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GEOPHYSICAL CHARACTERIZATION OF SEISMIC STATION SITES IN THE UNITED STATES – THE IMPORTANCE OF A FLEXIBLE, MULTI-METHOD APPROACH

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Abstract

Noninvasive geophysical site characterization methods were used in two recent projects to obtain shear-wave velocity (V_S) profiles to a minimum depth of 30 m and the time-averaged V_S of the upper 30 meters (V_{S30}) at seismic station sites. These projects include the 2009 American Recovery and Reinvestment Act (ARRA) funded U.S. Geological Survey site characterization project for 191 sites in California and the Central-eastern United States (CEUS), and the 2012 Electric Power Research Institute (EPRI) funded project for 33 additional CEUS sites. These sites are located in rural to urban settings with topographic conditions ranging from relatively flat sedimentary basins to mountaintop ridges. About 60 percent of the ARRA sites and 80 percent of the EPRI sites are located on rock or have thin sediment cover over rock, including Quaternary volcanic rock, Tertiary sediments and sedimentary rock, and Mesozoic (or older) crystalline or sedimentary rock. The remaining sites consist of thick sequences of Quaternary sediments overlying older sediments and rock.

ARRA sites were characterized using non-invasive active and passive surface-wave methods, including the horizontal-to-vertical spectral ratio (HVSR) method and one or more of the following: spectral analysis of surface waves (SASW), multi-channel analysis of surface waves (MASW; Rayleigh and Love waves) and, occasionally, array microtremor (linear and 2-D arrays) methods. P-wave seismic refraction data were also acquired at rock and shallow-rock sites. S-wave seismic refraction and/or Love-wave MASW methods were applied at sites where characterization proved difficult with Rayleigh-wave methods. Based on our experience from the ARRA project, we acquired Rayleigh- and Love-wave based MASW and P- and S-wave refraction data for the EPRI project at CEUS sites.

The HVSR method was found to be useful for identifying shallow-rock sites and for evaluating the relative variability of the depth-to-rock interface beneath the seismic station and the testing array(s). The fundamental mode modeling assumption was generally valid at most of these sites; nevertheless, multi-mode or effective-mode modeling routines were occasionally required, particularly in the case of shallow high-velocity layers. Deep sediment sites were characterized using active and, when appropriate, passive surface-wave based methods. Rock and shallow sediment sites were generally more challenging to characterize than deep sediment sites. About 10 percent of rock sites could not be characterized using surface wave methods, thus these sites were characterized using body-wave refraction methods. Love wave methods were found to be more effective than Rayleigh wave methods at some rock and shallow-rock sites (e.g., sites with shallow rock and sites with a thin low-velocity, highly attenuating surface layer). Lateral velocity variability was found to be very common at rock and shallow-rock sites, often causing significant scatter in the surface-wave dispersion data. Seismic refraction models have demonstrated that it may not be unusual for V_{S30} to vary by 20 percent, or more, over small distances (several tens of meters) at such sites. Based on these experiences, it is important to consider the application of combinations of methods when using noninvasive geophysical approaches to characterize seismic site conditions.

Keywords: seismic site characterization; active surface wave; passive surface wave, seismic refraction

1. Introduction

From 2010–2012, the 2009 American Recovery and Reinvestment Act (ARRA) funded geophysical characterization at 187 seismic station sites in California and four sites in the Central and Eastern United States (CEUS) for the U. S. Geological Survey (USGS) [1]. In 2012, the Electric Power Research Institute (EPRI) funded characterizations of an additional 33 seismic station sites in the CEUS—24 sites were characterized by GEO*Vision*, Inc., and 11 sites by the University of Texas at Austin (UTA) [2]. Two EPRI sites were characterized by both groups [2]. The objectives of these investigations were to develop shear (S) -wave velocity (V_S) profiles to a depth of 30 m (or greater) from the surface to estimate the time-averaged V_S of the upper 30 m (V_{S30}) and to assign the National Earthquake Hazards Reduction Program (NEHRP) Site Class.

The station sites are located in a wide variety of geologic conditions, which are situated in both rural and urban settings. Topographic conditions range from flat sedimentary basins to mountaintop ridges. The locations of seismic stations are presented in Fig. 1 and Fig. 2.

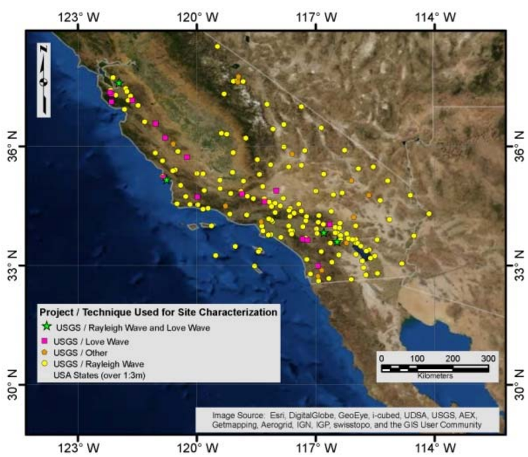

Fig. 1 – California seismic station sites

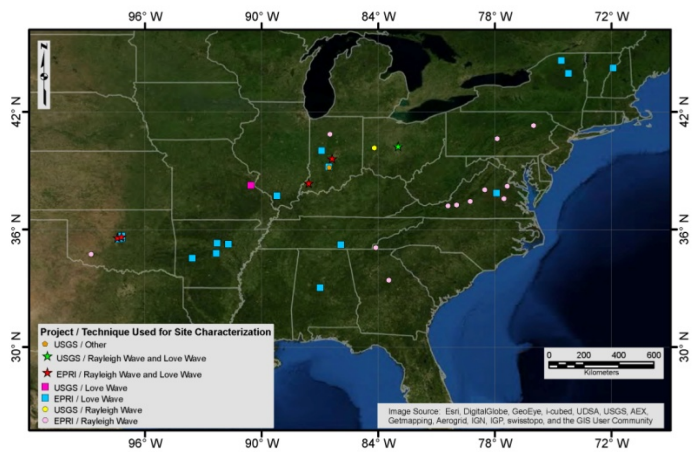

Fig. 2 – CEUS seismic station sites

In practice, a number of standalone noninvasive seismic methods can be used to characterize seismic velocity structure at seismic station sites, including active and passive (ambient vibration or microtremor) surface-wave methods and compressional- (P) and shear-wave (S) seismic refraction methods. The seismic reflection method can also be used in some cases, especially when the secondary objective is to map subsurface stratigraphy and faulting in the vicinity of the seismic station. Active surface-wave methods consist of the spectral analysis of surface waves (SASW) and multi-channel analysis of surface waves (MASW) methods, which generally involve either measurement of Rayleigh or Love waves. The SASW method is optimized for developing one-dimensional (1-D) velocity profiles, whereas the MASW method can be used to develop either 1-D or two-dimensional (2-D) velocity profiles. Passive surface-wave methods include the single-station horizontal-to-vertical spectral ratio (HVSR) and multi-station array microtremor methods. The HVSR method involves collection of ambient vibration data using a single, three-component seismometer; whereas, array microtremor recordings are typically made using either 1-D (linear) or 2-D (e.g., circular, triangular, "L" shaped) arrays of vertical or three-component sensors. One-, two-, or three-dimensional seismic reflection and refraction surveys can be conducted using either P- or S-wave energy sources and receivers to characterize site conditions.

Initially, it was expected that Rayleigh-wave based surface wave methods including the MASW (herein referred to as MAS_RW), SASW and array microtremor techniques would be sufficient to characterize ARRA sites. However, early in the field investigation it was determined that additional techniques such as P- and S-wave seismic refraction and Love wave MASW (MAS_LW) would be required to characterize some sites. Cost restrictions, however, made it impractical to utilize the full suite of geophysical methods for site characterization. Rather, a flexible-phased approach was applied, such that a single active surface-wave method was used for site characterization with additional geophysical methods supplemented, as necessary, after preliminary field review of the data.

Based on lessons learned from the ARRA project, the site characterization strategy for the EPRI project was to utilize the best quality data set comprised of MAS_RW, MAS_LW, and P- and S-wave seismic refraction data at sites characterized by GEO*Vision*. UTA utilized the Rayleigh-wave based SASW method and a vibratory energy source for site characterization of other EPRI sites. The EPRI sites are generally located in rural environments; thus, ambient vibration methods were not needed to satisfy project objectives. HVSR data were acquired at a number of EPRI sites characterized by GEO*Vision* to investigate the applicability of the technique in the CEUS. The following sections describe details about select geophysical methods and sites where the methods were utilized.

2. Methodology

Surface-wave methods are based on the dispersive characteristics of Rayleigh or Love waves when propagating in a layered medium. The Rayleigh- (V_R) and Love-wave phase velocity (V_L) depend on the material properties over a depth of approximately one wavelength (λ). V_R primarily depends on parameters such as V_P, V_S, ρ (mass density), and ν (Poisson's ratio); V_L primarily depends on V_S and ρ. Surface-wave phase velocities at different λ (or frequencies, f), referred to as a dispersion curve, reflect velocity structure at different depths.

