{S30} and NEHRP site class. Station locations indicated with yellow dots, V_{S30} in m/s is numeric value in magenta, followed by NEHRP site class in parentheses. BAC-N = Bacon Island North, BAC-S = Bacon Island South, CC = Clifton Court Forebay, HOL = Holland Tract Marina , EMR-N = Empire Tract North, EMR-E = Empire Tract East, EMR-S = Empire Tract South, SMB = Sandmound Boulevard, SIA = Sherman Island, SRB = Bethel Island, WEB-N = Webb Tract North, and WEB-S = Webb Tract South.

Method

The multichannel analysis of surface waves (MASW) method and microtremor array method (MAM) were used to determine a 1D V_S (shear-wave velocity) depth profile and V_{S30} for each of the twelve sites described above. Two-station spatial autocorrelation (SPAC) surveys were conducted at four of the sites. MASW is an active method utilizing an impulsive source (Xia et al., 1999), while MAM is a passive method utilizing ambient noise (Okada, 2003). MASW and

MAM surveys were conducted at each site using a using a 48-channel seismographic system with a linear array of vertical-component 4.5 Hz geophones, 1 m geophone spacing, and 47 m spread length. Acquisition parameters were chosen to provide adequate spatial resolution and depth penetration. Theoretical minimum wavelength and depth resolution are determined by geophone spacing, while maximum wavelength and depth penetration are determined by geophone resonant frequency and spread length. A relatively small geophone spacing (1 m) was used in order to provide sufficient vertical resolution to resolve details of the near surface velocity structure. When using the combined active and passive methods, a spread length of about 1-2 times the target depth is required. The target depth of this survey was 30 m, and a spread length of 47 m was used.

The survey target was the natural lithologic sequence starting beneath the base of the levees, not the levee body. Surveys were accordingly located off the levee (along the toe) if possible. Examples of field setup at two sites is shown for two locations in Figure 5, one along the toe of a levee and the other along the crown of a levee. Two-station SPAC surveys utilized two long-period seismographs placed at a series of several different offsets, with a maximum offset of 1800 m.

Multichannel Analysis of Surface Waves (MASW)

For MASW surveys, shots were normally taken at six different locations, three at each end of the receiver spread with offsets of 1, 5, and 10 m from the last geophone (Figure 6). Data quality was generally quite good. There was very little motor vehicle traffic or cultural noise, with the rare exception of farm equipment. The main source of noise affecting MASW records was afternoon wind. Differences between sites in frequency content and velocity are apparent in field records (Figure 7).

a **b**

Figure 5. Photographs of sites showing field setup: a) Toe of levee, Bacon Island South. Seismic line is visible in the left foreground, crown of levee is to the right. b) Survey recorded along the crown of a levee, Empire Tract South (EMR-S).

Microtremor Array Method (MAM)

In addition to active (MASW) surveys, passive (MAM) data were recorded at each of the sites using the microtremor survey method. The same recording system and recording geometry that were used for the active survey were used for the passive survey. Instead of using the sledgehammer source, ambient noise was recorded. Twenty records per site were recorded with a record length of 65 s and a sample interval of 4 ms.

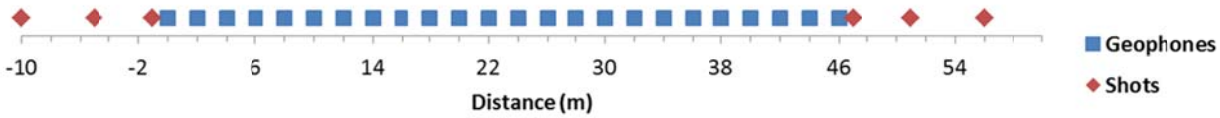

Figure 6. Recording geometry for an MASW survey showing shot locations (red diamonds) at offsets of 1, 5, and 10 m from each end of the spread. Geophone locations are shown with blue squares. In this figure, a 24-receiver spread is shown with a 2 m receiver spacing, for a spread length of 46 m. The actual surveys were recorded using 48 channels, 1 m geophone spacing, and 47 m spread length.

