Revisiting levees in southern Texas using Love-wave multi-channel analysis of surface waves (MASW) with the high-resolution linear radon transform (HRLRT)

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Summary

The primary objective of this work was to determine compressional and shear velocity distribution within the body of five levees and any relationship to existing core taken from the levee and airborne EM data. Several different types of seismic data were recorded at each of the five levee sites, each of which possessed unique core and/or EM characteristics. Several seismic data-analysis techniques were appraised during our main efforts in 2004, including, P- and S-wave refraction, P- and S-wave refraction tomography, Rayleigh and Love-wave surface-wave analysis using multi-channel analysis of surface waves (MASW), and P- and S-wave cross-levee tomography. While the P-wave methods provided reasonable results, the S-wave methods produced surprising shear-wave velocity (Vs) properties. The reason for the latter effect is not clear; possibly the result of mode conversion, which is likely at sites with Poisson's ratio greater than 0.438. Furthermore, the Rayleigh-wave MASW method could not sample the levees due to lack of high-frequencies of the fundamental mode and complexities of higher modes and, as a result, there were no reliable Vs estimates for the levees. The most recent technological developments that included the use of the high-resolution linear radon transform (HRLRT) with the MASW method for imaging and Love wave inversion, encouraged us to revisit the analysis of horizontal-component data. The combined contribution of both techniques was essential to successfully obtaining Vs estimates that imaged to levees.

Introduction

The original research project was designed to evaluate the applicability of several seismic techniques to identify, delineate, and estimate the physical characteristics or properties of materials within and beneath levees (Ivanov et al., 2004). Several surface seismic measurements using state-of-the-art equipment were made and analyzed using many well-established methods and some that are in the research stage. These methods included: (P & S) refraction, (P & S) tomography (both 2D turning ray and 3D straight ray through levee), surface wave propagation, and surface wave (Rayleigh wave and Love wave) dispersion curve analysis (MASW).

Seismic data analysis in 2004 provided reasonable Vp estimates but did not provide reliable Vs results from either the refraction tomography (Figure 1) or the MASW method. Refraction tomography Vs values appeared unrealistically high (Figure 1b), most likely due to P-S mode-converted energy (Xia et al., 2002; Ivanov et al., 2004). Fundamental-mode Rayleigh wave observations did not possess high frequencies necessary to sample the very shallow part of the section including the levee even after applying various techniques (Park et al., 2002; Ivanov et al., 2005) for filtering higher mode energy (Figure 2). As well, some of the dispersion images from shear-wave data (Love waves) appeared encouraging with a well-developed dispersion curve from around 5 Hz to over 32 Hz, while others did not have high enough frequencies to sample the shallow levees (Figure 3) and was limited to dispersion curve 2D sections due to technological limitations at that time (Ivanov et al., 2004).

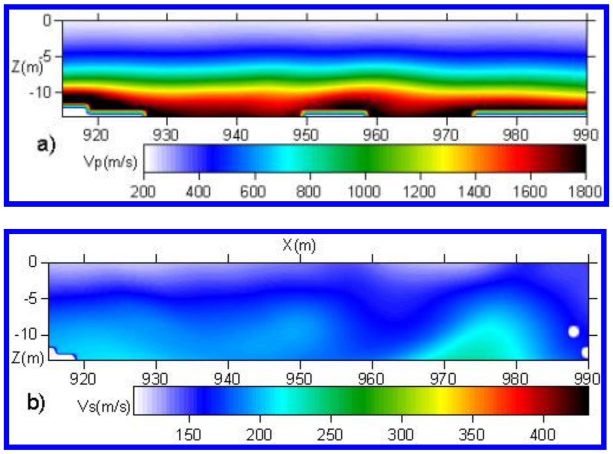

Figure 1. Refraction tomography solutions for the second levee site, a) P-wave and, b) S-wave.