Active surface-wave methods, such as MASW and SASW, are proven non-destructive geophysical methods for estimating the variation of V_S with depth [3, 4]. The general process includes: recording V_L and/or V_R data in the field, generating a dispersion curve, and then using iterative forward- and/or inverse-modeling methods to estimate the corresponding V_S profile. These methods, particularly those utilizing Rayleigh waves, have undergone significant research and development over many decades [5-8]. One of the earliest applications of an active-source Love-wave method for characterizing near-surface V_S is discussed in [9], but the method has only gained traction in the last decade [10-13]. The SASW method requires a smaller maximum source-receiver offset range and, therefore, less space to evaluate V_S to a particular depth than the MASW method; thus, the application of the SASW method is advantageous at sites where there is limited access or significant lateral velocity variability. The SASW method also can be more cost-effective than the MASW method at evaluating V_s to depths in the 40–100 m range by using a large energy source, such as a bulldozer or vibroseis. An advantage of the MASW method, relative to the SASW method, is that it is possible to visualize and interpret higher-mode surface waves, which is important when higher modes are dominant and data must be modeled using multi-mode modeling routines. In the case of Rayleigh-wave measurements, the SASW method compensates for this limitation by utilizing sophisticated effective-mode inversion routines that are able to can account for body wave and higher mode effects [14]. Effective mode routines [15-17] are also available to model MAS_RW and array microtremor (Rayleigh wave) data. Effective mode routines are not currently available for analysis of Love-wave dispersion data. Multi-mode modeling routines are the only option for sites with complex Love wave propagation. Site characterization can also benefit from the joint inversion of Rayleigh- and Love-wave dispersion data [18, 19].

Unlike active surface-wave methods, passive or ambient-vibration based surface-wave methods record background vibrations emanating from ocean wave activity, atmospheric conditions, wind effects, traffic, industrial, and construction activities, etc., which collectively are referred to as microseisms. Typically, microseisms with frequencies below 1 Hz have natural origins, whereas those above 1 Hz are largely due to human activities [20]. Passive surface-wave methods can be categorized into the single-station (e.g., HVSR) [21-24] or the multi-station (e.g., array microtremor) [20] approaches. HVSR analysis is based on the ratio of the Fourier spectra of the horizontal and vertical components of microtremor recordings [22]. The most common methods used for analysis of array microtremor data include frequency-wavenumber methods, such as beam-forming [25] and maximum-likelihood [26], and the spatial-autocorrelation (SPAC) method, which was originally based on work by [27]. The SPAC method has since been extended and modified [28, 29] to permit the use of noncircular arrays and is now collectively referred to as extended spatial autocorrelation (ESPAC or ESAC). Additional modifications to the SPAC method permit the use of irregular or random arrays [30]. Although it is common to apply SPAC methods to obtain a surface-wave dispersion curve for modeling, other approaches involve direct modeling of the coherency data, referred to as SPAC coefficients [31, 32]. Microtremor data can also be acquired along linear arrays [33], although 2-D arrays are generally accepted as more robust. Microtremor data collected along linear arrays can be analyzed using a number of methods, including ReMi™ [33], ESAC, and seismic interferometry [34, 35].

The body-wave seismic refraction method has a much longer history in geotechnical exploration than surface wave methods. Detailed discussions of the seismic refraction method can be found in many exploration geophysics texts, e.g., [36, 37]. Seismic refraction surveys are designed to measure either P- or S-waves, although P-wave seismic refraction surveys are more routinely conducted. It is possible to combine acquisition of surface-wave and body-wave seismic refraction data by adding the interior source locations required for seismic refraction analysis paired with the small sample interval required to pick refraction first arrivals and long record length required for capture the surface wave. When the purpose of a seismic refraction survey is only to constrain depth to the saturated zone when modeling Rayleigh-wave dispersion data, it is sufficient to model P-wave refraction first arrival data from single forward and reverse source locations using the slope-intercept method [37]. When the subsurface velocity structure is layered (e.g., shallow bedrock surface), then layer-based analysis routines, such as the generalized reciprocal method [38], may be adequate for modeling the seismic refraction first-arrival data. When subsurface velocity structure is complex and cannot be adequately modeled using layer-based modeling methods (i.e., complex weathering profile in bedrock, numerous lateral velocity variations, dipping layers, gradual increase in velocity with depth), then Monte Carlo or tomographic inversion methods [39, 40] are required to model seismic refraction data.

3. Geophysical Site Characterization Observations

3.1 Utilization of the HVSR Technique

HVSR measurements were made at all ARRA sites to estimate the fundamental site period, to determine if the velocity structure was relatively one-dimensional beneath the testing arrays, and to demonstrate that the velocity structure (e.g., depth to rock) beneath the seismic station and testing arrays were similar. HVSR data were also used to guide the modeling of surface-wave dispersion data. The joint inversion of HVSR and surface-wave dispersion data, which is becoming more routinely applied today, was not used during these investigations. With some a priori knowledge of site geologic conditions, the HVSR method can also be used to cost-effectively determine the relative depth to rock over small areas with similar geologic conditions and, thereby, helpful for anticipating the need to acquire Love wave or refraction data or to apply more sophisticated Rayleigh-wave modeling techniques, such as effective- or multi-mode routines. To demonstrate that the velocity structure (e.g., depth to rock) beneath the seismic station and testing arrays were similar, Fig. 3 shows HVSR results from measurements made near seismic station CE.13929 and along the seismic recording array. A nearby outcrop indicated that bedrock should be relatively shallow at this site, which was corroborated by the 7.5-Hz HVSR peaks (Fig. 3). Similar HVSR peaks beneath the seismic station and the MASW or seismic refraction array indicate that bedrock is at similar depths at both locations. Figure 4 shows HVSR data collected near seismic station CE.13922 and along the MASW array. The combination of the 6.5–9 Hz HVSR peaks and geologic map data indicates CE.13922 is a shallow-rock site. The differences in frequencies and amplitudes of the HVSR peaks may indicate that bedrock is shallower at the seismic station than beneath the surface wave array. Because there was not sufficient space to test closer to the seismic station, the HVSR data were used to account for the geologic conditions at CE.13922 by adjusting the depth to rock in the V_S model using HVSR modeling routines and the quarter-wavelength approximation.

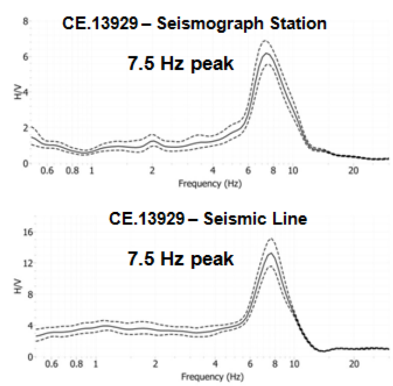

Fig. 3 – CE.13929 HVSR data

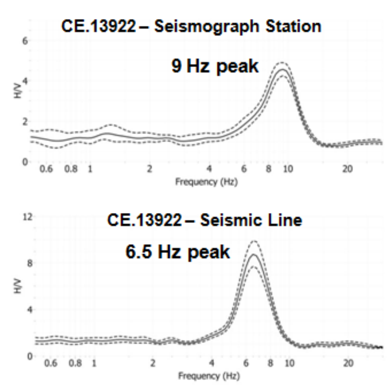

Fig. 4 – CE.13922 HVSR data

3.2 Rock and Shallow-rock Site Observations Using MAS_LW, MAS_RW and Seismic Refraction Methods

3.2.1 Background

Approximately 60 percent of the ARRA sites and 80 percent of the EPRI sites have soft or hard rock at the surface or at relatively shallow depths. In the context of this paper, the term rock refers to Quaternary volcanic rock, Tertiary sediments/sedimentary rock, and Mesozoic, or older, crystalline or sedimentary rock. Such a liberal interpretation of rock is used because these types of sites share similarities with respect to challenges in characterizing their site conditions. In general, rock and shallow- rock sites were are much more difficult to characterize with surface-wave methods than Quaternary sediment sites, and a flexible field approach was found to be crucial to successful characterization.

The primary site characterization method utilized at rock and shallow- rock sites on the ARRA project was the MAS_RW method. The MAS_RW method, however, was not able to robustly characterize all the possible site conditions encountered. P-wave seismic refraction data were acquired at all rock sites to support site characterization efforts, primarily to assess lateral velocity variability beneath the array in unsaturated conditions or to estimate depth to the saturated zone so it could be constrained when modeling Rayleigh wave dispersion data. When deemed necessary, both MAS_LW and S-wave seismic refraction methods were applied at ARRA sites. MAS_RW, MAS_LW, and P- and S-wave seismic refraction methods were applied at all EPRI sites.. Love-wave based SASW data were not acquired in the projects; however, the SASW analytic method was occasionally utilized to extract small-wavelength Love-wave phase velocity data from MAS_LW records.