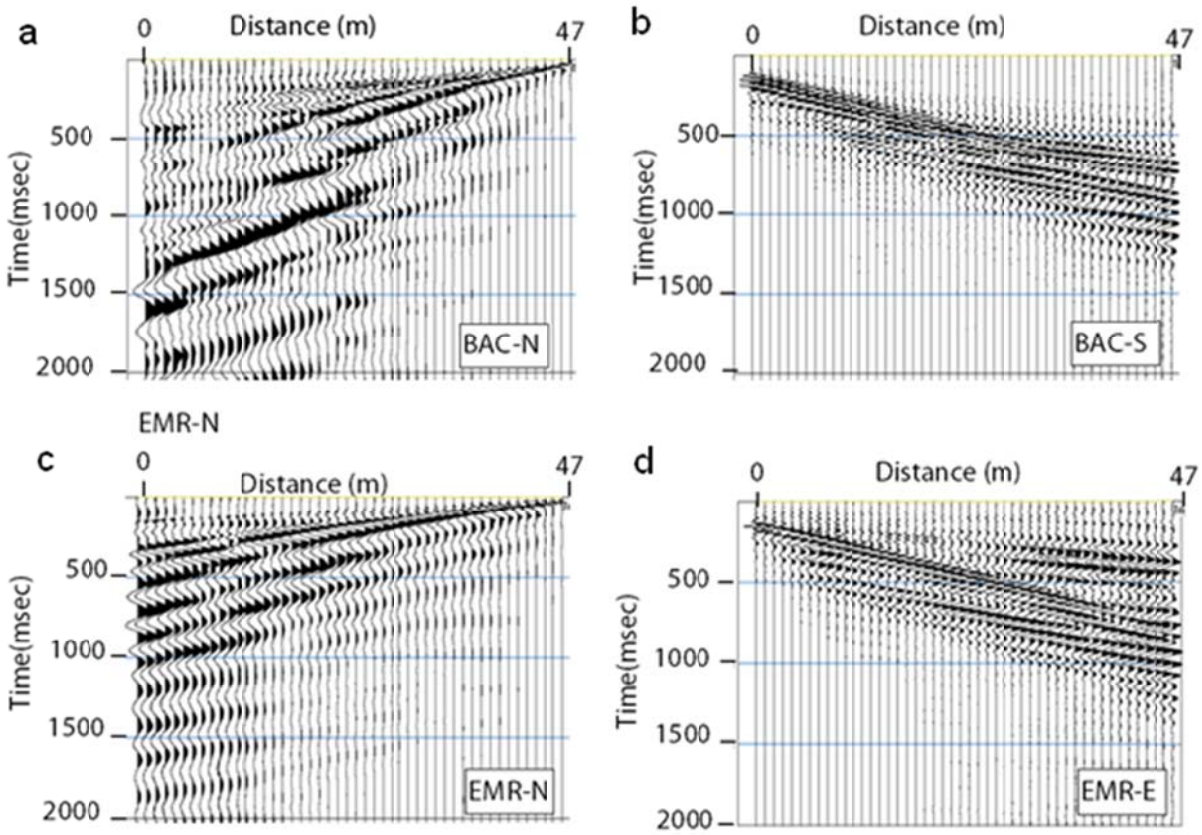

Figure 7. Seismic field records, MASW survey. a) BAC-N, b) BAC-S, c) EMR-N, d) EMR-E. Each record is a 48-trace gather with a 2.048 s record length. The records from BAC-N and EMR-N have much lower frequency than BAC-S and EMR-E. BAC-N has the lowest velocity of these four sites, as is evident from the steep slope of its arrivals.

Data Processing

Surface wave data processing was performed using SeisImager/SW software (Geometrics, 2009). For MASW processing, one shot record was processed at a time. First the shot record was transformed into the velocity-frequency domain, then the fundamental mode dispersion curve was picked. Next an initial velocity model was prepared by mapping each velocity-frequency pick from the dispersion curve to a depth equal to one-third wavelength. A nonlinear inversion was then performed to obtain an improved velocity model. In most cases, RMS error between inverted and theoretical models was less than 5%. For additional details on the MASW method, including inversion, see Xia et al. (1999).

Sample MASW velocity-frequency spectra from four sites are shown in Figure 8. Bands of blue with small red dots are surface wave dispersion curves. The spectra for BAC-S and EMR-E (Figures 8b and 8d) show typical fundamental mode dispersion curves, with velocity decreasing as frequency increases over the range 6 - 20 Hz. The dispersion curves for BAC-N and EMR-N (Figures 8a and 8c), however, show an *increase* in velocity with increased frequency. This type of dispersion curve cannot be explained by fundamental mode energy, it arises due to multiple higher modes.

