

Near surface void detection using seismic Q-factor Waveform Tomography

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January 20, 2008

(to be submitted to the EAGE Annual Meeting, Rome, June 2008)

Summary

Several shallow, engineering-scale seismic surveys were carried out in Seven Sisters, Manitoba, between 1999 and 2001. The surveys were designed to locate three buried rip-rap targets, located within a constructed clay embankment as a blind test of geophysical imaging methods. While previous studies used near-offset reflection methods to image the targets, in this paper we use Waveform Tomography of the long-offset, refracted arrivals to image the seismic velocity and the seismic attenuation. The refraction surveys were carried out with a 2 m spacing on both source and receiver positions, with 70 source positions and 48 receiver positions respectively. The targets were buried approximately 7 m below the surface of the constructed embankment. Using weight-drop data, with frequencies between 20 and 130 Hz, we were able to resolve the sub-wavelength targets using the seismic-Q images. A very good fit between model and observed data is an indication of the reliability of the results.

Major Objectives Our objective was to demonstrate the feasibility of Waveform Tomography in locating defects and other anomalies within earthen embankments, for targets located at several metres depth. Waveform Tomography is an advanced method for imaging from refracted waveform data. The method shows some promise in this application, and the experiment also may be viewed as an analogue model of much larger scale applications in seismic exploration and production.

New Aspects Covered The method of Waveform Tomography is used here for the first time in shallow seismic refraction work. Moreover, the imaging of seismic-Q is also used here for the first time in this context. The experiment is an example of successful data fitting of complex seismic waveform data in an environment with high attenuation, and poor signal-to-noise ratios.

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Introduction

Several shallow seismic datasets were collected in 1999 through 2001 on an engineered clay embankment at Seven Sisters Falls, Manitoba. The effort represented a blind test of seismic imaging methods using a real constructed embankment. If successful, the methodology could be applied to assessing the state of existing embankments and planning repair efforts. The data collection was carried out by Hayles GeoScience Surveys Ltd., and the project was sponsored by Manitoba Hydro (Hayles *et al.*, 2005).

The test embankment (Figure 1) contained three targets composed of granitic rip-rap. Previous studies (Zantout, 2005; Hayles *et al.*, 2005) dealt primarily with conventional reflection processing of short-offset data. In this paper we describe the inversion of a long-offset refraction dataset recorded at the site, using a low-frequency weight drop source.

Waveform Tomography (Pratt *et al.*, 1998) was applied to invert for 2D models of velocity and attenuation below the embankment centreline. The survey was composed of 48 geophones and 70 shots (see Figure 1), recorded on two engineering seismographs. Time and offset windowing were applied to the data in order to remove ground roll prior to inversion. The starting velocity model for Waveform Tomography was approximately one-dimensional, based on the output of travelt ime tomography. Initial velocity modelling was carried out using First Arrival Seismic Tomography (“FAST”, after Zelt and Barton (1998)), based on hand-picked first arrivals. Frequencies from 20 Hz to 130 Hz (see Figure 2) were used in Waveform Tomography, representing wavelengths between approximately 100 m and 15 m. Of principle interest was the region indicated in Figure 2, where characteristic diffractions are visible.

Expectations

The buried riprap targets were approximately 3x2 m, 4.5x2 m, and 3.5x3 m in width by height cross section, and started 2 m below the embankment baseline. The resolution of the ray theory approximation is constrained by the Fresnel zone $\sqrt{\lambda L}$, with L representing the source-receiver path length (Williamson, 1991). At the test embankment site, with in-situ clay velocities of approximately 2000 m/s, the 20 Hz to 130 Hz data have wavelengths between 100 m and 15 m, and propagation distances are of the order of 40 m. These data are therefore expected to yield travelt ime tomography images with resolutions between $\sqrt{\lambda L} \approx 63$ m and 24 m, probably too large to be able to detect the targets.

Waveform Tomography is a more complete inversion method that uses the detailed waveform data to resolve velocity anomalies (Pratt *et al.*, 1998). When implemented in the frequency domain, the method can additionally be used to resolve variations in the seismic attenuation (parameterised as the seismic Q-factor) (Hicks and Pratt, 2001). The resolution of the waveform