It was not possible to utilize surficial seismic methods at all seismic station sites during the ARRA project. For example, no attempts were made to characterize three ARRA rock sites using surface methods because there was insufficient space for testing; instead, alternate seismic station sites were characterized. One of these sites is located in a mine shaft on the side of a hill, another is located in a building that rests on a small rock outcrop, and the third site is located in the basement of a building located immediately adjacent to a rock outcrop. Surface wave and seismic refraction measurements made to characterize a fourth ARRA shallow rock site were not effective, thus, the site was characterized using a PS-suspension log acquired during a previous investigation. Surface-wave data collected at 12 other ARRA sites could not be used for site characterization because a dispersion curve could not be developed over sufficient frequency/wavelength range for modeling; thus, the sites were characterized using S- and/or P-wave seismic refraction data. MAS_LW data were acquired at 33 ARRA sites and 24 EPRI sites, and were the primary method used to characterize 17 of the ARRA sites and 16 of the EPRI sites. An additional five ARRA sites and four EPRI sites were characterized using both Rayleigh- and Love-wave dispersion data. Only four EPRI sites evaluated by GEO*Vision* were characterized using only Rayleigh-wave dispersion data. Even when it was possible to characterize shallow-rock sites using Rayleigh-wave data, the first higher mode was often observed to be dominant at low frequencies; thus, it was necessary to use multi-mode or effective mode inversion routines to model the data. It should be noted that on these investigations Rayleigh wave data was acquired using vertical geophones and that some sites with complex Rayleigh wave propagation may have benefited from acquisition of the horizontal, radial Rayleigh wave component [18]. One of the biggest challenges for characterizing rock and shallow-rock sites was lateral velocity variability, e.g., seismic refraction models often reveal 25 percent variation in the time-averaged velocity over relatively small distances. Several case histories are presented herein to demonstrate the challenges encountered in both projects when characterizing rock and shallow-rock sites and the need for a flexible field approach.

3.2.2 Data acquisition and processing strategies

Flexibility in data acquisition and processing strategies were required to successfully characterize rock and shallow-rock sites, and to a lesser degree, deep sediment sites. In practice, the MASW method can be applied using a single energy source location. However, when working in complex environments and where there is a need to quantify error or the influence of lateral velocity variability on the dispersion data, it is important to have multiple source offsets and interior source locations to estimate robust V_S models for the site. Small energy sources (e.g., different types of hammers) at small offsets from the near receiver are useful to generate the high-frequency (short-wavelength) surface waves needed to image shallow velocity structure. Larger energy sources (e.g., weight drops) at larger offsets from the nearest receivers are needed to generate the lower frequency surface waves needed to image to 30 m (and greater) depth. Construction of a dispersion curve, over the wide frequency/wavelength range necessary to develop a robust V_S model while also limiting the maximum wavelength based on an established near-field criteria [41, 42] requires the use of multiple source-receiver offsets. Reversed source locations are required at sites with complex velocity structure and/or complex Rayleigh-wave propagation patterns as shown in Fig. 5. The velocity-frequency transform of the seismic record for the source located at -1.5-m in Fig. 5 shows a dominant fundamental mode at frequencies < 12 Hz and dominant first higher-mode Rayleigh-wave dispersion at higher frequencies. The transform associated with the seismic record for the source located at 72 m has a dominant first higher mode at all frequencies, and if this record were the only available data, the first higher mode may have been incorrectly interpreted as the fundamental mode by an inexperienced practitioner.

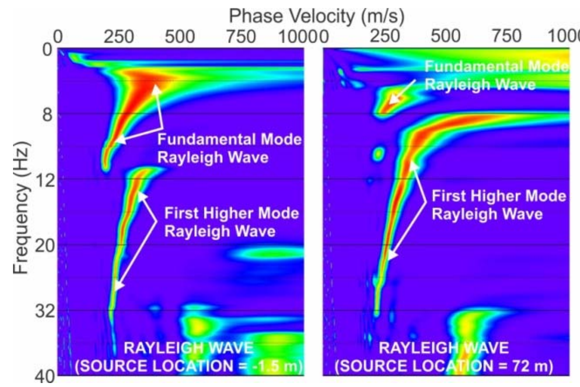

Fig. 5 – Rayleigh wave dispersion data from forward (left) and reverse (right) source locations at NC.BBGB

The resolution of near-surface layers in the V_S model directly impacts the accuracy of modeled layer velocities at greater depths. Therefore, it is important to obtain surface-wave dispersion data at as short a wavelength as feasible when conducting 1-D MASW tests. The shortest wavelength surface wave that can be extracted from an MASW data set is equal to the geophone spacing. It is often not possible to extract surface-wave phase velocities close to this wavelength by applying the wavefield transform to the entire receiver array or by using the larger energy source necessary to image to 30 m depth. The use of smaller energy sources and limited offset range receiver gathers when reducing the data can provide higher frequency (shorter wavelength) dispersion data than can be obtained using longer receiver arrays (Fig. 6). In this case, the dispersion curve has a maximum frequency of 16 Hz when using the entire 141-m-long receiver gather but extends to over 40 Hz from a shorter (27 m) receiver gather.

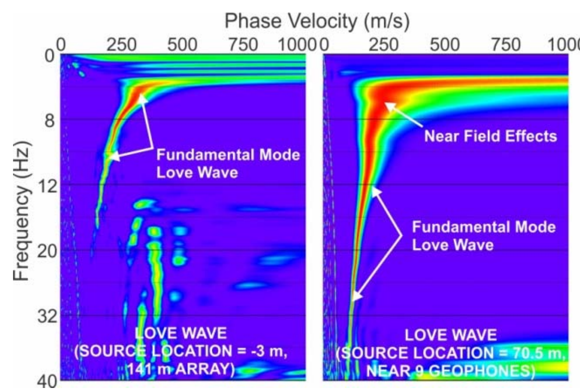

Fig. 6 – Love wave dispersion data using maximum offset range of 144 m (left) and 28.5 m (right) at NC.BBGB

3.2.3 Site characterization using the seismic refraction technique

Surface wave techniques were not effective for about 10 percent of the rock and shallow-rock sites investigated in the ARRA projects. However, it was possible to characterize most of these sites using the S- and/or P-wave seismic refraction methods. Several sites with shallow, crystalline rock could only be characterized using P-wave refraction models. In all such cases, the rock was unsaturated and a realistic Poisson's ratio was inferred from the limited, useable S-wave refraction or surface wave dispersion data recovered from the data sets.

One site characterized using seismic refraction data is station CI.EML (El Monte County Park, San Diego County, California; Fig. 7), which is located at the base of an outcrop of Cretaceous metavolcanic rocks [1]. MAS_RW and P-wave seismic refraction data were first acquired along a 48-channel, 70.5-m-long array aligned parallel to the base of the outcrop. Field inspection of the Rayleigh-wave dispersion data revealed complex Rayleigh-wave propagation; thus, MAS_LW and S-wave seismic refraction data were acquired along the same array. As in the Rayleigh-wave data, the Love-wave dispersion data were also complex—likely because bedrock dips steeply orthogonally to the seismic line. As a result, the site was characterized on the basis of an S-wave seismic refraction model (Fig. 8).

Fig. 7 – Site CI.EML at base of rock outcrop

Typically, the velocity structure in the portion of the seismic model closest to the seismic station would have been used for site characterization. In this case the seismic refraction profile was not acquired immediately adjacent to the seismic station due to space limitations and, therefore, the average 1-D S-wave velocity structure was computed from the S-wave seismic refraction model by averaging slowness horizontally across the model cells between the positions of 24 and 46.5 m, where the depth of investigation is greatest (Fig. 9). The average 1-D velocity structure computed from the seismic refraction model is also useful when comparing seismic refraction models to V_S models developed from surface-wave dispersion data, which reflect average conditions beneath the entire array. The average V_{S30} is 805 m/s for the central portion of the seismic profile, thus the site is classified as NEHRP Site Class B. Similar to surface-wave V_S models, seismic refraction V_S models are not unique because the final model developed from tomographic inversion of the seismic refraction first-arrivals is heavily infuenced by the selection of parameters in the starting model. However, similar to the V_S model derived from the surface wave method, time-averaged parameters derived from refraction measurements, such as $V_{S30,}$ are not significantly affected by the non-uniqueness.