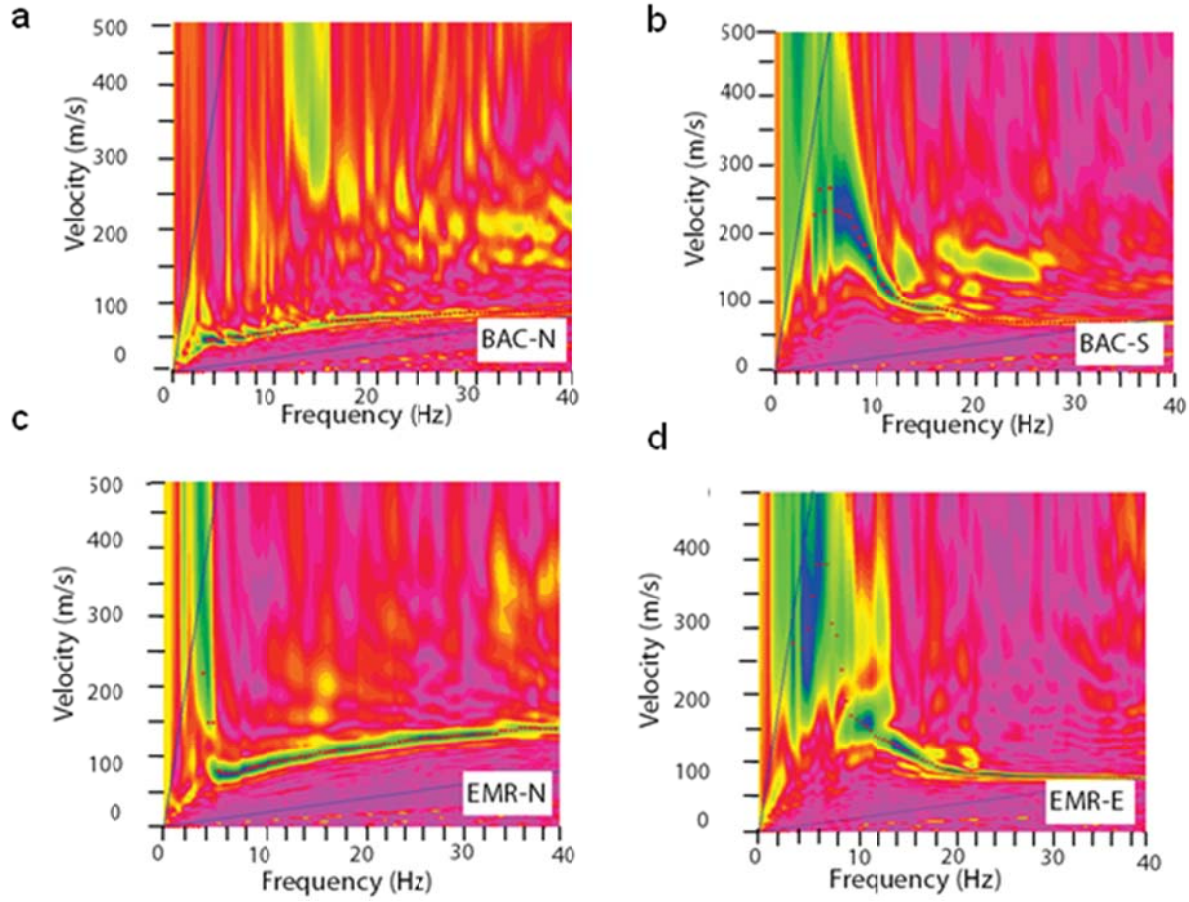

Figure 8. Velocity-frequency spectra, active method. Sample spectra from MASW surveys at four sites: a) BAC-N, b) BAC-S, c) EMR-N, d) EMR-E. Dispersion curves are areas of dark blue with red symbols. BAC-S and EMR-E show typical fundamental mode dispersion curves. BAC-N and EMR-N show inverted curves that are likely due to multiple higher modes.

Passive data were treated differently from MASW data during the initial stages of processing. The spatial autocorrelation (SPAC) method was used to calculate the signal coherence for each ambient noise record. At each site, a total of 20 passive records, 65 seconds in length, were used to compute coherence. Phase velocity was then determined for each wavelength by finding the best fit between theoretical and observed coherence. Sample velocity-frequency spectra are shown in Figure 9. Dispersion curves are picked in the velocity-frequency spectra in the same manner as for the active (MASW) data.