Recent developments in the use of the high-resolution linear radon transform (HRLRT) for dispersion-curve imaging (Luo et al., 2008) and Love-wave inversion (Xia et al., 2012) encouraged us to revisit the application of the MASW method on acquired transverse horizontal component (i.e., SH) data from SH sources for estimating Vs from Love-wave analysis.

The MASW method was initally developed to estimate near-surface shear-wave velocity from high-frequency (≥ 2 Hz) Rayleigh-wave data (Song et al., 1989; Park et al., 1998; Miller et al., 1999b; Xia et al., 1999). Shear-wave velocities estimated using MASW have been reliably and consistently correlated with drill data. Using the MASW method, Xia et al. (2000) noninvasively measured Vs within 15% of Vs

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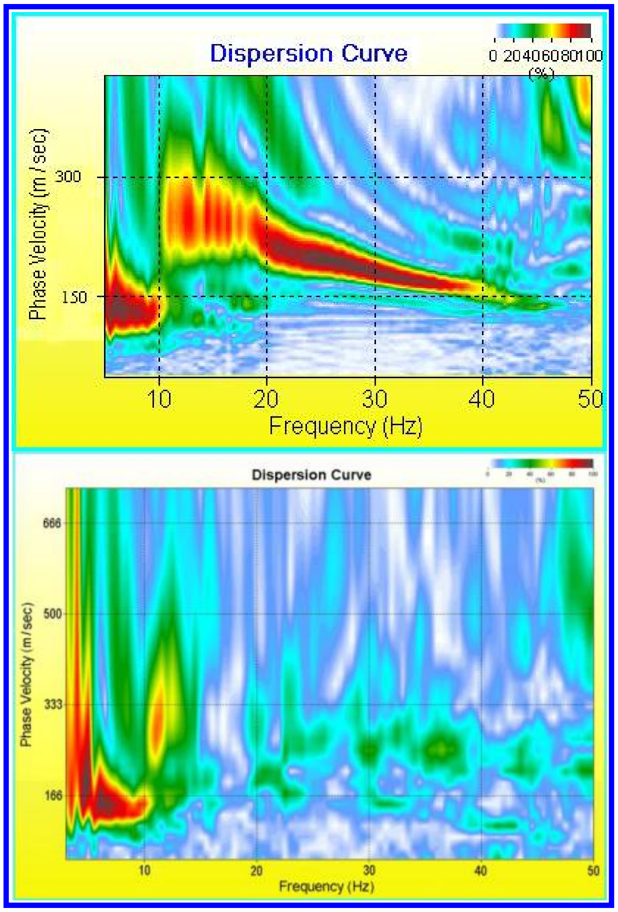

Figure 2. Rayleigh-wave dispersion curve images in the phase-velocity - frequency domain from a) raw data and b) after filtering higher mode energy.