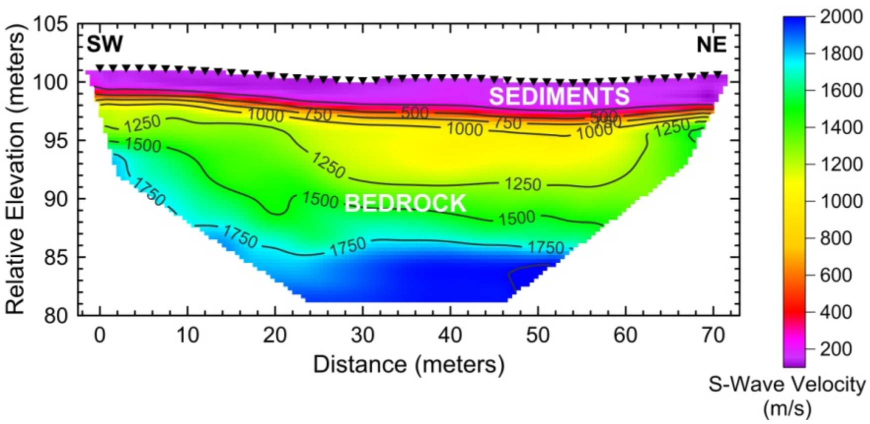

Fig. 8 – S-wave seismic refraction model for site CI.EML

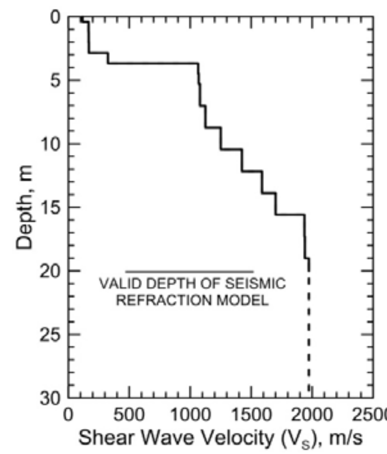

Fig. 9 – Average S-wave velocity structure between 24 and 46.5 m on seismic refraction model for site CI.EML

In retrospect, most sites that could only be characterized using the seismic refraction method are located at base of a hill, such as site CI.EML, or where sites have high-velocity and/or an irregular bedrock boundary at shallow depths. It is generally a fair assumption that velocity increases with depth in weathered crystalline-rock terrains, in which case, the velocity models can be expected to accurately reflect subsurface velocity structure. There is, however, a possibility that first-arrival data can be associated with out-of-plane refractors, which may result in seismic refraction models that overestimate time- or depth-averaged velocities. The presence of such geologic structure can also make S-wave refraction data very difficult to interpret, whereby resulting V_S models have significant error. Velocity inversions occur in some sedimentary rock terrains, which result in seismic refraction models that do not accurately reflect the intricate details of the subsurface velocity structure. Many of the CEUS sites are located on sedimentary rock and S-wave seismic refraction surveys often yielded high-quality S-wave first-arrival data. The resulting velocity models, however, often overestimated V_{S30} relative to velocity models developed from Love-wave dispersion data. Thus, care should be taken when using seismic refraction models for site characterization in such sedimentary rock environments.

3.2.4 Site characterization using MAS_LW technique

The MAS_LW technique was found to be more effective than the MAS_RW technique at a number of sites, and several examples are presented to demonstrate the need to have the MAS_LW technique available for site characterization. Station site CE.13929 (Riverside County Fire Station #68, Menifee, CA) was the first site where it was apparent that Rayleigh-wave based methods could not accurately characterize V_S structure. CE.13929 is located in a suburban area with moderate traffic along a nearby road. Based on nearby rock outcrop [1] and a 7.5-Hz HVSR peak (Fig. 3), subsurface geologic conditions consist of a thin sediment layer overlying crystalline rock.

Initially, P-wave seismic refraction and MAS$_R$W data were acquired along a 70.5-m-long array at the site. The P-wave seismic refraction model (Fig. 10) indicates weathered crystalline rock is located in the 5 to 7 m depth range. Weathering of the bedrock unit appears to decrease with depth with V_P exceeding 3,500 m/s at depths from 10 to 15 m. This type of velocity structure (low-velocity layer overlying a high-velocity layer at shallow depth) has been shown to excite a dominant Rayleigh-wave higher mode at low frequencies [43, 44]. At this site, the fundamental and/or first higher mode Rayleigh-wave dispersion curve cannot be reliably picked at low frequencies (Fig. 11). Thus, S-wave seismic refraction and MAS$_L$W data were subsequently acquired along a coincident array. The low signal-to-noise ratios of the S-wave seismic refraction data, due to significant noise from a nearby road, made the data less useful. The MAS$_L$W data, however, yielded a clearly identifiable Love-wave fundamental mode (Fig. 11). The V_S model derived from the inversion of the Love-wave fundamental mode dispersion data (Fig. 12) is constrained by the shallow (7 m) bedrock described for the P-wave seismic refraction model. The estimated V_{S30} is 565 m/s, which categorizes the site as NEHRP Site Class C. As is the general case with modeling of surface-wave dispersion data, bedrock velocities were not well constrained and multiple alternate (equivalent) V_S models were developed to demonstrate the non-uniqueness of the solution (Fig. 12). V_{S30} of these models varies from 555 to 568 m/s, demonstrating that V_{S30} is not sensitive to the non-uniqueness in the V_S models, as has been observed by others, e.g., [45, 46]. Based on this experience, S-wave seismic refraction and MAS$_L$W data were acquired at other sites where the fundamental or first-higher mode Rayleigh waves could not be clearly identified over a sufficient wavelength range to develop a V_S model to 30 m depth.

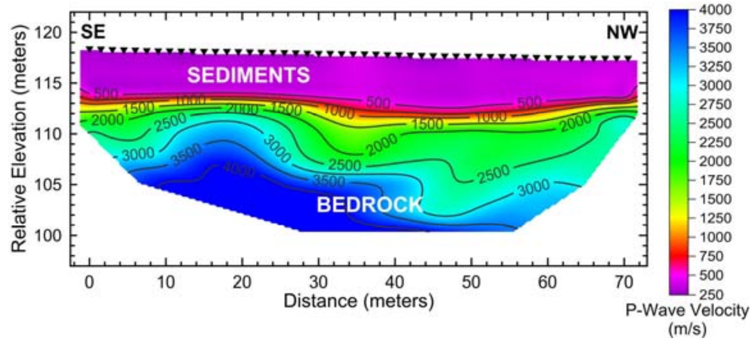

Fig. 10 – P-wave seismic refraction model for site CE.13929

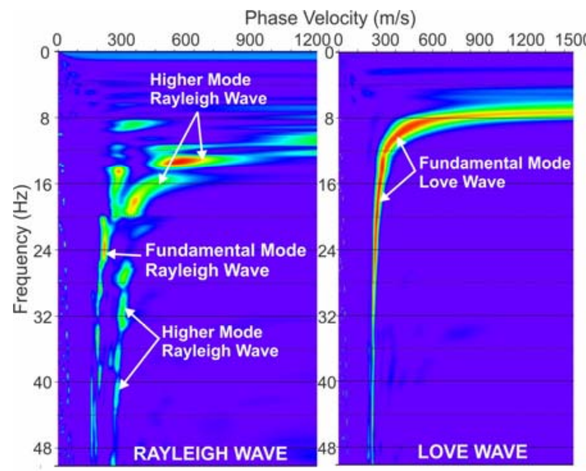

Fig. 11 – Comparison of Rayleigh and Love wave *f-v* transforms

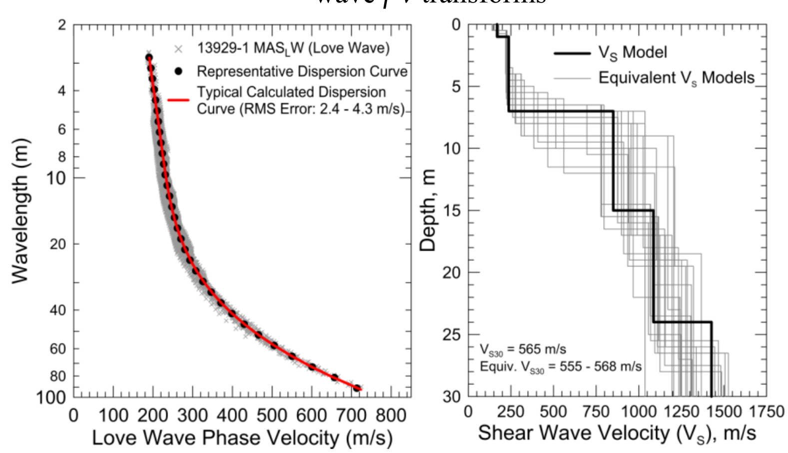

Fig. 12 – Field, representative and calculated Love wave dispersion data (left) and associated V_S models (right) for CE.13929

Another station site where MAS$_L$W proved more effective than the MAS$_R$W is CI.LJR (Lone Juniper Ranch, Gorman, California), which is located on top of a hill mapped as Mesozoic (Cretaceous) quartz monzonite [1]. The surface topography in the vicinity of the site is relatively smooth, implying that bedrock is intensely weathered. Field inspection revealed that residual soils overlie bedrock at the site and that rock outcrops are generally intensely weathered. V_{S30}, based on various proxy-based V_{S30} predictions [47-50], was expected to be in the 519 to 748 m/s range at this site. MAS$_R$W and P-wave seismic refraction data were first acquired along a 48-channel, 70.5-m-long array. Field review of the MAS$_R$W data indicated that higher

Rayleigh-wave modes are dominant over a wide frequency range and varied significantly with source offset (Fig. 13). Thus, MAS_LW and S-wave seismic refraction data were acquired along the same array, with the MAS_LW data yielding a dominant fundamental mode Love-wave (Fig. 13).

The S-wave seismic refraction model (Fig. 14) indicates that V_S gradually increases with depth and that high-velocity rock is not present in the upper 20 m, which is supported by a 1.6 Hz HVSR peak observed at the site. V_{S30} ranges from 317 to 332 m/s between the positions of 24 and 45 m, where the depth of investigation is greatest; a 5 percent variation in V_{S30} over a 21 m distance. The V_{S30} calculated from inverse modeling of the Love-wave fundamental mode dispersion data (Fig. 15) is 303 m/s. The scatter in the Love-wave dispersion data indicates that there is at least 5 percent variation in V_{S30} beneath the seismic line. V_{S30} is 323 m/s for the average V_S model between meters 21 and 48 m of the S-wave refraction model, about 6 percent higher in V_{S30} than that derived from the Love wave dispersion data. V_{S30} estimated from the seismic refraction and surface wave data is about 50 percent of that estimated using various V_{S30} proxies [47-50], demonstrating the importance of seismic site characterization. The V_S models developed from the Love-wave dispersion data and S-wave refraction data should excite a dominant fundamental mode Rayleigh wave, which was not observed in the field. We suspect that the higher mode Rayleigh waves are prevalent at this site because the fundamental mode Rayleigh wave is rapidly attenuated in low-V_S, near-surface residual soil layers that have a low seismic quality factor (Q).