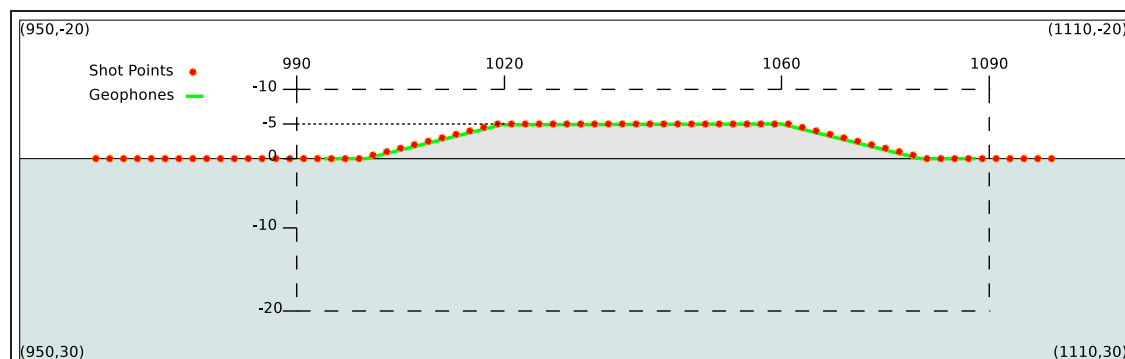
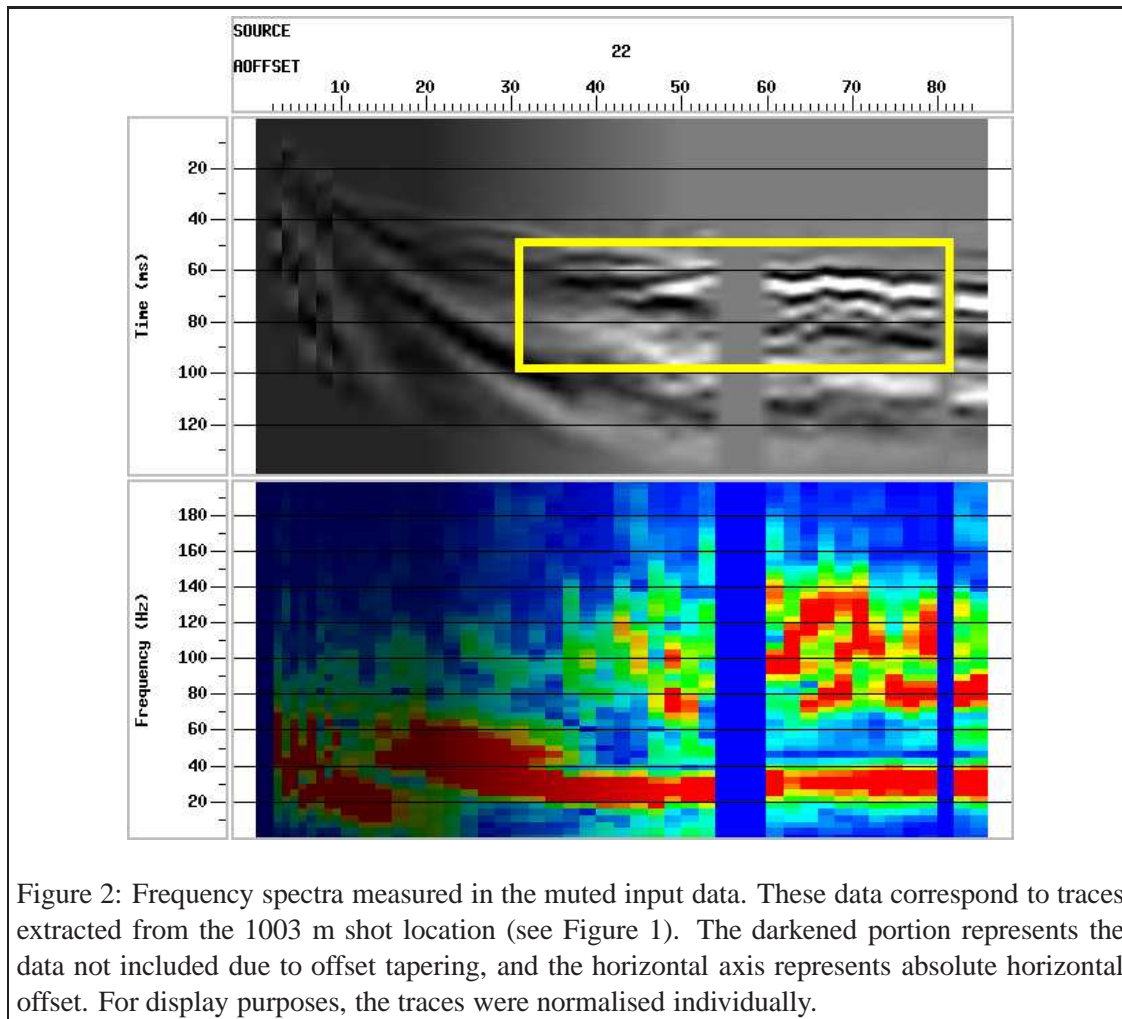


Figure 1: A schematic view of the constructed test embankment. The boxed region indicates the area depicted in velocity and attenuation models throughout this paper. Shot points are indicated by red circles, and the geophone array is indicated by a green solid line; shot points and geophones are spaced at 2 m intervals.