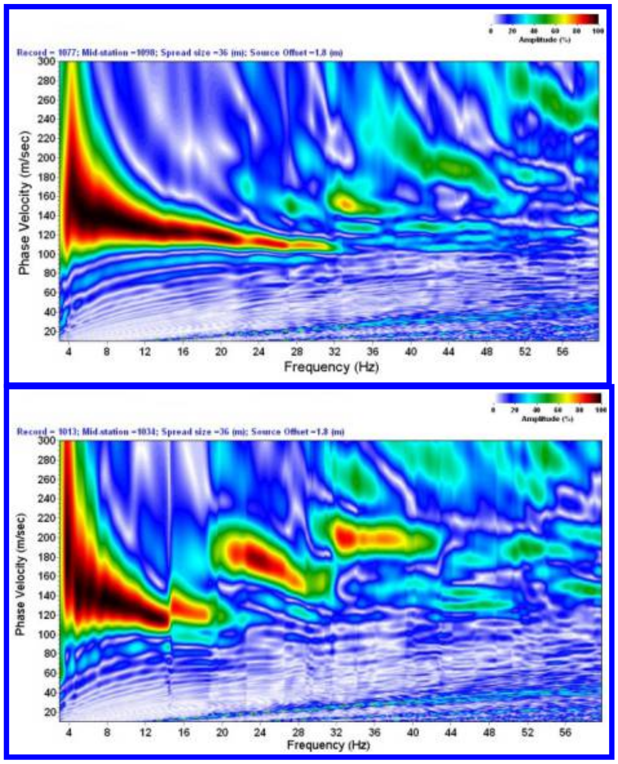

Figure 3. Love-wave dispersion curve images with a) and without b) high frequencies of the fundamental mode at ~120 m/s in the ~20-32 Hz range.

measured in wells. Miller et al. (1999b) mapped bedrock with 0.3-m (1-ft) accuracy at depths of about 4.5-9 m (15-30 ft), as confirmed by numerous borings.

The MASW method has been applied to problems such as characterization of pavements (Ryden et al., 2004), the study of Poisson's ratio (Ivanov et al., 2000a), study of levees and subgrade (Ivanov et al., 2004; Ivanov et al., 2006b), investigation of sea-bottom sediment stiffness (Ivanov et al., 2000b; Kaufmann et al., 2005; Park et al., 2005), mapping of fault zones (Ivanov et al., 2006a), study of Arctic ice sheets (Tsoflias et al., 2008; Ivanov et al., 2009), detection of dissolution features (Miller et al., 1999a), and measurement of Vs as a function of depth (Xia et al., 1999). Applications of the MASW method have been extended to determination of near-surface quality factor Q (Xia et al., 2013) and the acquisition of more realistic compressional-wave refraction models (Ivanov et al., 2006c; Ivanov et al., 2010; Piatti et al., 2013). A review of established approaches of surface wave methods (SWM) can be found in Socco et al. (2010). Most recent developments of the SWM include the expansion of the use of the horizontal component of the Rayleigh wave (Boaga et al., 2013), the simultaneous use of guided-waves with multi-mode surface waves in land and shallow marine environments (Boiero et al., 2013), and evaluation at landfill sites (Suto, 2013).

The MASW method is applied by performing the following steps. A single seismic-data record is acquired. These data are transformed into a dispersion-curve image (Park et al., 1998; Luo et al., 2009), which is used to evaluate a dispersion-curve trend(s) of the Rayleigh wave. This curve is then inverted to produce a 1D Vs model (Xia et al., 1999). By assembling numerous 1D Vs models, derived from consecutive seismic shot records, 2D (Miller et al., 1999b) or 3D (Miller et al., 2003) Vs models can be obtained.

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MASW analysis of SH data using the HRLRT transform allowed us to observe Love-wave fundamental mode in a wide and high-frequency range sufficient to obtain (after inversion) 2D Vs estimates that sampled the levees.

Data Acquisition

Seismic investigations were conducted at five levee sites located in the San Juan Quadrangle, Texas, USA (Figure 4). At each site, one 2D, two-component (2-C) profile was acquired along the crest and one at the toe of the approximately 5-m-high levees with a 1-to-3 slope on each side. Receiver station spacing was 0.9 m with two receivers at each location (10-Hz compressional wave geophones and one 14-Hz shear wave geophone). Shear-wave receivers were oriented to be sensitive to motion perpendicular to the axis of the levee (S_H). Sources tested included various sizes of sledgehammers and a mechanical weight drop, each impacting striker plates. The total spread length was 108 m with 120 channels recording compressional and 120 channels recording shear signals. Source spacing through the spread was 1.8 m for lines 1, 2, and 3, and 3.6 m for lines 4 and 5 with off-end shooting to extend a distance equivalent to the maximum depth of investigation. Each profile was acquired with the source in compressional-wave orientation and a second time with a shear-wave source orientation.

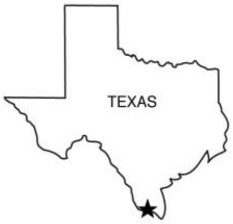

Figure 4. Location of the San Juan Quadrangle, Texas, USA.