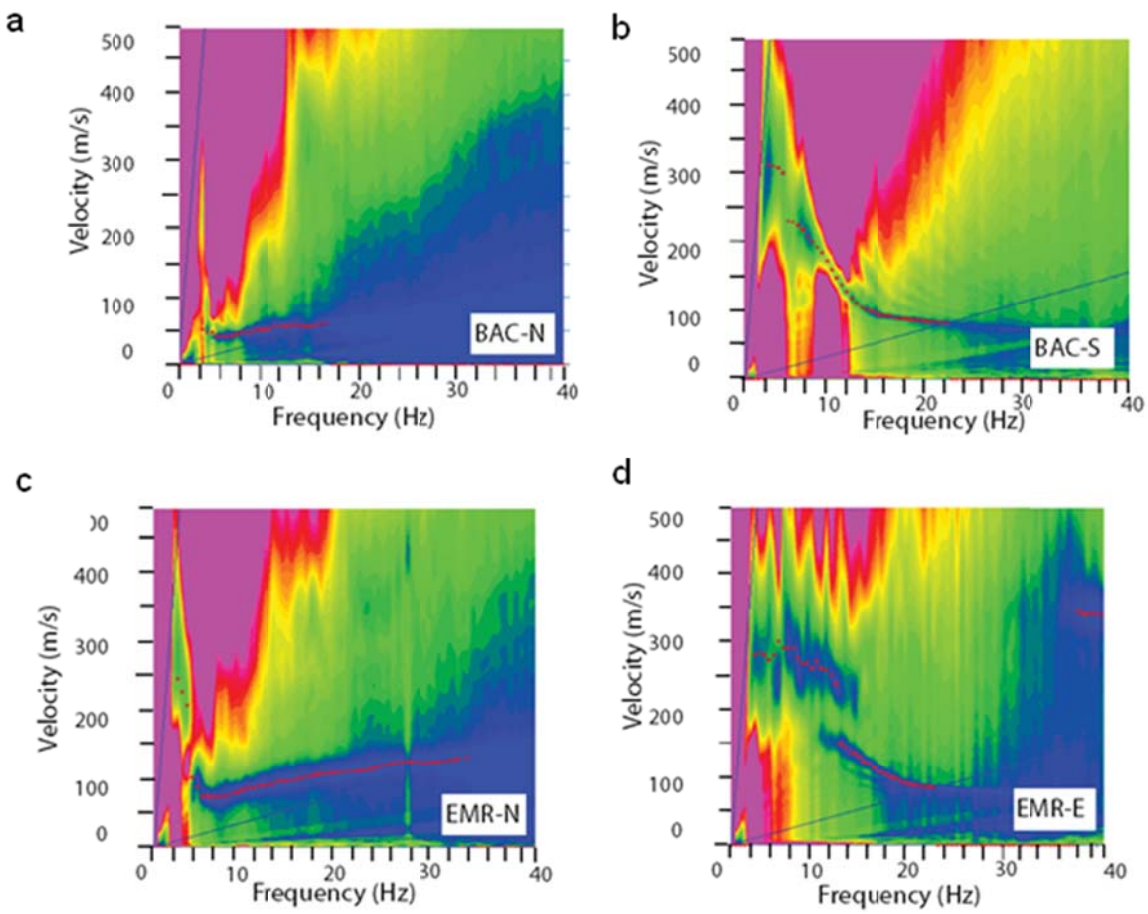

Figure 9. Velocity-frequency spectra, passive method. Sample spectra from four sites: a) BAC-N, b) BAC-S, c) EMR-N, d) EMR-E. Dispersion curves are areas of dark blue with red symbols. BAC-S and EMR-E show typical fundamental mode dispersion curves. BAC-N and EMR-N show inverted curves that are likely due to multiple higher modes.

Active (MASW) and passive (MAM) data were combined to increase the frequency bandwidth of the frequency-velocity spectrum and achieve greater depth penetration. Dispersion curve picks from MASW and MAM surveys were combined to form a single curve (Figure 10). At sites where a two-station SPAC survey was performed, the curve from it was also combined (Figure 14a). The combined dispersion curve was then inverted to obtain a 1D velocity model for the site. A nonlinear inversion was used to estimate V_S profiles to depths ranging from 20 to 40 m for sites where MASW and MAM were used (e.g. Figure 11a), and to depths of ~2000 m at sites where SPAC was used (Figure 14b).

