Time-lapse seismic study of levees in southern Texas

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Summary

The primary objective of this work was to measure changes in compressional- (Vp) and shear-wave (Vs) velocities in an earthen levee during a ponding experiment designed to simulate flood conditions on the Rio Grande in south Texas. Preliminary testing at five levee sites, all within a 10 km radius and each with unique physical, EM, and core characteristics, was completed and a single low-conductivity, highly fractured site was selected for investigation. Several different types of seismic data were recorded. Seismic data analysis techniques appraised included P- and S-wave refraction tomography and Rayleigh surface-wave analysis using multichannel analysis of surface waves (MASW). P-wave methods provided reasonable results, but no change was observed in velocity even after full pool had been maintained against the levee side for two days. The S-wave velocity change was rapid and isolated to one area within the confines of the pool. The reason for the latter effect cannot be uniquely determined; however, it may possibly be the result of an isolated variable expansion of the clay core, a likely explanation considering the preceding years of drought. Alternatively, these changes could be related to mechanical compaction variability and variable 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 changes in physical characteristics or properties of materials within levees during a simulated flood event. Several surface seismic measurements were taken using state-of-the-art equipment and analyzed using well-established and new research methods. These methods included P- and S-wave refraction tomography, surface-wave propagation, surface-wave dwell, and surface-wave (Rayleigh wave and Love wave) dispersion curve analysis (MASW).

Seismic investigations of this flood simulation were conducted at a levee site located in the San Juan Quadrangle, Texas, USA (Figure 1). This site was selected after evaluating five different levee sites, all within a 10 km radius.

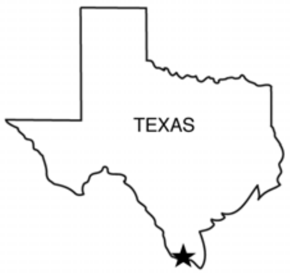


Figure 1. Location of the San Juan Quadrangle, Texas, USA.

A pond, approximately 20 m wide, was designed and built using earth material and a plastic liner on the south side of a levee segment, which had experienced expansion/contraction cracks due to years of drought. The pond was gradually filled with water from a nearby oxbow lake at a rate that simulated Rio Grande flood conditions.

Turning-ray tomography was used to define Vp 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).

Multichannel surface wave inversion techniques have proven capable of revealing anomalous shear-wave velocity zones within and below fill materials (Park et al., 1999; Xia et al., 1999). Surface-wave analysis provided the greatest reliability in shear-wave velocity determination in the levee.

Data Acquisition

Two 2-D, two-component (2-C) survey lines were deployed along adjacent edges of the levee road. The levee crest was approximately 6 m wide, while the levee itself was 5 m high with a 1-to-3 slope on each side. One line was on the south side, next to the pond, and the other was on the north side, 6 m away from the pond. 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 sensitive to motion perpendicular to the axis of the levee (S_H) (transverse). Sources tested included various sized 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 with off-end shooting out to a distance equivalent to the maximum depth of investigation. Each profile was acquired twice, once with the source in compressional-wave orientation and a second time with a shear-wave source orientation at each sampling time. Vibrator dwell experiments were run spherically to appraise the changes in phase and amplitude of surface waves with increased saturation.

Seismic data were acquired for both seismic lines (south and north) seven different times, at 12-hour intervals. Baseline data were acquired before the flooding test. After the artificial pond began filling with water, several different types of geophysical data were acquired other than seismic, including electrical resistivity and self potential (SP).

This paper focuses on the analysis of compressional-wave data sets from each time slice. Each data set (P and S) was processed using a variety of methods. The following is a list of each data type and the processing completed so far:

1. P-wave source, P-wave receivers—refraction tomography (compressional-wave velocity for each subsurface cell), and MASW (shear-wave velocity cross-section).
2. S-wave source, S-wave receivers—refraction tomography (shear-wave velocity for each subsurface cell).

