On the origin of source and receiver amplitude perturbations in land seismic data

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Summary

In this paper we discuss the characteristics of source and receiver amplitude perturbations retrieved from land seismic data acquired in Manistee County, Michigan. In this survey, the wavefield was emitted by a short array of explosive sources, and data were recorded by individual receivers. We determined the source and receiver characteristics using a reciprocal acquisition geometry. The redundancy in the data obtained by recording data with nearly identical source and receiver positions is used to estimate the perturbations induced by the sources and receivers.

The source perturbations retrieved showed a strong correlation with the moisture content of the near-surface sediments. The source signal was strongly attenuated for explosive sources located in dry sand, whereas a good source coupling was observed for sources in moist-to-wet sediments. For frequencies above 40 Hz, an explosive source located in the moist-to-wet sediments transmitted more than 100 times more energy into the ground than an explosive source located in the dry sand. This difference is a result of high absorption rates in the dry sand due to nonlinear deformation, i.e. closing of the pores, whereas for sediments with fluid-filled pores, the absorption rates are low.

The receiver terms are determined for vertical component data, and these do not show a significant correlation with the moisture content of the soil. Dominant are the changes from receiver to receiver, indicating that these are related to the geophone plant itself. Although the receiver perturbations are much smaller in magnitude compared to the source perturbations, an energy differences of a factor 5 between the responses of two adjacent geophones are no exception. Therefore, it is important to correct land seismic data for both the source and receiver perturbations. Furthermore, we compared the receiver responses to the generally accepted damped-harmonic oscillator model. For low frequencies, the retrieved receiver variations are larger than predicted by this model. We could not fit the receiver responses retrieved for vertical component data using a single resonant frequency and damping factor. This damped-harmonic oscillator model may need to be revised for future land seismic applications.

Introduction

The variability of recordings obtained in land seismic settings cannot be fully explained using linear wave propagation models because it partially depends on changes in source and receiver behavior within a given survey. For example, the source strength and signature are mainly determined by nonlinear deformation of the near-source region, and are therefore related to the anelastic properties of the near-source region (Aritman, 2001). On the receiver side, several authors have reported discrepancies recorded by geophones which are only a few meters apart (e.g. Berni and Roever, 1989; Blacquière and Ongkiehong, 2000). Some of the causes of these perturbations are imperfect geophone coupling, localized variations of the soil, shallow elastic property variations in consolidated rock, and variations of the ambient or recording equipment noise.

Although variations in source and receiver responses have a detrimental effect on the recorded seismic data, their influence on land seismic data is not well understood, because these effects are difficult to separate from near-surface wave propagation effects due to near-surface inhomogeneities. We used the recently developed method by Van Vossen et al. (2004) to obtain the source and receiver corrections. This method uses reciprocity as an indicator for source and receiver perturbations, and is therefore not sensitive to perturbations induced by near-surface wave propagation effects. As a consequence, this technique is only sensitive to the acquisition effects, and not to near-surface wave propagation effects. An important difference between acquisition and near-surface effects is that changes in near-surface conditions on a sub-wavelength scale can influence wavefield *measurements*, whereas wavefield propagation variations are usually only significant for medium variations over length scales of the order of a wavelength.

In this paper we study the characteristics of source and receiver corrections retrieved from seismic data acquired in Manistee County, Michigan. At this site, changing near-surface conditions affect the quality of the recorded data. In the accompanying paper (Van Vossen et al. 2005) we show that compensating these data for the relative source and receiver amplitude perturbations significantly improves the signal-to-noise ratio of both prestack and poststack data. The goal of this paper is to investigate the relationship between source and receiver characteristics and changing near-surface conditions. Furthermore, we compare the receiver terms obtained to the classical damped-oscillator response which is commonly used to describe the geophone-ground coupling response (Hoover and O’Brien, 1980; Krohn, 1984).

Method and data description

We briefly review the procedure to obtain the source and receiver amplitude responses. The vertical component of the particle velocity is denoted by $v(t, \mathbf{x}_s, \mathbf{x}_r)$, with $\mathbf{x}_s$ and $\mathbf{x}_r$ the source and receiver positions, respectively.