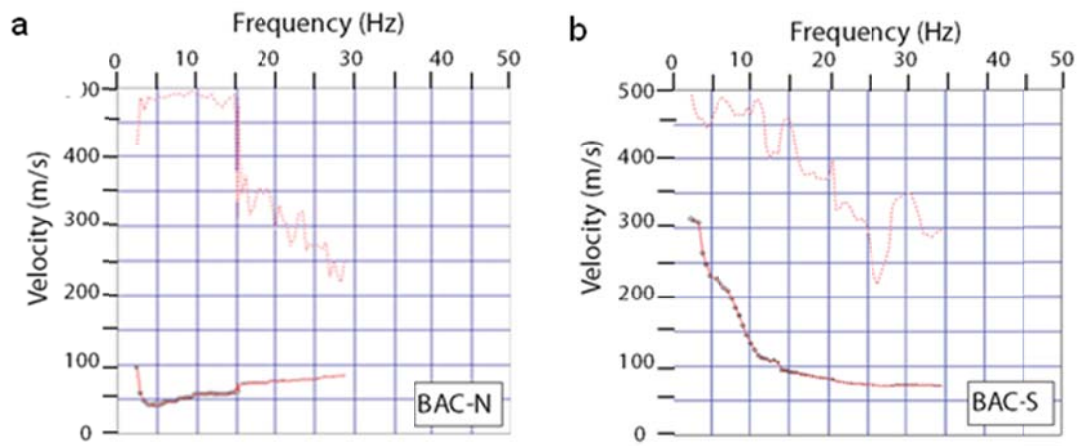

Figure 10. Dispersion curves after editing. a) BAC-N, b) BAC-S. The curves have been constructed by combining data from active and passive methods and are used as input to inversion to obtain velocity-depth models.

Comparison of Velocity Profiles with Borehole Logs

The velocity profile obtained from the seismic surface wave survey for each site was compared with the nearest available soil borehole log. Logged sediment types in the upper 40 m include levee fill, peat, organic mud, silty sand, eolian sand, and alluvial sand. V_S profiles from several sites contain a low-velocity layer at or near the surface that corresponds to a peat or organic-rich mud up to 8 m thick in boreholes. This layer is underlain by higher velocity silts and sands. The transition from peat to the underlying unit corresponds to a distinct lithologic boundary and large increase in standard penetration test (SPT) blow count N. It also coincides with an abrupt increase in V_S measured in the present study.

Two examples are provided that illustrate typical lithologic sequences and corresponding velocity profiles, one with a peat layer and one without. At BAC-N (Figure 11), a surficial layer of silt about 1 m thick overlies a peat layer 5 m thick. The velocity solution indicates a decrease in velocity at 1 m depth, which appears to correspond to the transition from silt to peat. Abrupt increases in velocity at 7 m and 23 m are in good agreement with base peat and top sand in the borehole log. In the second case, BAC-S, no peat is present. Velocity steadily increases from the surface to a depth of 10 m, with a slower rate of increase at greater depths, but with a slight step at 27 m that correlates with top sand (Figure 12).

In general, portions of velocity models that correspond to peat layers in the uppermost 8 m exhibit extremely low values of V_S , ranging from 42 m/s to 150 m/s. For portions of velocity models that correspond to a deeper sand unit, V_S ranges from 220 m/s to 370 m/s.

In addition to standard soil borehole logs and SPT blow count, cone penetration test (CPT) logs were available at a few of the survey sites. CPT tip resistance was compared with V_S for three sites, BAC-N, SIA, and HOL (Figure 13). Data are clustered according to lithology. Peat has low values of V_S and CPT tip pressure, sand has high values of each.

V_{S30} was computed for each site, values ranged from 98 m/s to 257 m/s (Table 2, Figure 4). This velocity range is spanned by NEHRP site classes D and E. However, sites that contained a surface peat layer were assigned to class F in accordance with the NEHRP guidelines. The two sites with the lowest V_{S30} were EMR-S (98 m/s) and BAC-N (99 m/s). Both sites have a 1-2 m thick silt layer at the surface overlying a peat layer 5-7 m thick (e.g., Figure 11).

