Interrogating levees using seismic methods in southern Texas

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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 and airborne EM data. Several different types of seismic data were recorded at each of the five different levee sites, each site possessing unique core and/or EM characteristics. Several seismic data analysis techniques were appraised 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 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. Alternatively, these could be real and related to mechanical compaction and material distribution within the levees.

Introduction

This applied 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. Several surface seismic measurements using state-of-the-art equipment were made and were analyzed using many well-established methods and some that are in the research stage. These methods include: (P & S) refraction, (P & S) tomography (both 2-D turning ray and 3-D straight ray through levee), surface wave propagation, and surface wave (Rayleigh wave & Love wave) dispersion curve analysis (MASW).

The delayed-time method of first arrival/refraction analysis was attempted along the 2-D profiles at the crest of the levees to investigate potential variations in layer velocities (Vp and Vs) at the core/fill contact, core/native earth interface, and any discrete velocity contrast within the first 9 m below the base of the core along both crest and toe profile lines (Scott, 1973).

Turning-ray tomography was used to define Vp and Vs for subsurface cells filling the space between the levee/ground surface and 9 m below the base of the levee along the crest profile lines (Zhang and Toksoz, 1998).

Through-levee tomographies were acquired for both compressional and shear energy. A 2-D surface grid was designed with sources on one side of the levee and receivers on the other side relative to the levee centerline at two unique locations. Analysis relied on a relatively straightforward travel time delay technique analogous to crosshole tomography (Gaffran et al., 1999).

Multi-channel surface wave inversion techniques (MASW) have proven capable of detecting anomalous shear wave velocity zones within and below fill materials (Park et al., 1999).

Data acquisition

Seismic investigations were conducted at five levee sites located in the San Juan Quadrangle, Texas, USA (Figure 1).

At each site, one 2-D, 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 size 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.

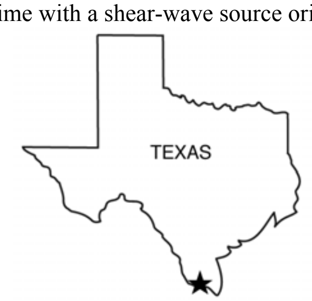

Figure 1. Location of the San Juan Quadrangle, Texas, USA.

This paper focuses the analysis on these two different data sets from each levee site. Each data set was processed using a variety of methods. The following is a list of each data type and the processing that has been done so far:

1. P-wave source, P-wave receivers—refraction (layer model defining each interval V_p and layer depth), refraction tomography (V_p for each subsurface cell), and MASW (shear wave velocity cross-section).
2. S-wave source, S-wave receivers—refraction (layer model defining each interval V_s and layer depth), Love Wave (dispersion, inversion, derivative), and refraction tomography (V_s for each subsurface cell).

At sites 1 and 2 a 3-D through-levee tomographic study was conducted to investigate internal variations in levee conditions (physical properties).

Results

As it turns out, even extremely advanced techniques and some clearly considered research were not able to define a unique shear-wave velocity that was consistent with current thinking on Vp/Vs ratios. Unconsolidated materials have Vp/Vs ratios that generally range from 3 to as much as 8. However, at all the levee sites the Vp/Vs ratios based on first arrival analysis are in the 2.1 to 2.6 range for the shallow portion (upper 4.5 m) of the levee (Figure 2).