Compressional-wave data were processed using both first-arrival measurements and dispersion analysis of the surface wave to extract 2-D Vp and Vs profiles.

Results

The ponding test was done at a fracture-suspect area interpreted from a resistivity survey and core data. The MASW technique was appraised by evaluating the ability of the method to estimate the dispersion curve of the fundamental mode of the Rayleigh wave from compressional-wave data recorded on the levee crest (Figure 2). The fundamental mode of the surface wave was well defined within a wide frequency range from 5 to about 50 Hz. In view of the refraction nonuniqueness problem (Ackerman et al., 1986; Burger, 1992; Ivanov et al., 2005), the MASW method was considered to be more reliable for estimating Vs in comparison with S-wave refraction tomography. An MASW survey, performed before the test, was designed to acquire an initial 2-D Vs section necessary for reference or baseline (Figure 3a). An anomalous lower-velocity zone can be observed within the levee body at a depth of about 2 to 5 m between locations 950 and 955 m.

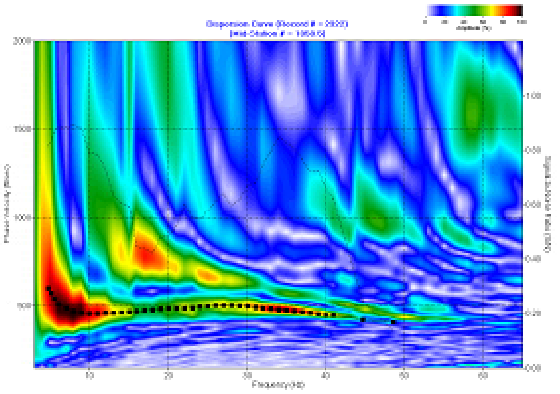
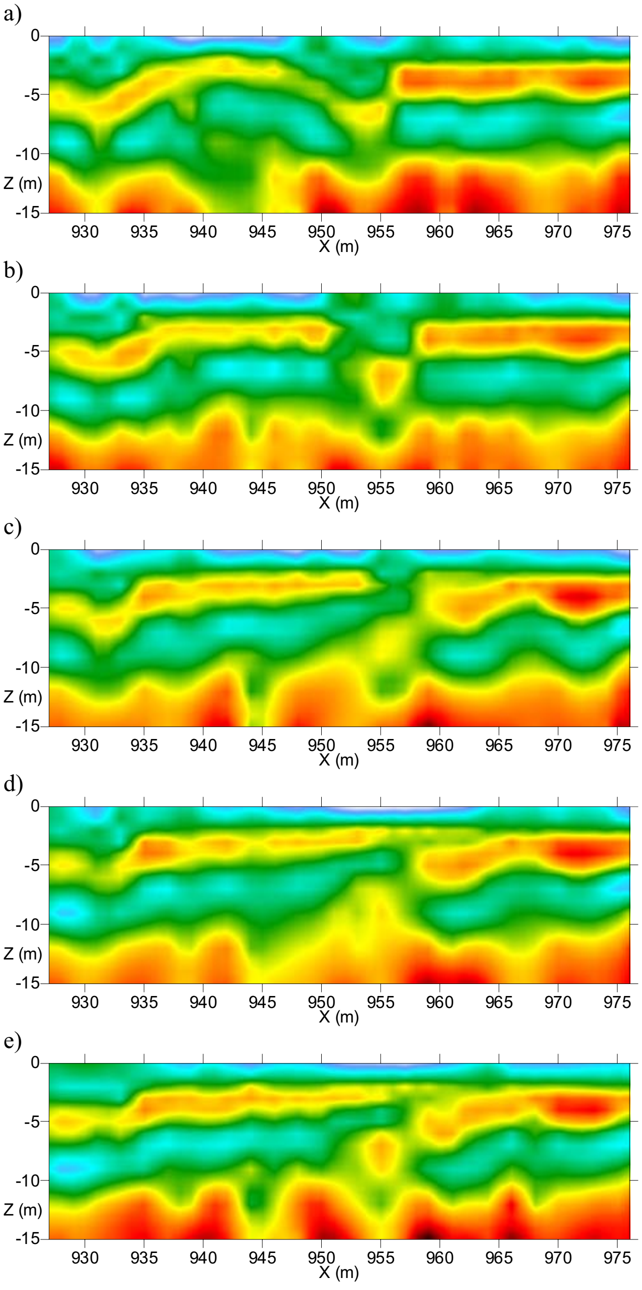


Figure 2. Rayleigh-wave dispersion curve analysis image of phase-velocity versus frequency domain.