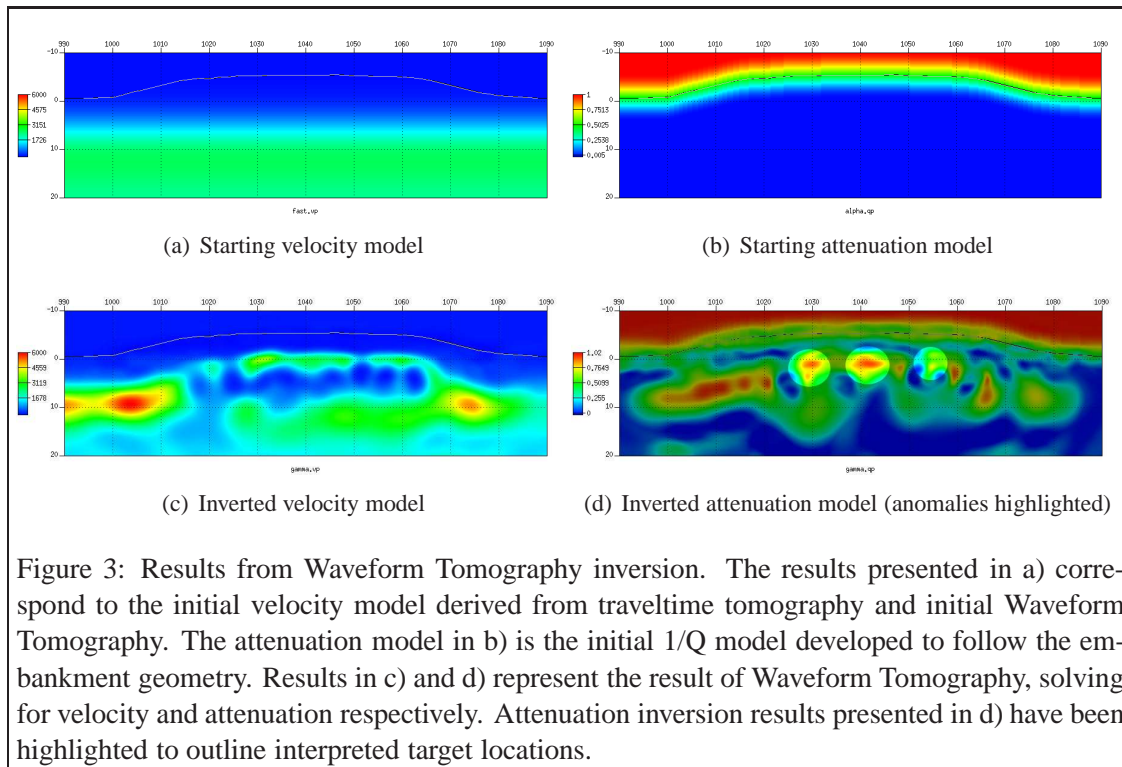


tomography method is on the order of $\lambda/2$ (Wu and Toksöz, 1987), or between 50 m and 8 m at the site.

Inversion

In Waveform Tomography, a starting velocity model is required that predicts the seismic waveforms within a half-cycle. This avoids convergence to a local minimum of the objective function at a given frequency. FAST was used to develop a smooth velocity model from hand-picked first arrivals. This result was re-inverted using Waveform Tomography and then smoothed to 1D to provide a starting model for inversion (Figure 3 a). The attenuation starting model (Figure 3 b) was designed as a best guess to allow the majority of energy to propagate while discouraging updates in the air layer.

Resolving the sub-wavelength targets with the weight drop data proved challenging. The Waveform Tomography velocity inversion delineated the major structural features of the site, including the embankment clays, the in-situ clays and the bedrock interface below the site. Inversion for seismic velocity was dominated by the embankment structure, and was not sensitive to the targets. The velocity inversion result presented in Figure 3 c) shows a relatively high-velocity layer near the embankment surface, and a low velocity layer in the vicinity of the targets. This could indicate the presence of granitic riprap, but is not sufficient for identification. Although the velocity images failed to show the targets, they were successfully identified on the seismic-Q images. The target locations are evident as areas of apparent high attenuation as highlighted on Figure 3 d.