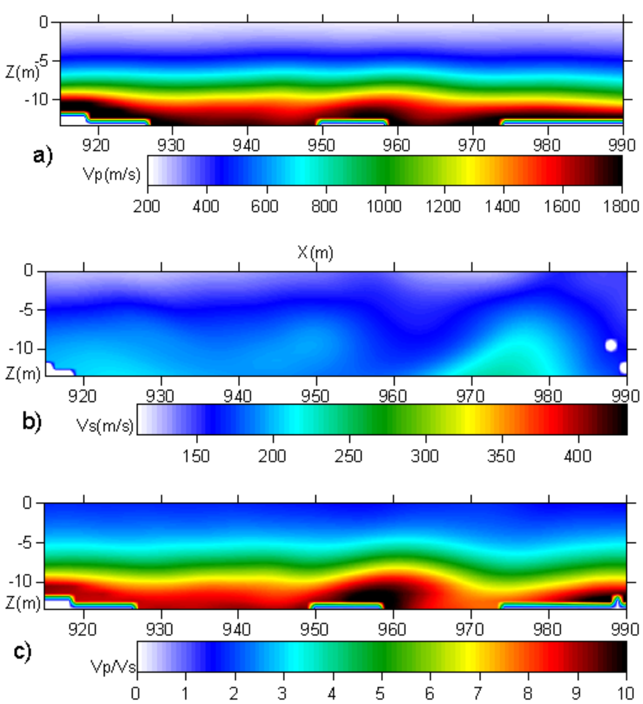

Figure 2. Refraction tomography solutions for the second levee site. a) P-wave, b) S-wave, and c) Vp/Vs ratio

From refraction tomography the following solution were obtained for cells within the 3.6 to 4.5 m range:

Line	Vp	Vs	Vp/Vs
1	1273	535	2.38
2	1310	514	2.54
3	1410	555	2.54
4	1070	496	2.16
5	1045	455	2.30

Vp/Vs at depths greater than 6 m increases to between 4 and 10, values much more consistent with the literature and laboratory measurements. A notable increase in P-wave velocity from just over 300 m/sec to over 1500 m/sec is likely indicative of the known change from sand to clay 5 m or so below the base of the levees.

Based on the velocity information and geology, it appears likely that the wavelets arriving at near offset on shear-wave records are energy that has gone through some kind of mode conversion where part of their travel path has been as a compressional wave and part as a shear wave; therefore, these energy wavelets arrive with an apparent velocity higher than the actual shallow shear wave velocity, but lower than compressional. This phenomenon is likely a direct result of the levee construction and material. Velocity inversions and extremely high Vp/Vs ratios could result in P-S mode conversions, which have resulted in the problems we are seeing here. P-S mode-converted energy such as the non-geometric P-S mode-converted waves (Roth and Holliger, 2000) is possible when Poisson's ratio exceeds 0.438 (Vp/Vs ratio greater than 3). Our measured Vp/Vs is unbelievably low, which could be an artifact of it actually being very high.

Looking now at the surface wave data recorded on the levee crest of these sites, it becomes quite clear that the fundamental mode on compressional-wave data is seriously deficient in frequencies above about 15 Hz (Figure 3).

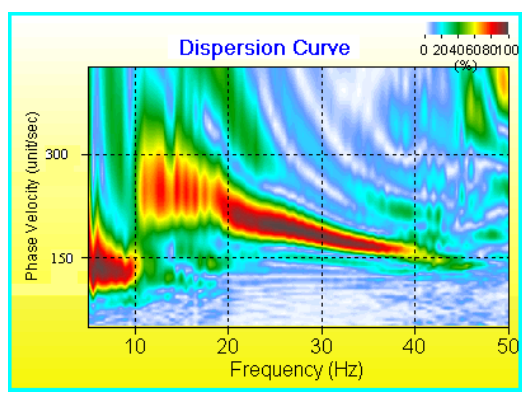

Figure 3. Rayleigh-wave dispersion curve analysis image of phase-velocity versus frequency domain.

All the surface-wave data with frequencies above 15 Hz are classified as higher mode. These higher modes do not travel in the same first order fashion as the fundamental and therefore cannot be inverted for shear-wave velocity using the same model constraints and assumptions possible with fundamental mode energy.