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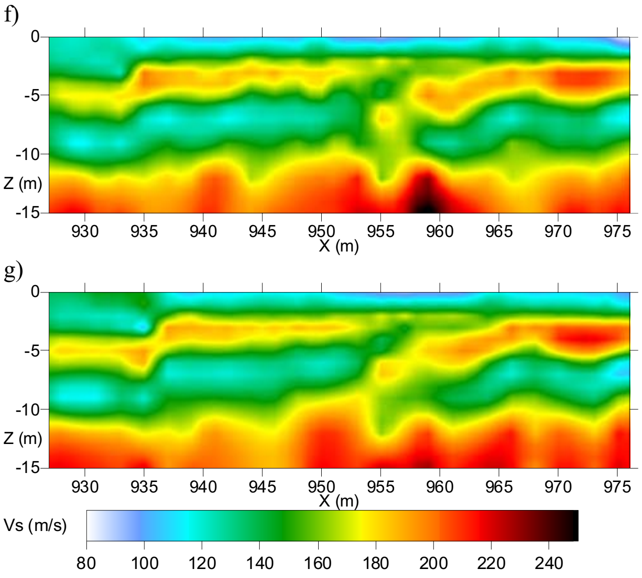
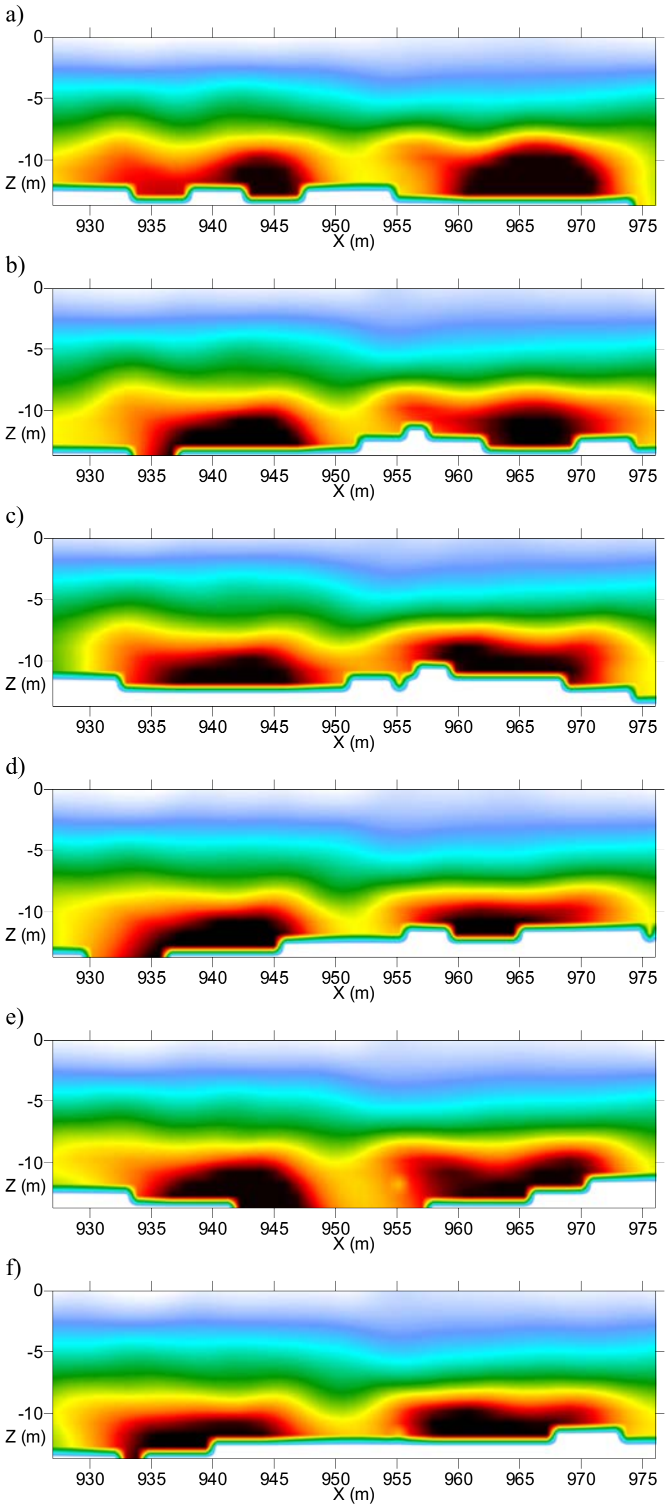