Discussion and Conclusions

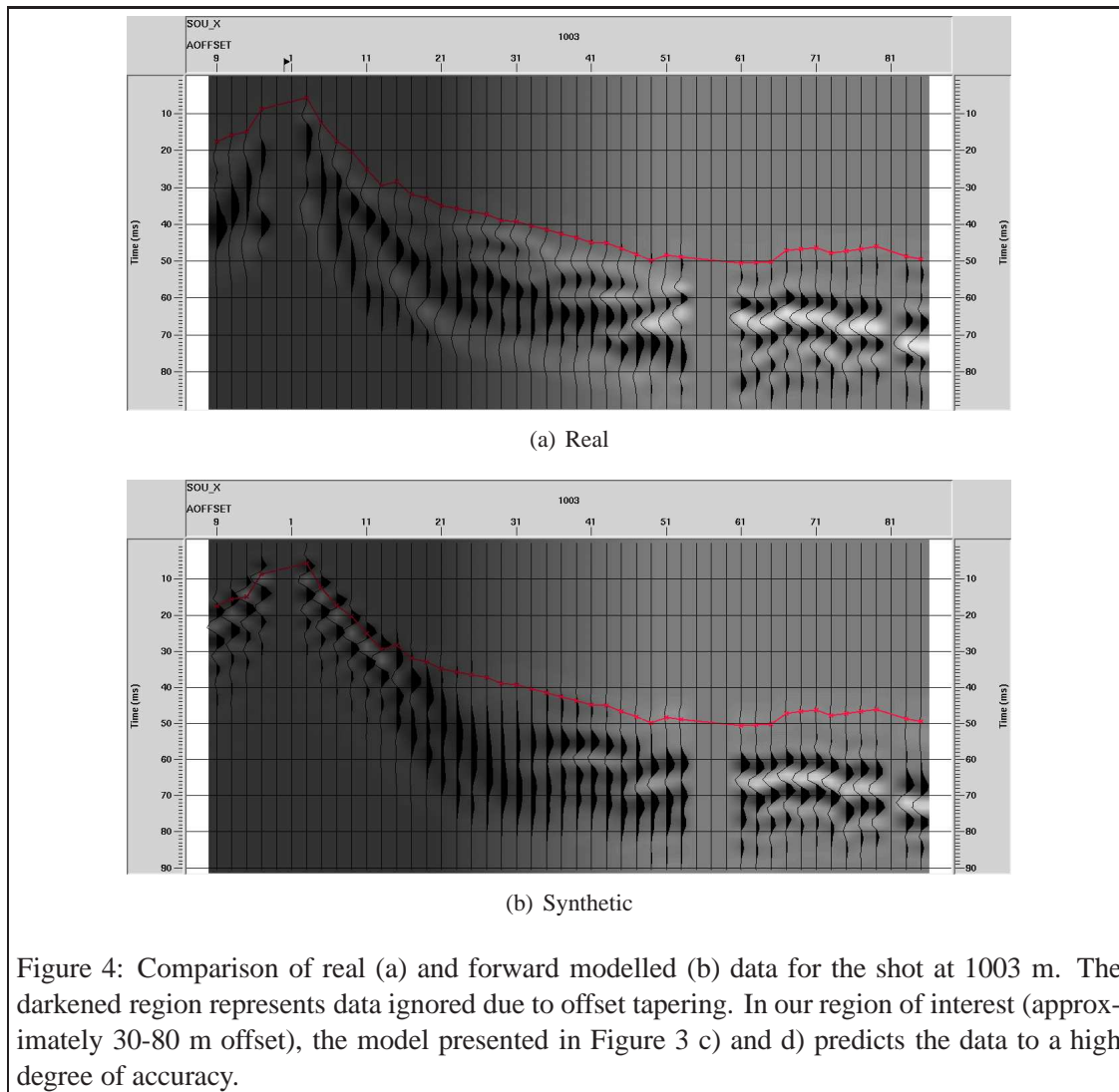
In comparison to short-offset reflection studies conducted previously (Zantout, 2005; Hayles *et al.*, 2005), the Waveform Tomography model presented (Figure 3 a and b) provides clear indications of two of the three expected targets. The high apparent attenuation of two of the three targets is reasonable considering the large number of scattering interfaces in the riprap fill. The third target is weakly resolved on the attenuation image (Figure 3 c), and would most likely not be interpreted in absence of a priori knowledge of the target sizes and locations. The apparent high attenuation on the flanks of the structure makes the identification of the targets difficult. This is believed to be due to the heterogeneity of the emplaced clays and possibly the limited compaction during construction. Further development of the Waveform Tomography technique in the context of near-surface investigations may prove valuable in locating voids and attenuative anomalies. In order to apply these results to the engineering problem of assessing embankment integrity, a combination of the results from this study and short-offset reflection interpretation might provide a “best of both worlds” result; in the presence of detailed velocity and attenuation models, the confidence of high-resolution depth sections could be improved.

Acknowledgements

The authors would like to acknowledge the work of Sary Zantout; much of the original data preparation was carried out as part of his thesis work (Zantout, 2005). The processing methodology followed closely the work of Brenders and Pratt in recent large-scale investigations (Brenders and Pratt, 2007).

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