Results

We reprocessed the shear-wave data using SurfSeis software developed by the Kansas Geological Survey. Initially we obtained dispersion curve images (Figure 3) using the conventional phase-shift method (Park et al., 1998) but parts of the profile lacked necessary high-frequencies of the Love-wave fundamental mode and the inversion failed to provide shallow Vs estimates for the levee (results not shown for brevity). Next we used the HRLRT for dispersion-curve images. For many of the dispersion curve images the HRLRT helped extend Love-wave fundamental-mode frequency range (Figure 5). In the latter example the ~6-14 Hz at 150-120 m/s fundamental mode was extended by ~14-52 Hz range. Furthermore, the HRLRT helped resolve the interfering patterns in the 14-20 Hz range (Figure 5b).

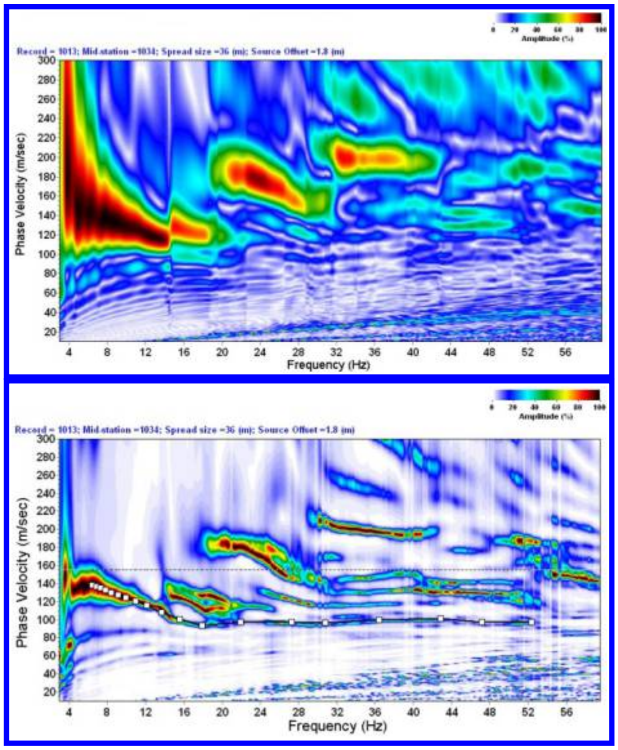

Figure 5. Love-wave dispersion curve images using a) the phase-shift method and b) the HRLRT. Dispersion curve picks between 20-52 Hz are intentionally a little bit above the fundamental mode energy for visualization purposes.

The obtained 2D Vs image from inverting Love-wave dispersion curves (Figure 6) was consistent with the geological expectations, showing a high-velocity anomaly between 2 and 4 m depth for the most part of the section, which was interpreted as the levee core. The Vs image also showed a few locations with low-velocity levee core anomalies, the most notable of which is between ~979-987 m X coordinates.

Love-wave Vs results supported our hypothesis from the 2004 evaluation that shear-wave refractions were influenced by P to S-wave mode conversions

These seismic data also demonstrated that Love waves can also lack fundamental-mode high frequencies (just like Rayleigh waves), contrary to the overall impressions from using synthetic and real-world data that Love-wave fundamental-mode generally spans a wide frequency range.