Figure 3. MASW Vs solutions for seven time slices estimated at 12-hour intervals after the beginning of the test at the south seismic line.

At time slice 2, 12 hours after the start of the water fill, change is observed in the shear-wave properties about 5 m below the surface at about horizontal location 950 m (Figure 3b). After 12 more hours, at time slice 3, as the water level approached the top of the levee, the shear-wave velocity of the levee core (2 to 4 m below the surface) starts to increase at horizontal locations between 950 and 955 m (Figure 3c). After another 12 hours, at time slice 4, the water level reaches the maximum levee capacity and the previously low-velocity zone has reached a shear-wave velocity similar to other parts of the levee (Figure 3d). A possible explanation for the observed phenomena is that the water flooding into the relatively drier clay section of the levee caused the clays to expand and fill in the existing cracks, which in turn increased the stiffness of the levee-core material and its shear-wave velocity. Maintaining the water level high during the next 36 hours, represented by time slices 5, 6, and 7, does not correspond to a significant change in levee properties (Figures 3e, 3f, and 3g).

Refraction-tomography analysis was performed at the site in an effort to detect relative changes in the Vp properties due to the water-flooding experiment, regardless of the refraction nonuniqueness problem. Refraction-tomography Vp analysis of the south line suggests compressional-wave velocity is not sensitive to the material changes that occurred in this segment attributed to the ponding (Figure 4).



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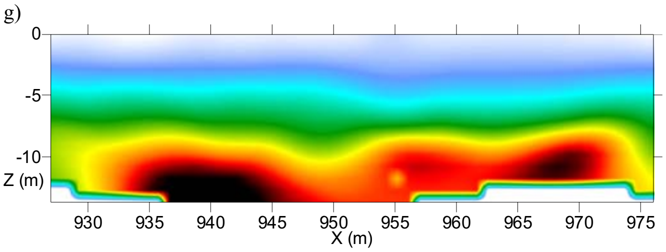

Figure 4. Refraction tomography Vp solutions for the seven time slices estimated at 12-hour intervals after the beginning of the test at the south seismic line.

Conclusions

Shear-wave velocity, as calculated from surface-wave energy using the MASW method, apparently changed in response to increased levee saturation caused by water infiltration during the flood simulation. This inflow, however, did not cause any noticeable changes in the compressional-wave properties of the levee material. Vs was the property most significantly affected by the increased saturation and the material property most sensitive to changes occurring during the levee ponding experiment.

One possibility for the lack of expected change in compressional-wave data relates to percentage of saturation and effect on compressional-wave velocity. The clay core may have become re-saturated during the rain events of the months preceding this study but after the initial geophysical survey (Dec. 2003). If the levee core was reasonably well saturated after the wetter-than-usual fall, changes in saturation resulting from flooding might not have affected compressional-wave velocities.

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