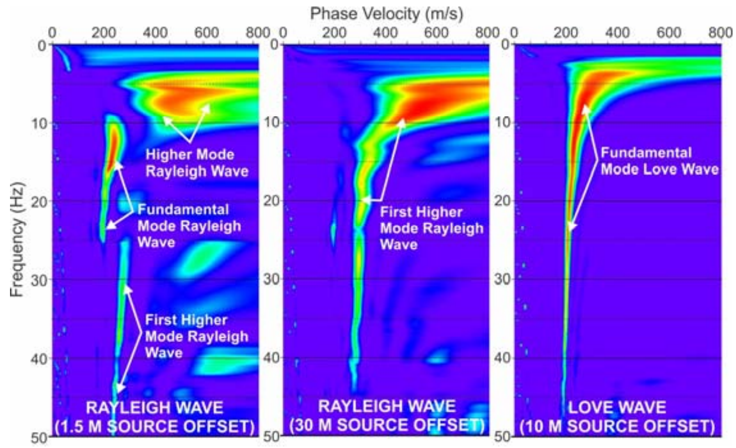

Fig. 13 – Comparison of Rayleigh (left and center) and Love wave (right) f-v transforms

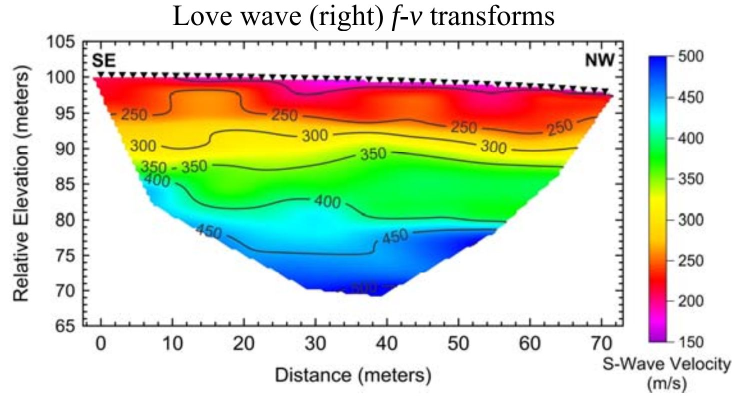

Fig. 14 – S-wave seismic refraction model for CI.LJR

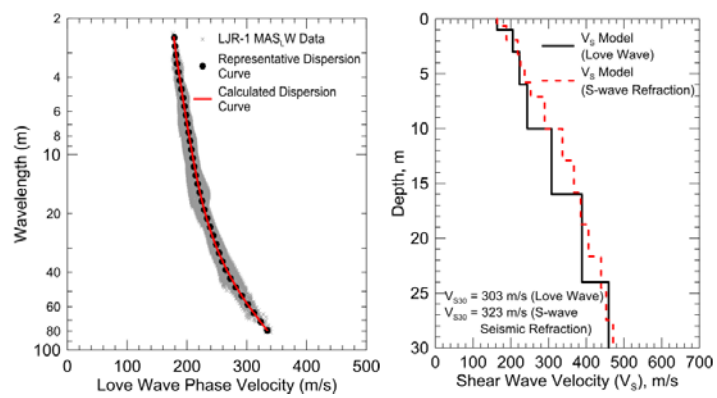

Fig. 15 – Field, representative and calculated surface wave dispersion data (left) and associated V_S models from Love wave and S-wave seismic refraction data (right) for CI.LJR

3.2.5 Site characterization requiring effective or multi-mode inversion of MAS_RW data

Effective- and/or multi-mode modeling of Rayleigh-wave dispersion data was useful at a number of sites with relatively shallow rock or steep velocity gradients. Field inspection of MAS_RW data at such sites generally revealed that Rayleigh-wave dispersion data were of sufficient quality for site characterization, and therefore, MAS_LW data were rarely acquired. Sites with high-velocity layers/velocity inversions can also require multi-mode modeling in many cases.

Station site US.ACSO (Alum Creek State Park, Delaware, Ohio) has a thin layer of sediments overlying Paleozoic shale, siltstone, and sandstone [1]. MAS_RW data were initially acquired along a 70.5-m-long array at this site. A P-wave refractor, at greater depth than could be imaged using a 70.5-m-long array, was identified on the seismic records from far-offset source locations; thus, MAS_RW and P-wave seismic refraction data were also acquired along a colocated 141-m-long array. Field inspection of Rayleigh-wave dispersion data indicated that they were of sufficient quality for site characterization. Preliminary analysis of Rayleigh-wave dispersion data indicated that the first higher mode Rayleigh-wave data might be dominant at low frequencies. To test this hypothesis, MAS_LW and S-wave seismic refraction data were subsequently acquired along 70.5- and 141-m arrays during a separate mobilization. Rayleigh-wave dispersion data were modeled using an effective mode inversion routine. Love-wave dispersion data were modeled using the fundamental mode assumption. V_S models developed from Rayleigh-wave effective mode inversion and Love-wave fundamental-mode inversion yielded similar V_S models. Fig. 16 shows the Rayleigh-wave dispersion data with the calculated effective-, fundamental- and first-higher modes (left plot) for the effective-mode V_S model (right plot). The figure also shows the V_S models resulting from fundamental-mode inversion of the Rayleigh- and Love-wave dispersion data. Equivalent V_S models are not presented, and it is important to note that there is significant non-uniqueness in the half-space depth and velocity (> 25%) because it is located near the maximum depth of investigation. V_{S30} is 421 and 523 m/s for the Rayleigh-wave-effective and fundamental-mode, respectively, and 413 m/s for the Love-wave-fundamental mode. At this site, V_{S30} would have been overestimated by 24 percent if the Rayleigh-wave data have been incorrectly modeled as fundamental mode. Although not presented, MAS_RW source locations that were offset from the northwest end of the array only yielded first higher-mode dispersion data. Without the source locations at the opposite end of the array and/or the Love wave data, this data set may also have been modeled as fundamental mode, resulting in overestimated V_{S30}, thus highlighting the importance of using reversed-source locations when acquiring MASW data.

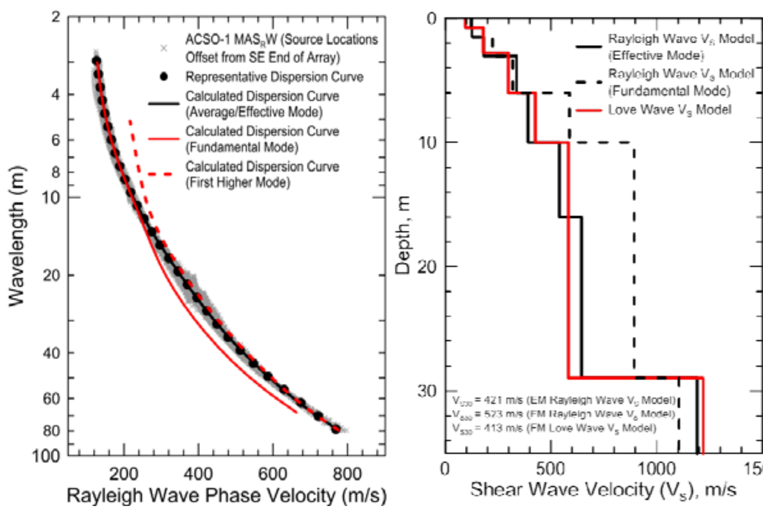

Fig. 16 – V_S models for seismic station US.ACSO

3.2.6 Observations of lateral velocity variability

One of the most significant challenges when characterizing rock and shallow-rock sites is lateral velocity variability. The effects of lateral velocity variation have been studied by [51, 52], with the primary goal of identifying segments of long seismic arrays with 1-D velocity structure. However, when characterizing seismic stations, MASW arrays are typically already at the minimum length required to model V_S to 30 m depth because there is often insufficient space for longer arrays. In the worst case of lateral velocity variation, it is not possible to construct a coherent Rayleigh- or Love-wave dispersion curve; thus, it is necessary to characterize the site using seismic refraction (or borehole seismic methods, when allowed). In fact, we recommend combined acquisition of seismic refraction and surface-wave data at rock and shallow-rock sites. Seismic refraction models are useful for quantifying the degree of lateral velocity variation beneath the array, and it is not unusual to observe upwards of 25 percent variation in V_{S30} over relatively short distances (several tens of meters). If lateral velocity variation is not too severe, it is possible to develop a dispersion curve over sufficient wavelength range for modeling, albeit there will be significant scatter in the curve. In this case, modeling the average dispersion trend will result in V_S models that are representative of the overall site conditions, even though the V_S model may not be representative of the actual velocity structure beneath any segment of the array. Depending upon if the lateral velocity variability is located near the surface or at greater depth, dispersion curves for forward and reverse source locations can diverge at either short or long wavelengths. The scatter in Rayleigh-wave phase velocity data at the 40-m wavelength (V_{R40}) and the empirical relationship between V_{S30} and V_{R40} (V_{S30} =