Notice that the HRLRT did not image the Love-wave fundamental mode in a very narrow range (~3-6 Hz) at the very low frequency end of the spectrum (Figure 5). There are various techniques to handle such situations but we did not resort to them because these low frequencies were important

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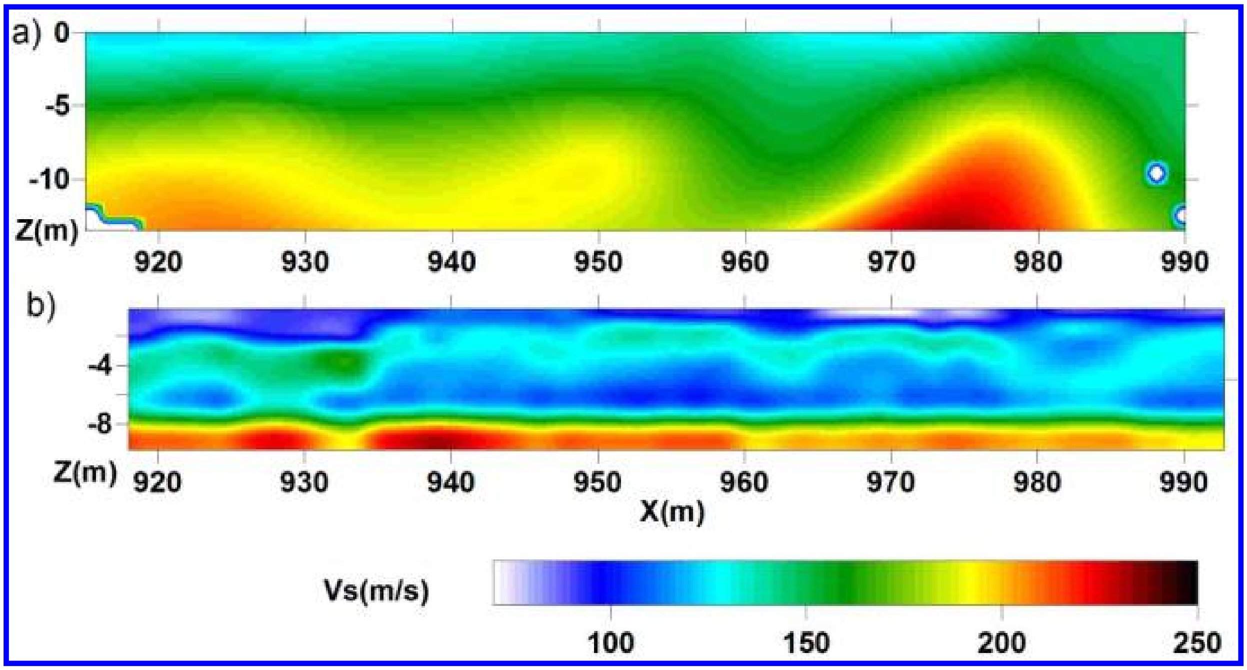

Figure 6. Shear-wave data Vs estimates from a) refraction tomography and, b) Love-wave inversion.

for imaging the deep parts of the section and were insignificant for imaging the shallow part of the section including the levees, which were the primary goal of our current efforts.

Reprocessing vertical component geophone data with the HRLRT for MASW analysis did not help observe fundamental-mode Rayleigh-waves at frequencies above ~20 Hz (images not shown for brevity), just like with the 2004 processing with the conventional dispersion curve imaging. We hypothesize that for the higher frequency range the Rayleigh-wave fundamental mode was not observed because it only had a horizontal component, i.e., it did not have a vertical component. Such a phenomenon was observed at low-frequencies for models with high-velocity contrast (Boaga et al., 2013) and we think that this could be possible for other models, including those from the Brownsville levees. Further research can clarify if this is the case for these velocity models.

Further research can also include the use of higher-mode Love waves and the application of the JARS method (Ivanov et al., 2006a; Ivanov et al., 2010) using 2D Vs models from the Love-wave inversion.

Conclusions

We managed to obtain Vs estimates for the Brownsville levees from the 2004 seismic data when only analyzing horizontal-component seismic data for Love waves and only when using both HRLRT (for dispersion curve imaging) and Love-wave inversion. Such an approach can be used for Vs studies of other levees and other sites at which the often preferable (for its ease of data acquisition) Rayleigh wave MASW method presents analysis challenges and at which other methods, such as shear-wave refraction tomography, provide unrealistic results.

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