Time-lapse seismic study of levees in southern New Mexico

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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 New Mexico. Although similar to such experiment, performed an year earlier on the Rio Grande in south Texas, the levee seismic response results are different. This work was similar to previous Preliminary testing at three levee sites, all within a 1 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- refraction tomography and Rayleigh surface-wave analysis using multichannel analysis of surface waves (MASW). P-wave velocity change (decrease) was rapid and isolated to one section within the pool confines, which already had anomalously high velocity most likely related to burrowing animals modification of the levee structure. S-wave velocity change was gradual and could be observed along the whole width of the pond within and below the levee. The results within the levee sand core were consistent with the observations of sand S-wave velocity changed due to saturation.

Introduction

This work is a continuation of an applied research project that 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 La Mesa Quadrangle, New Mexico, USA (Figure 1). This site was selected after evaluating five different levee sites, all within a 1 km radius.

A pond, approximately 30 m wide, was designed and built using earth material and a plastic liner on the south side of a levee segment, which had experienced invasion from small mammals leaving burrows 0.07-0.10 m in diameter. The pond was gradually filled with water from the Rio Grande river at a rate that simulated flood conditions.

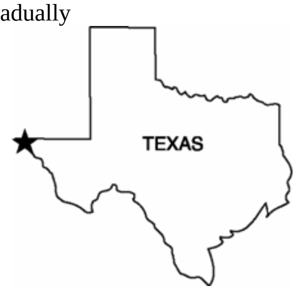

Figure 1. Location of the La Mesa Quadrangle, New Mexico, USA.

Turning-ray tomography was used to define Vp for sub-surface 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.

The seismic response results were different from the similar experiment performed an year earlier on the Rio Grande in south Texas (Ivanov et al., 2005a), which can be explained with the different earthen material used to build the levee cores (sand vs. clay).

Data Acquisition

A 2-D, compressional-wave geophone survey line was deployed along the edge of the levee road toward the pond. The levee crest was approximately 6 m wide, while the levee itself was 3 m high with a 1-to-3 slope on each side. The line was on the south side, next to the pond. 10 Hz compressional-wave geophones were spaced at 0.6 m

Sources tested included various sized sledgehammers and a mechanical weight drop, each impacting striker plates. The total spread length was 72 m with 120 channels recording compressional signals. Source spacing through the spread was 2.4 m with off-end shooting out to a distance equivalent to the maximum depth of investigation. Vibrator dwell experiments were run spherically to appraise the changes in phase and amplitude of surface waves with increased saturation.

Seismic data were acquired nine different times, at 4-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 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—
   a. refraction tomography (compressional-wave velocity for each subsurface cell), and
   b. MASW (shear-wave velocity cross-section).

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 field observations of burrows produced by small mammals. In view of the refraction nonuniqueness problem (Ackerman et al., 1986; Burger, 1992; Ivanov et al., 2005b), the MASW method was considered to be more reliable for estimating Vs in comparison with S-wave refraction tomography. 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).

At the time of the ponding experiment the fundamental mode of the surface wave was well defined only within a narrow frequency range 5-18 Hz and was difficult to interpret at higher frequencies, especially above 30 Hz. Because of that the V_s estimates for the top 1.5 m of the levee have lesser degree of confidence and need to be regarded with caution.

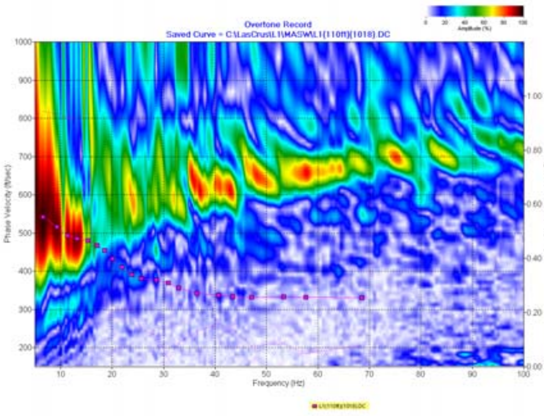

Figure 2. Rayleigh-wave dispersion curve analysis image of phase-velocity versus frequency domain.

An MASW survey, performed before the test, was designed to acquire an initial 2-D Vs section necessary for reference or baseline (Figure 3, top section). Two anomalous high-velocity zones can be observed within the levee body at a depth of about 2 m between locations 638 and 641 m, and 654 and 658 m. At time slices 2 and 3 (Figure 3, 2nd and 3rd sections from the top), 4 and 8 hours after the start of the water fill, change is observed in the shear-wave properties and the high-velocity anomalies start disappearing. As the flooding simulation continues at time slices 3, 4 and 5 (corresponding image numbers from top of Figure 3) the V_s values within the levee continue to decrease with about 10-15 %. At the same time a low-velocity zone begins to form between horizontal locations 639 and 643 m. This trend continues at time slices 6and 7, and at time slices 8and 9 the low-velocity anomaly is well established. It probably represents ground water movement under the levee. Such water movement may cause subsurface erosion, which can potentially weaken the levee subgrade sufficiently for failure to occur. Observation of such anomalies meets one of the objective of the survey, which is to detect old streambeds running under the levees that can become weak spots during flooding.

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. The base line survey revealed a high-velocity Vp anomaly at the burrowed area between locations 646 and 657 m. This anomaly rapidly disappeared with depth at the start of the flooding experiment and could still be observed only at the very top 1 m of the levee. Refraction-tomography Vp results for the rest of the line suggests compressional-wave velocity is not sensitive to the material changes that occurred in this segment attributed to the ponding (Figure 4).