$1.045V_{R40}$), developed by [53], can also be used to quantify the overall variability of V_{S30} beneath the surface-wave array. However, it is important to note that this approach will underestimate the variability in V_{S30} because the V_{S30}-V_{R40} relation estimates the average V_{S30} beneath a segment of the array of sufficient length to extract 40-m-wavelength dispersion data, while applying the near-field criteria of [41]. The scatter in the dispersion data could also be used to define error bars, and global inversion routines could be used to develop an ensemble of V_S models that fit the dispersion data. Alternatively, V_S models could be developed that fit the upper and lower envelopes of the dispersion data. For the same reason as noted about the V_{R40} approach, these methods will likely underestimate the variation in V_{S30} beneath the array. Common center point SASW tests, which can image to 30 m depth with a maximum 30-m receiver spacing, can be effective in such environments. By comparison, MASW receiver arrays need to have a minimum length of 60 to 90 m to image velocity structure to 30 m depth. However, it would be useful to conduct a seismic refraction survey (S-wave or P-wave, if unsaturated) prior to the SASW sounding to identify an area with relatively 1-D velocity structure over a 30-m distance. Another field approach would be to acquire MASW data using longer arrays (e.g., 141 m array with 48 geophones spaced 3 m apart) and, when necessary, identify a 60-m or longer segment of the array with relatively 1-D velocity structure for MASW data analysis.

Station site CI.CHF (Chilao Flat Ranger Station, Los Angeles County, California), located on weathered Mesozoic granodiorite [1], was characterized using a 70.5-m-long MAS_RW and P-wave seismic refraction array. The P-wave seismic refraction model at this unsaturated, crystalline rock site shows clear lateral velocity variation in the upper 10 m (Fig. 17). The average V_P was calculated between the positions of 18 and 51 m, where the depth of investigation is greatest. Fig. 18 presents the average V_P model, along with the V_P models with the lowest and highest V_{P30} at the 42 m and 18 m positions (respectively), which reveal a 23 percent variation in V_{P30} beneath the central portion of the seismic profile.

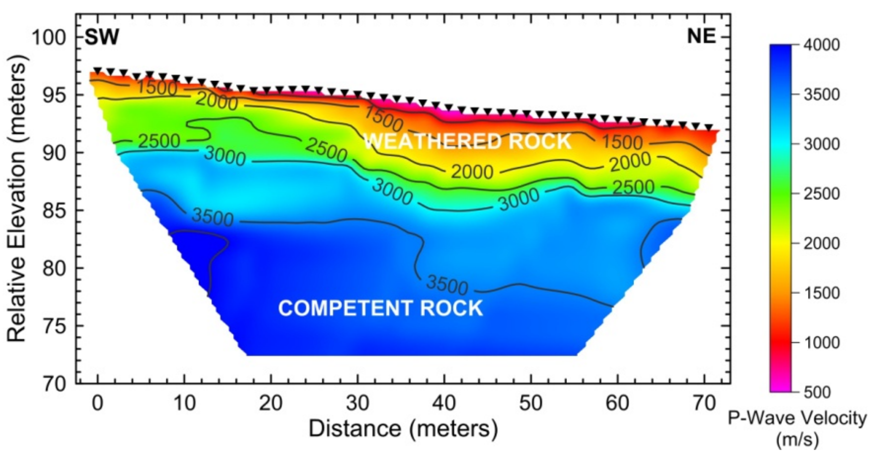

Fig. 17 – P-wave seismic refraction model for CI.CHF

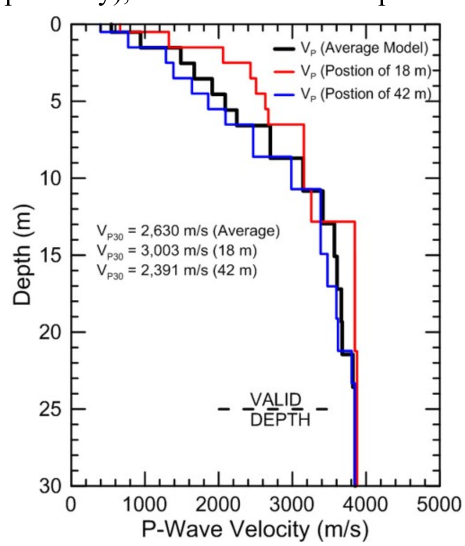

Fig. 18 – 1-D P-wave velocity models from seismic refraction model for site CI.CHF

At this site there is also visible lateral velocity variation in the seismic record from the center source location (Fig. 19) as shown in the *v-f* transforms from the forward and reverse segments of the seismic record (Fig. 20), where there is a 300 m/s difference in V_R at 75 Hz. Using 29 seismic records collected at this site from the combined MAS_RW and seismic refraction surveys (21 source locations with multiple source types used at near offset and center source locations), it was possible to extract 150 distinct dispersion curves associated with different receiver gathers (Fig. 21). A total of 50 to 75 dispersion curves were more typically used to characterize rock and shallow-rock sites and a total of 25 or fewer dispersion curves to characterize less-complicated soil sites. There is clear lateral velocity variation at $\lambda < 20$ m and a small difference in dispersion curves from forward and reverse source locations at $\lambda > 30$ m. Dispersion curves associated with receiver gathers confined to the southwest half of the array (furthest away from the seismic station) were not used for modeling. After removing these dispersion curves, a 100–150 m/s scatter in the dispersion data still remains. Fig. 21 also shows the need to use short-offset range receiver gathers during the data reduction process for complex sites. The *v-f*

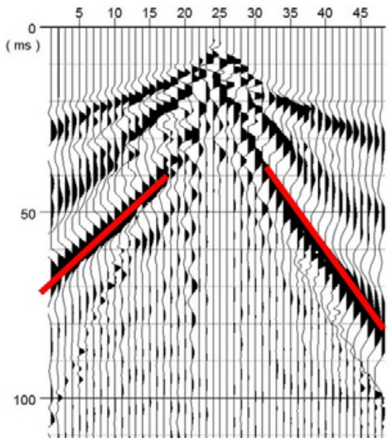

Fig. 19 – Center source location seismic record showing Rayleigh wave lateral velocity variation

transform using all 48 channels only yields dispersion data at $\lambda > 20$ m for this site, and only by utilizing a receiver gather with shorter offset range for the *v-f* transform was it possible to extract dispersion data at $\lambda < 20$ m. This data reduction strategy is not typically utilized when processing surface-wave data, but is necessary to develop a dispersion curve over a wide-frequency (or wavelength) range at sites with dominant higher mode energy and/or significant lateral velocity variability. Some seismic station sites only yielded fundamental mode dispersion data at $\lambda > 40$ m when the data were reduced using the full offset range (all seismic traces).. At some sites with significant lateral velocity variability, V_S models were developed to fit both the average and upper and lower envelopes of the dispersion data. The scatter in V_{R40} was also used to estimate the variation in V_{S30} beneath the array. At site CI.CHF, V_{R40} varies from about 895 to 995 m/s, implying an approximate 10 percent variation in V_{S30}, which is much less than the 23 percent variation in V_{P30} as indicated by the seismic refraction model.

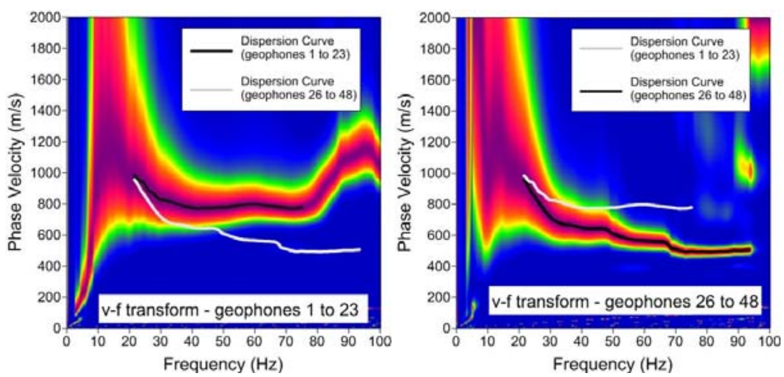

Fig. 20 – Comparison of Rayleigh wave *f-v* transforms from SW and NE sides of center source location