A variety of processing variations were attempted on the surface-wave data in further hopes of extracting higher frequencies. However all the fundamental mode energy is concentrated between about 8 and 12 Hz. Other surface wave energy is present with higher frequency content, but it is all clearly higher mode. A variety of processing techniques were attempted including filtering, f-k filtering, muting (Ivanov et al., 2001), higher mode filtering (Park et al, 2002), and increasing and decreasing the number of traces and therefore the offset and offset range. Based on MASW processing, 1-D shear velocity estimates have been made; however, with no reliable data above 12 Hz, no useful shear wave information was obtained within the upper 4.5 m of the levees using inverted surface wave energy.

To clearly discern the seismic contributions of the levee from the underlying native materials an equivalent set of seismic data were collected at the toe of each levee site approximately adjacent to the equivalent crest line. These data provide an excellent means of verifying technique consistency and differentiating where the various seismic wavefield characteristics originate. On toe data, unlike crest data surface-wave fundamental-mode energy was present within a wide range of frequencies (between about 6 and 42 Hz). Overlay of MASW measured 2-D Vs profiles from toe and levee show excellent correlation and clearly demonstrate the reliability of the method. As well, tomographic analyses of these data sets suggest native materials were mapped from both crest and toe and match well within expected errors.

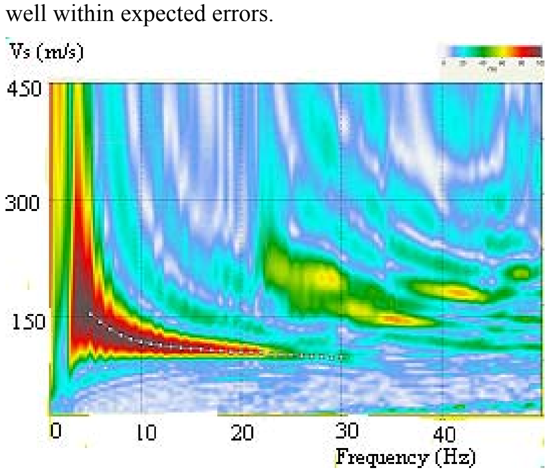

Figure 4. Love-wave dispersion curve analysis image of phase-velocity versus frequency domain.

Dispersion analysis on shear-wave data (Love waves) appears very encouraging with a well-developed dispersion curve from around 5 Hz to over 30 Hz (Figure 4). Unfortunately, like the higher mode Rayleigh waves, the methodology for inverting Love-wave dispersion curves has not been fully developed.

Considering broadband Love-wave dispersion curves that resulted from MASW analysis of the shear-wave data and our lack of the appropriate tools to accurately look at Love waves, only very general observations and correlations to geology are appropriate from shear surface waves (Love waves). Calculating and displaying the dispersion curve as a function of frequency, phase velocity, and offset provides a very interesting glimpse at the different characteristics of these levee sites. However, assuming that this type of data would likely be most sensitive to changes in the subsurface, a first derivative was taken to look at the gradient of the change (Figure 5). Interpreting this dispersion curve gradient relative to material or geology is not possible without more modeling, but it is encouraging that the anomaly on one of the lines is coincident with a trench cut in the levee to accommodate detailed mapping of internal levee structure and stratigraphy.

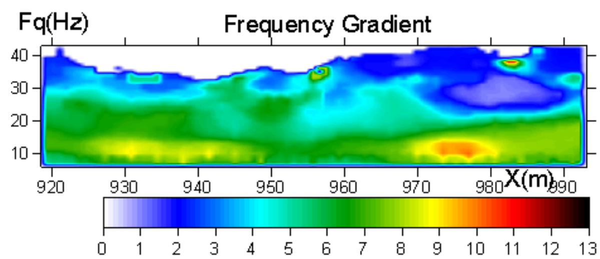

Figure 5. Love-wave dispersion curve spatial gradient.