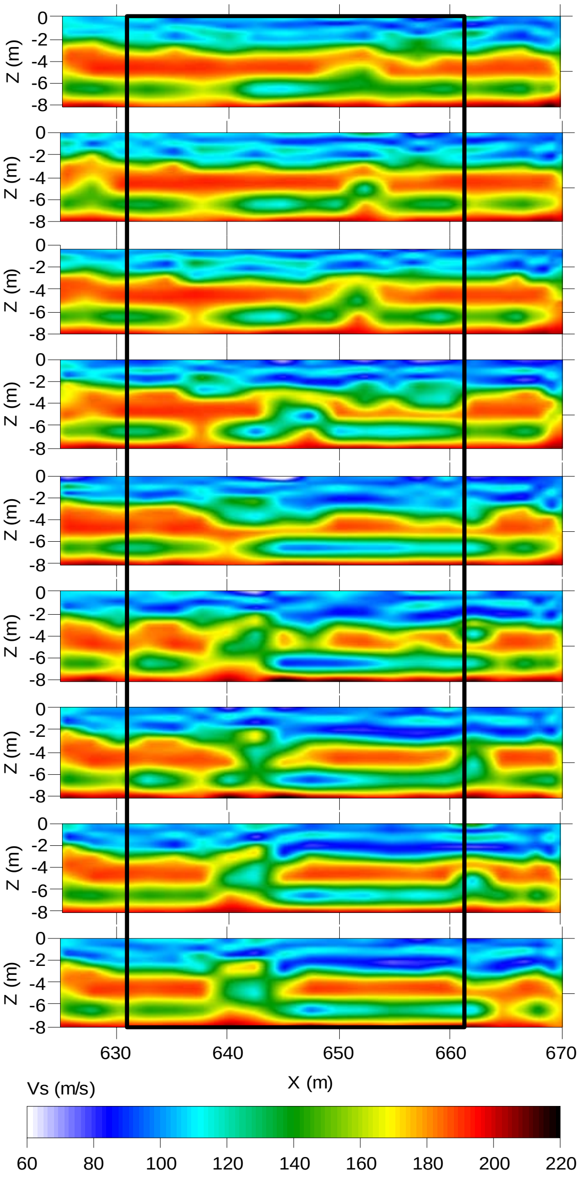

Figure 3. MASW Vs results at the top of the levee next to the pond for nine time slices estimated at 4-hour intervals after the beginning of the test with the initial survey at the top and the last survey at the bottom of the display. The pond location is indicated by the thick lines.

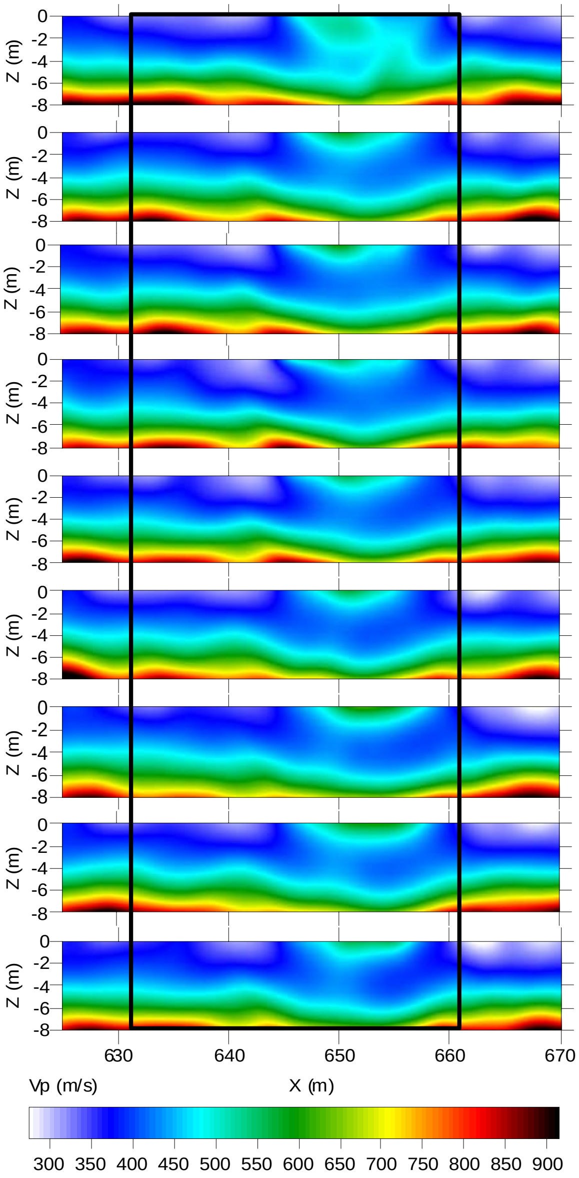

Figure 4. Refraction tomography Vp results at the top of the levee next to the pond for nine time slices estimated at 4-hour intervals after the beginning of the test with the initial survey at the top and the last survey at the bottom of the display. The pond location is indicated by the thick lines.

Conclusions

Shear-wave velocity, as calculated from surface-wave energy using the MASW method, apparently changed in response to increased saturation below the levee 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 except for small area withing the levee affected by burrowing. 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.

In general, both compressional- and shear-wave velocity estimates for these type of sand made levees indicate that changes in saturation resulting from flooding might lead to lower Vp and Vs values and thus in effect decrease levee strength.

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