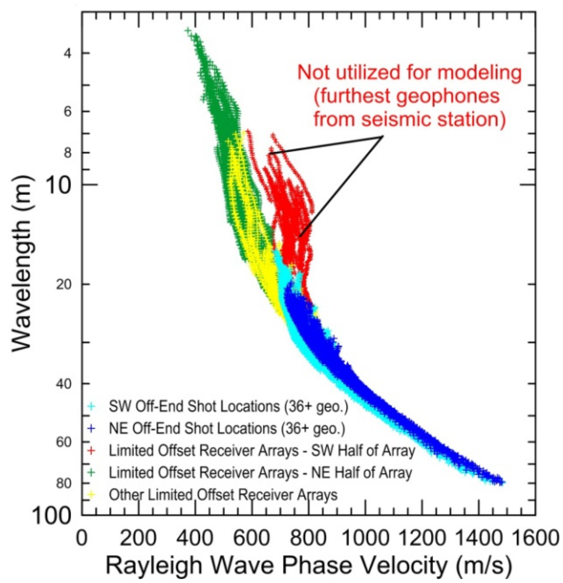

Fig. 21 – Rayleigh wave dispersion data from CI.CHF

3.3 Quaternary Sediment Site Observations

3.3.1 Background

Approximately 40 percent of the ARRA sites and 20 percent of the EPRI sites have a thick sequence of Quaternary sediments overlying Tertiary (or older) sediments and/or crystalline bedrock. These sites were generally much easier to characterize than rock and shallow-rock sites. All deep-soil sites were characterized using Rayleigh-wave methods, including the SASW, MAS_RW, and array microtremor methods. The array microtremor method was only applied at sites located in suburban and urban environments to meet the required 30-m depth of investigation and to extend the depth of investigation to between 45 and 100 m in many cases. Array microtremor measurements were made using both 2-D arrays (48-channel “L”-shaped array with 4.5-Hz geophones or 10-channel nested triangle array with 1-Hz geophones) and linear arrays (24 channel array with 4.5-Hz geophones). HVSR measurements were also made at each site.

The fundamental-mode Rayleigh-wave assumption was generally found to be valid at deep soils sites; although there were a number of cases where the presence of a stiff surface layer or shallow high-velocity layer required effective- or multi-mode modeling. Whenever possible, seismic refraction first-arrival data were used to constrain the approximate depth to the saturated zone, thereby increasing accuracy of the V_S model by use of realistic Poisson’s ratio in the model.

3.3.2 Site characterization using active-source surface-wave techniques

MAS_RW was the primary active-source surface-wave method used to characterize deep soil sites and was generally the only method needed to develop a V_S model at rural soil sites. SASW measurements were also made at 20 deep soil sites to demonstrate that the two methods are compatible. As an example, both MAS_RW and SASW data were acquired at site CI.PHOB (Hog Canyon #3, Parkfield, California), a rural site with surficial geology mapped as Pleistocene/Pliocene Paso Robles Formation [1] (alluvial conglomerate). All HVSR data are similar at this site and have a 0.35 Hz peak, indicating dominantly 1-D velocity structure and that bedrock is deeper than the 35 m depth of investigation. Surface-wave dispersion data from the SASW and MAS_RW datasets are almost identical, and therefore, a single V_S model was developed for the combined dataset (Fig. 22). There is no evidence of saturated sediments in the upper 30 m in P-wave seismic refraction data. Only a single V_S model was developed for this data set because V_S gradually increases with depth below 4 m, and an assessment of non-uniqueness is unnecessary in such a case. V_{S30} is 376 m/s; thus, the site is categorized as NEHRP Site Class C. The SASW and MAS_RW dispersion data are effectively identical, and either data set would have been sufficient to characterize the site. Similar observations were made at all combined MAS_RW and SASW data sets acquired for the ARRA project, with the exception of minor differences in dispersion curves likely associated with near-surface velocity variability.

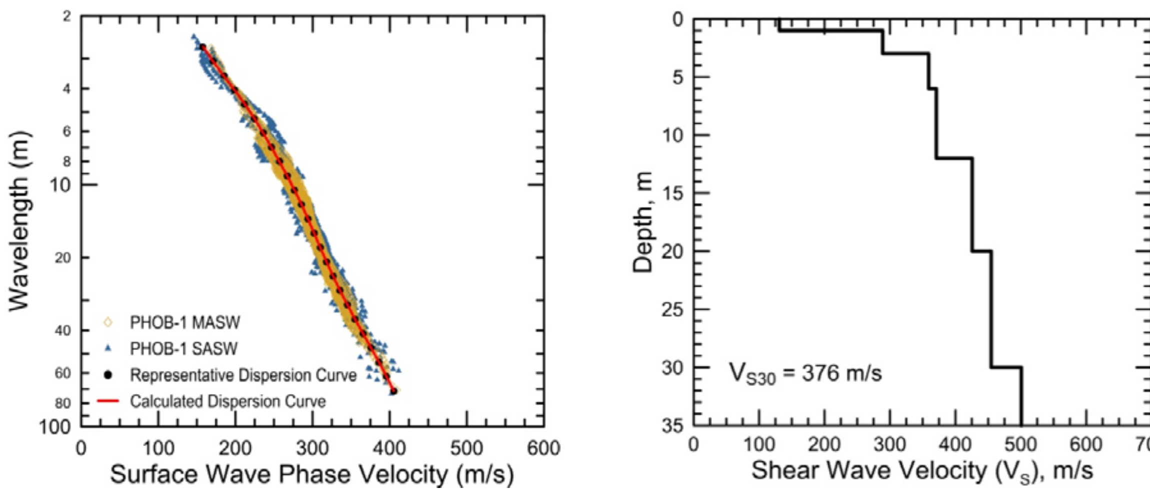

Fig. 22 – Field, representative and calculated surface wave dispersion data (left) and associated V_S model from MAS_RW and SASW data (right) for CI.PHOB

3.3.3 Site characterization using active- and passive-source surface-wave techniques

In urban and suburban settings, it is often difficult to use active-source surface-wave methods to image to 30 m depth using portable, cost-effective energy sources. Thus, when working in such environments active-source surface wave measurements should be supplemented by array microtremor measurements. The array microtremor method was utilized at 38 ARRA sites, primarily at deep sediment sites, but not at the rural EPRI sites. The array microtremor method was only utilized at sites where the multi-directional ambient vibration condition was thought to be sufficient. Further investigations are necessary to study the performance of the array microtremor method in environments thought to have unsuitable ambient vibration conditions.. Both linear and 2-D arrays were utilized at all sites where the array microtremor method was applied; thus, the performance of the linear arrays relative to the more reliable 2-D arrays can be assessed. The following sections describe case histories that demonstrate the types of geologic environments characterized using combination of MASW and array microtremor methods.

Station site CE.12076 (City of Coachella Fire Station #79, California) is typical of many of the sites where passive surface-wave methods were utilized. The site is located in a suburban area, underlain by a deep sedimentary basin with Holocene alluvium at the surface [1]; this geologic setting is also inferred by a 0.16-Hz HVSR peak. MAS_RW data were acquired using a 48-channel, 70.5-m-long array with multiple forward and reverse source locations and several interior source locations. Array microtremor measurements were made using a 10-channel (1-Hz geophones) nested equilateral triangular array with a side dimension of 60 m and a 24-channel (4.5-Hz geophones) linear array with 6-m geophone spacing (138 m total length). Approximately 40 minutes of ambient vibration data were acquired for each array. The linear passive array was also utilized to acquire additional MAS_RW data using an accelerated weight drop energy source. The passive surface-wave data, acquired using the triangle array, were reduced using the ESAC analysis method, and the passive surface-wave data, acquired using the linear array, were reduced using both the ESAC and ReMi™ methods. Dispersion data from all active and passive surface-wave datasets overlap in the 4.5- to 30-Hz frequency range and are in good agreement (Fig. 23). P-wave seismic refraction first-arrival data were used to constrain the saturated zone at the depth of 12 m. The depth of investigation is about 60 m, based on one-half of the maximum wavelength, and V_{S30} is 263 m/s (NEHRP Site Class D).

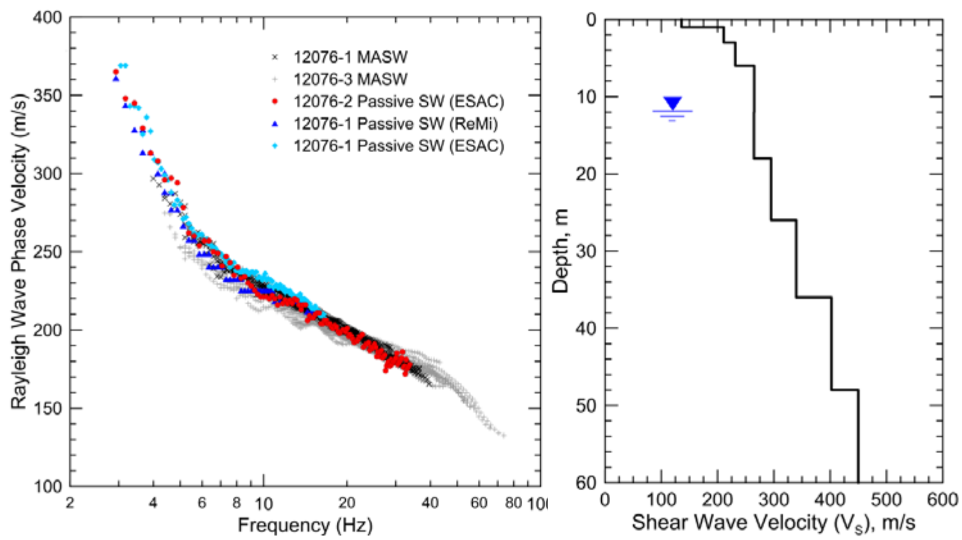

Fig. 23 – Rayleigh wave dispersion data from active and passive surface wave measurements (left) and associated V_S model (right) for CE.12076

The dispersion curve developed for the linear passive surface-wave array using the ReMi™ analysis approach is within about 5 percent of that estimated using ESAC. Both dispersion curves are in acceptable agreement with that developed using the nested triangle array. The agreement in the dispersion curves from the linear and 2D passive surface-wave arrays demonstrates that linear microtremor arrays can be effectively applied in some environments when it is not possible to deploy the more reliable 2-D arrays. However, there can be significant uncertainty in dispersion curves from linear passive arrays; thus, at a minimum, the linear method should not be used alone, but instead, coupled with MAS_RW dispersion data. When the two methods yield dispersion curves that are in good agreement in the overlapping frequency range, the passive surface-wave data from the linear array can be used to extend the depth of investigation. Additionally, increased confidence in the reliability of surface-wave dispersion data derived from a linear passive array could be realized when two data analysis methods (e.g. ReMi™ and ESAC) yield similar dispersion curves.