The same phenomenon was observed on through-levee studies as with the 2-D surface data. Excellent compressional wave arrivals and what appear to be mode converted shear first arrivals noisy from surface wave (higher mode) interference (Figure 6) were also recorded. First arrivals are very difficult to pick on shear data, even after these polarized data have been reversed and opposing shots added to enhance shear and attenuate compressional. Shear wave velocity estimates are all higher than expected for a mechanically compacted earthen structure. With these expectations as a guide, the first arriving shear must be mode conversions that have traveled at least half the ray path as compressional energy.

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Conclusions

It appears extracting reliable Vs properties at the analyzed levee sites is not possible with commonly available methods, or the true S-wave velocity make-up of levees and other earthen structures is radically different than intuitively expected or predicted based on native material studies. Studying levees for Vs properties may require the development of levee-specialized seismic techniques.

Acknowledgements

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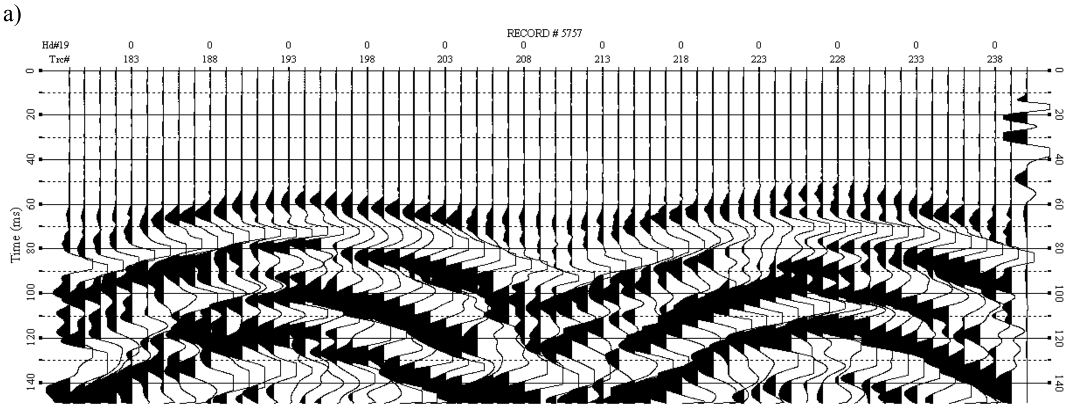

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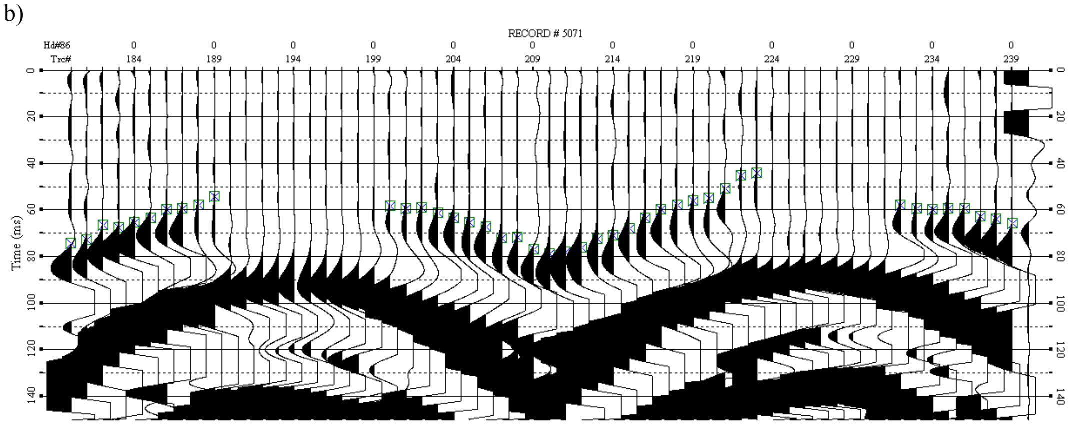

Figure 6. Cross-levee tomography traces: a) P-wave data, b) S-wave data. Source and receivers of both P- and S-wave records are at the same locations.