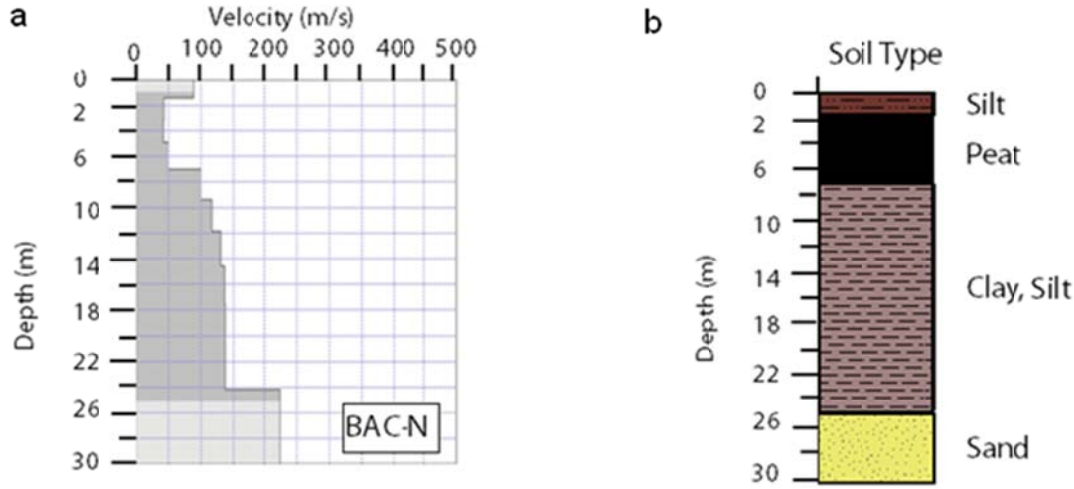

Figure 11. Velocity model and borehole log, peat present, BAC-N. a) 1-D velocity-depth model, b) soil borehole log. The decrease in velocity at 1 m depth correlates with the transition from silt to peat. Abrupt increases in velocity at 7 m and 23 m coincide with lithologic interfaces in the borehole log.

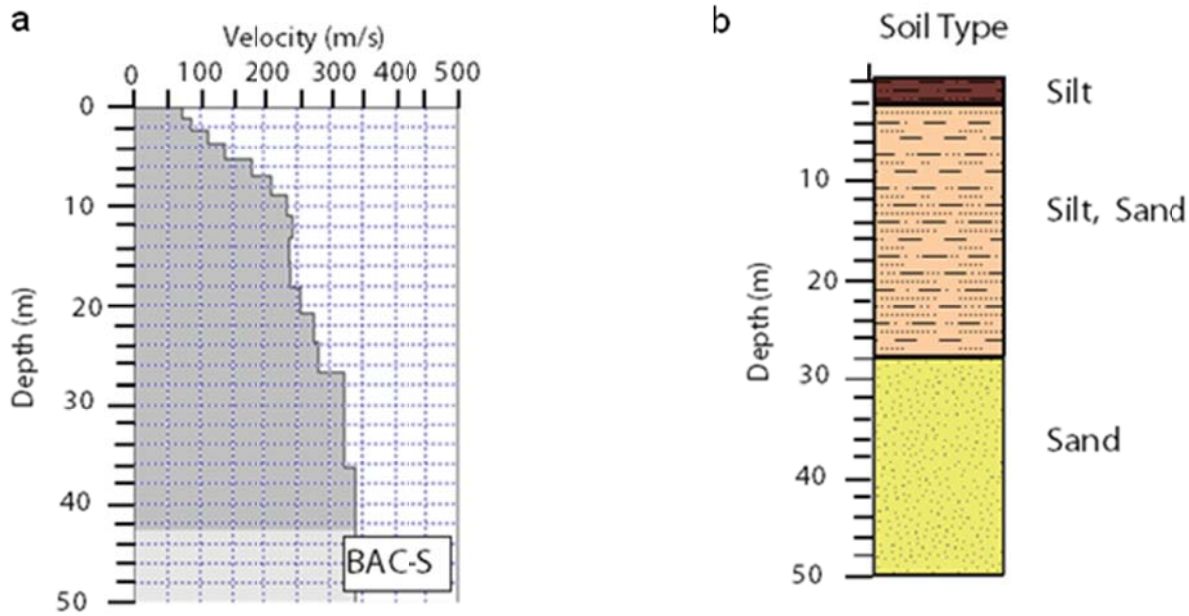

Figure 12. Velocity model and borehole log, no peat, BAC-S. a) 1-D velocity-depth model, b) soil borehole log. Velocity steadily increases from 0-10 m, with a slower rate of increase at greater depths, but with a step at 27 m that correlates with top sand.

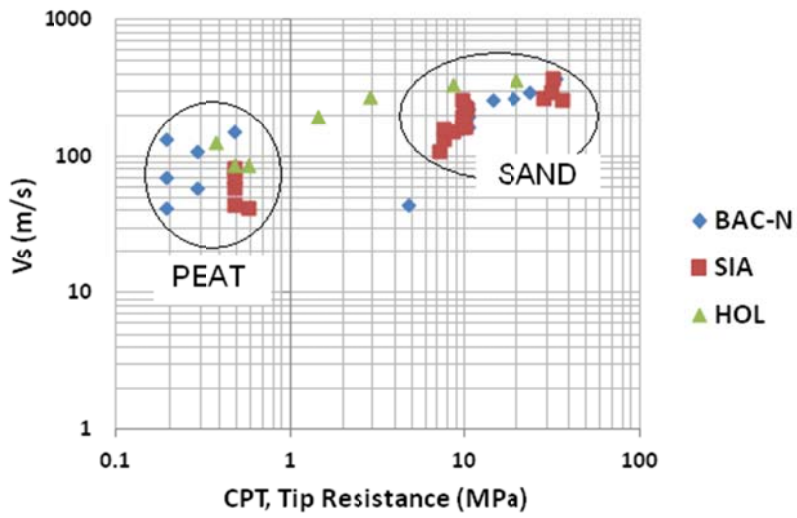

Figure 13. Velocity and CPT tip resistance at Bacon Island North (BAC-N), Sherman Island (SIA) and Holland Marina (HOL). Data are clustered according to lithology. Peat has low values of V_S and CPT tip pressure, sand has high values of both.