Station site CE.24967 (Marie Kerr Park, Palmdale, CA) is located on Holocene alluvium [1]; however, crystalline bedrock may be present within the expected depth of investigation of an active- and passive-surface-wave test, as indicated by an observed 2.1-Hz HVSR peak (Fig. 24). MAS_RW data were acquired using a 48-channel, 70.5-m-long array with multiple source locations offset from each end of the array and additional source locations along the array. Array microtremor measurements were made over an approximate 40-minute period using a 48-channel (4.5-Hz geophones) "L"-shaped array with 6-m geophone spacing.

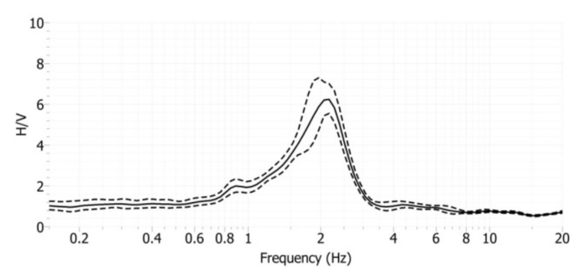

Fig. 24 – CE.24967 HVSR data

The passive surface-wave data acquired using the "L"-shaped array were reduced using the ESAC method, and the passive surface-wave data acquired along each linear leg of the "L" array were reduced using both the ESAC and ReMi™ methods. Dispersion data from all active and passive surface-wave datasets are in good agreement in the overlapping frequency/wavelength range (Fig. 25). The passive "L"-shaped array yielded surface-wave dispersion data to longer wavelengths than either of the linear arrays. P-wave seismic refraction first-arrival data provided no evidence of saturated sediments within 20–30 m of the surface, based on the absence of a 1,500 m/s, or greater, seismic refractor. The $V_{S,}$ model derived from the surface-wave dispersion data, is presented as Fig. 25. The velocity and depth of bedrock are not well-constrained in the V_S model. Because significant non-uniqueness is associated with depth to a sharp impedance contrast, multiple V_S models were developed with approximately equivalent dispersion curves, and the models show that bedrock depth can vary by ± 20 percent, which in our experience, appears typical for such velocity structures. The quarter-wavelength approximation predicts 2.1–2.3-Hz fundamental site frequency for the "equivalent" V_S models; thus, a joint inversion of the HVSR and surface-wave dispersion data may not significantly reduce the non-uniqueness associated with depth to bedrock. The depth of investigation is about 70–80 m, based on the one-third-maximum-wavelength criteria. V_{S30} is 330 m/s (NEHRP Site Class D).

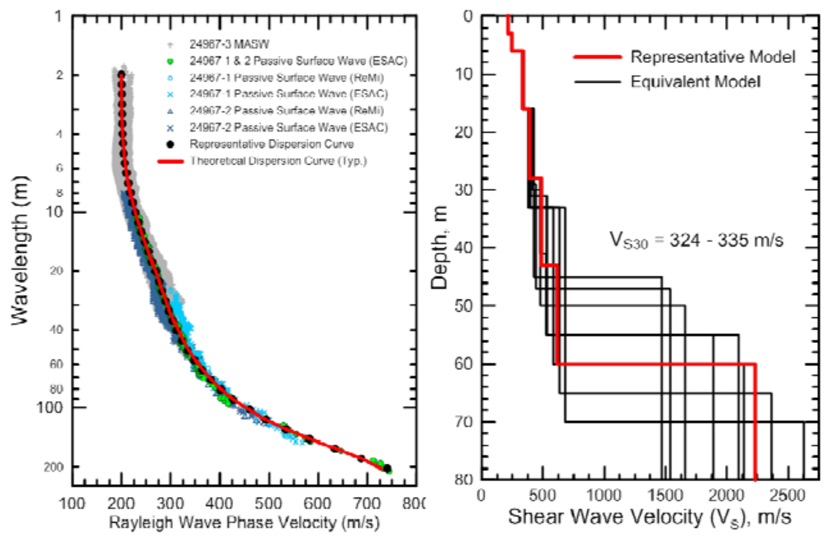

Fig 25 – Field, representative and calculated Rayleigh wave dispersion data (left) and associated V_S models (right) for CE.24967

4. Conclusions

A total of 224 seismic stations sites were characterized, encompassing a wide variety of geologic conditions in California and the CEUS, for the ARRA and EPRI projects. Active-source Rayleigh-wave methods (MAS_RW and SASW) were initially found to be effective at many sites; thus, these methods were used to characterize all California deep-sediment sites in rural environments, 65 percent of California rock/shallow-rock sites, all CEUS sites, and about 30 percent of GEO*Vision*-characterized CEUS sites. When characterizing sites using the MAS_RW method, multiple forward and reverse off-end source locations were found to be essential. Additionally, multiple energy sources and short-offset range receiver gathers allowed for the extraction of shorter wavelength surface-wave dispersion data. It was, nevertheless, difficult to characterize all sites using only active-source Rayleigh-wave methods. To extend the depth of investigation of active-source measurements to 30 m (and beyond), array microtremor methods were used at 38 California deep soil sediment sites located in urban and suburban environments. The fundamental-mode Rayleigh-wave assumption was not always valid, and it was necessary to apply effective- or multi-mode modeling routines in a number of cases. Active-source Love-wave methods were found to be more effective than Rayleigh-wave methods in certain geologic environments; thus, Love wave methods were used to characterize 25 percent of California rock/shallow-rock sites. Additionally, about 70 percent of CEUS sites characterized by GEO*Vision* used Love-wave methods. Several of the CEUS sites characterized using Love wave dispersion data could possibly have been characterized using a multi-mode Rayleigh-wave approach; however, the fundamental-mode inversion of Love-wave data was found to be less complicated to interpret. Significant lateral velocity variability was observed at many sites but primarily at rock and shallow-rock sites, resulting in variable degrees of scattering in surface-wave dispersion data. Lateral velocity variability can make it difficult to develop a coherent and continuous fundamental-mode dispersion curve for modeling, and as a result, alternate seismic methods may be needed to characterize the site. It is important to recognize that not all sites can be characterized using surface-wave methods. No attempts were made to characterize three ARRA seismic station sites due to unsuitable site conditions, and instead, alternate seismic station sites were selected to characterize. Unsuccessful attempts were made in characterizing one site, and instead an existing PS Suspension log was used for site characterization. S- and/or P-wave seismic refraction data were used to characterize about 10 percent of the rock/shallow-rock sites that could not be adequately characterized using surface-wave dispersion data.

In summary, the ARRA and EPRI investigations demonstrate that, although the MAS_RW and SASW methods can be used as primary methods for site characterization, other methods such as P- and S-wave seismic refraction, MAS_LW, SAS_LW, and array microtremor, should be available and utilized as necessary. At rock and shallow-rock sites, it has been observed that MASW surveys should be supplemented by seismic refraction surveys, which generally only require the addition of interior source locations. Seismic refraction models provide additional information on depth to rock and are useful for quantifying lateral velocity variability. By simply using a higher sample rate when acquiring MAS_RW data at deep sediment sites, it is possible to analyze P-wave seismic refraction first-arrival data and, thereby, constrain the depth to high Poisson's ratio, saturated sediments when modeling Rayleigh-wave dispersion data. The SASW method can be useful at sites with significant lateral velocity variation, as only a 30-m maximum receiver spacing is required to evaluate velocity structure to 30 m depth. In such cases, longer MASW arrays can also be considered, with the goal of extracting surface-wave dispersion data from a 1-D segment of the array. At sites with complex and difficult-to-interpret Rayleigh-wave dispersion data, we recommend using active-source Love-wave data and S-wave seismic refraction data. S-wave refraction data can, however, be difficult to interpret in some environments and care should be taken using S-wave refraction models in sedimentary rock environments where velocity inversions may occur. It is necessary to acquire microtremor data for HVSR analysis, particularly in shallow-rock environments, to estimate the site fundamental frequency, to demonstrate if the depth to rock is similar at the seismic station and beneath the surface-wave array, to demonstrate that the velocity structure is 1-D beneath the surface-wave array, and to identify shallow-rock sites that can benefit from Love-wave acquisition.

5 Acknowledgements

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