Table 2. V_{S30} , NEHRP site classes, and locations of all sites. Sites assigned to D or E based on V_{S30}. Sites with a surficial peat layer assigned to Class F. See Figure 4 for site map.

Site	V_{S30} (m/s)	Class	Location Lat, Lon (DD)
BAC-N	99	F	38.00238, -121.52651
BAC-S	198	D	37.941, -121.543
CC	194	D	37.827, -121.575
EMR-E	197	D	38.05909, -121.46066
EMR-N	150	F	38.07992, -121.49874
EMR-S	98	F	38.04658, -121.49843
HOL	257	F	37.97313,-121.58712
SIA	141	F	38.05049, -121.73677
SMB	173	E	37.99940, -121.62610
SRB	195	D	38.01114, -121.62275
WEB-N	116	F	38.085, -121.640
WEB-S	174	E	38.061, -121.605

Spatial Autocorrelation (SPAC)

Two-station spatial autocorrelation (SPAC) surveys were conducted long-period accelerometers at four sites; Bethel Island (SRB), Sandmound Boulevard (SMB), Sherman Island (SIA), and Empire Tract (EMR). Maximum separation between stations was typically 1600 m to 1800 m, providing coherent signal with frequency as low as 0.3 Hz, wavelength in excess of 5 km, and depth penetration to 2000 m. Results from SRB, SMB, and SIA are similar, with V_S increasing from ~ 250 m/s at the surface to 1000 m/s at a depth of 700-800 m, reaching 1500 m/s at depths of 1000-1250 m (Figure 14). Velocities for EMR are much faster than the other three sites and need to be verified.

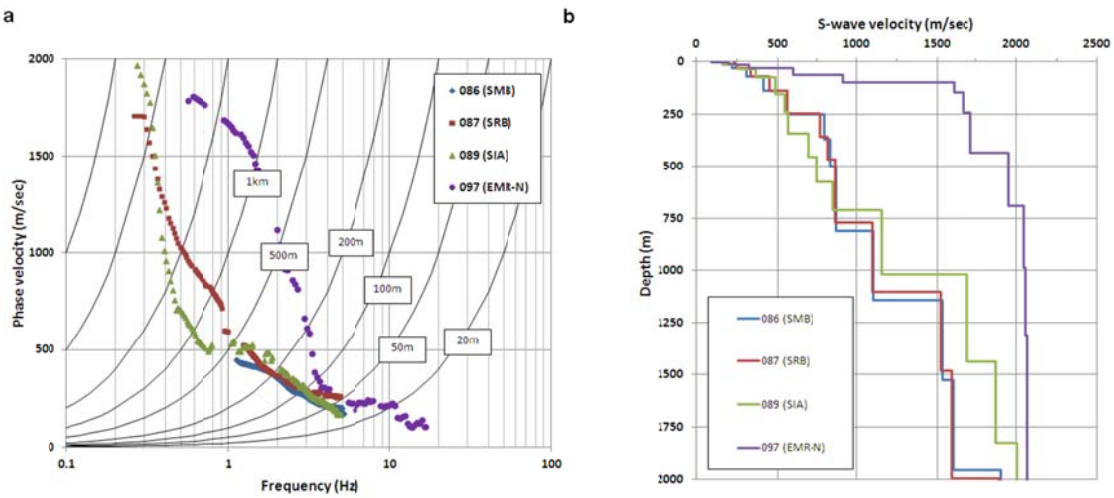

Figure 14. Two-station SPAC surveys at SMB, SRB, SIA, and EMR. a) dispersion curves, b) velocity models.

Seismic Reflection

While conducting MASW surveys for this study, additional off-end shots at longer offsets were recorded in order to check data quality and to look for coherent reflections. At several of the sites, reflections were in fact observed. In order to further evaluate the feasibility of conducting a seismic reflection survey, a test survey was conducted at Clifton Court Forebay using a larger receiver spacing, higher-frequency geophones, and regularly-spaced shots. The recording geometry consisted of a 48-channel spread, 3 m receiver spacing, 3 m shot spacing, and 141 m spread length. A sledgehammer source and 40 Hz vertical-component geophones were used. Preliminary results are encouraging. A sample field record is shown in Figure 16 with three different bandpass filters; 20-60 Hz, 20-90 Hz, and 20-120 Hz. Several reflected arrivals are apparent from 200 to 700 ms, and based on the presence of shallow reflectors in the Figure 16c, the data contain usable signal up to at least 120 Hz.

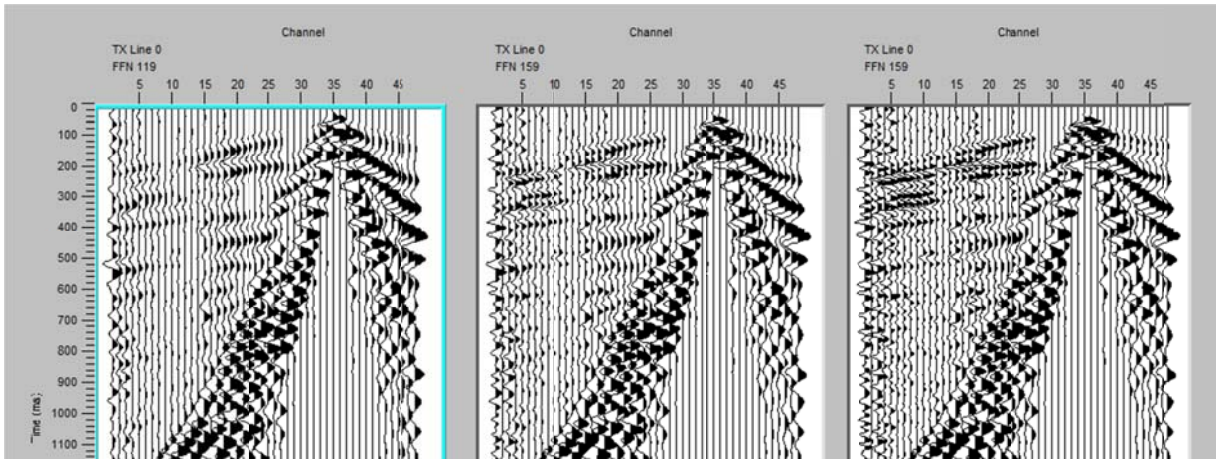

Figure 15. Sample field record from Clifton Court reflection survey with three different filters: a) 20-60 Hz, b) 20-90 Hz, c) 20-120 Hz. Several reflected arrivals are apparent from 200 to 700 ms.

Conclusions

Seismic surface wave surveys were performed at twelve sites in the Sacramento-San Joaquin Delta region, providing improved Vs models of the near surface. Data quality was good, with relatively little noise. A combined active and passive method utilizing the MASW and MAM techniques provided vertical resolution of 1 m and depth penetration 20 to 40 m. In most cases, the target 30 m depth penetration was achieved. MASW surveys were able to detect surficial layers as thin as 1 m, including velocity reversals due to faster levee fill material overlying slower peat. Velocity models derived from surface wave surveys were in good agreement with lithologic sequences from soil borehole logs. Measured peat velocities ranged from 42 m/s to 150 m/s. Velocities of a deeper sand unit ranged from 220 m/s to 370 m/s. Measured average V_S from the surface to a depth of 30 m (V_{S30}) ranged from 98 m/s to 257 m/s. Sites were assigned to NEHRP site classes D, E, and F. Assignments to class F were based on the presence of a near-surface peat layer up to 8 m thick. At four of the sites, SPAC surveys with longer offsets provided depth penetration to depths of approximately 2000 m. At four of the sites, additional surveys were performed using the two-station spatial autocorrelation (2ST-SPAC) method to provide depth penetration of approximately 2000 m. Velocity was determined to frequencies as low as 5 Hz, 1 Hz, and 0.3 Hz using MASW, MAM, and 2ST-SPAC, respectively. Tests indicate that near-surface seismic reflection data quality is good and that reflection profiling may be successfully conducted in the area using a relatively modest recording system.

Recommendations for Future Research

This study produced 1D V_S models at individual sites. In order to extend these results to produce a seismic hazard map, and laterally continuous velocity models, 2D MASW surveys could be conducted. Continuous surveys could be conducted along roads on levees, but surface wave data recorded on levees tends to be dominated by higher modes, requiring more complex data processing. Sites in the interior of islands, away from levees, are likely to yield better data quality.

During the course of conducting surface wave surveys for this study, field records for several sites were observed to contain coherent reflections. indicating that reflection profiling could be successfully used to image near-surface stratigraphy. Reflection profiling is more time intensive than surface wave surveying, but has the potential to provide higher resolution images needed to resolve stratigraphic and structural details associated with faulting.

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