Considering the earth as a linear system for the propagation of seismic waves, the recorded traces satisfy the convolutional model,

$$v(t, \mathbf{x}_s, \mathbf{x}_r) = R(t, \mathbf{x}_r) * G(t, \mathbf{x}_s, \mathbf{x}_r) * S(t, \mathbf{x}_s), \qquad (1)$$

where $R(t, \mathbf{x}_r)$ is the receiver response for the vertical component recordings at surface location $\mathbf{x}_r$, $S(t,\mathbf{x}_s)$ is the source signature at $\mathbf{x}_s$, and $G(t,\mathbf{x}_s,\mathbf{x}_r)$ is the corresponding medium response. The asterisk $(*)$ denotes convolution in the time domain.

If we interchange source and receiver positions, the medium response does not change:

$$G(t,\mathbf{x}_s,\mathbf{x}_r) = G(t,\mathbf{x}_r,\mathbf{x}_s). \tag{2}$$

As a result, differences between normal and reciprocal recordings can be attributed to the source and receiver perturbations, and this is an important diagnostic for detecting relative source and receiver perturbations. Van Vossen et al. (2004; 2005) demonstrated that reciprocity, combined with suitable regularization criteria, can be used to determine relative source and receiver amplitude responses.

We applied this technique to single-sensor data acquired in Manistee County, Michigan. The site is characterized by changing near-surface conditions along the acquisition line. As indicated in Figure 1, near-surface conditions change from moist-to-wet sediments between 0 and 600 m to dry sands beyond that point (noted at time of acquisition). The location of the dry sands coincides with the more elevated sections along the acquisition line. Both source and receiver spacing is 10 m. The wavefield is emitted by an array of closely spaced explosive sources which are located at approximately 5 ft depth. The receivers are 10 Hz geophones. An important aspect of the acquisition is that each geophone was deployed at only one surface location, i.e. the location of a geophone was fixed during the whole survey. Examples of the data recorded are shown by Van Vossen et al. (2005).

An important characteristic of the method used for estimating the source and receiver perturbations is that it can be directly applied to the recorded data. In the example shown in this paper we only performed trace editing to remove void records, and muted acausal noise in a few traces. In case of non-identical source-receiver positions, data interpolation is required. We did not have to apply data interpolation before the equalization procedure in this application, because the differences between the source and receiver positions are small (of the order of at most a few meters).

Characteristics of source corrections

Figure 2 shows the variation of the relative source corrections with frequency and surface location. The magnitude of the corrections is given on a logarithmic scale, where $\log$ denotes the natural logarithm. It shows that these corrections are strongly correlated to the moisture content of the near-surface sediments. At this site, this coincides with the surface topography (See Figure 1). For sources located in the dry sand, the absorption rate in the near-source region is high due to deformation of the medium (closing of the pores). This strongly attenuates the signal with frequencies above 40 Hz. On the other hand, the source coupling is good in the moist-to-wet sediments. Then, the absorption in the near-source region is low. This results in significant differences in source strength: for frequencies above 40 Hz, a source located in the moist-to-wet sediments transmits more than 100 times more energy into the ground than a source located in the dry sands. Compensating for these differences in source strength results in an increasing source strength in the dry sands, and a decreasing source strength in the moist-to-wet sediments, and these results are shown in Figure 2.

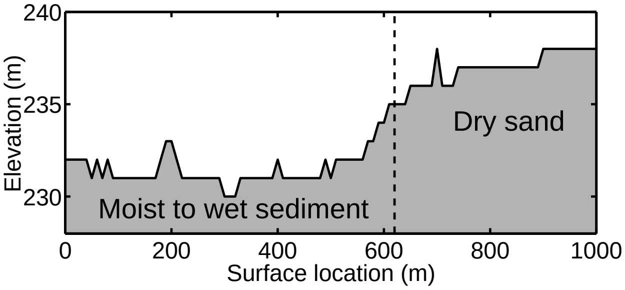

Fig. 1: Surface topography and indication of near-surface material properties along the acquisition line.

Characteristics of receiver corrections

Figure 3 shows the variation of the relative receiver corrections with location for the frequencies 20, 40, and 60 Hz. Contrary to the source corrections, there is no clear correlation between moisture content of the sediments and the receiver corrections: the receiver corrections vary rapidly from location to location, and this indicates that the plant of an individual geophone dominates perturbations in its amplitude response, rather than the near-surface conditions. We observed energy differences of about a factor 5 between adjacent geophones at 60 Hz. Because of the rapid spatial variations of the receiver perturbations, these also significantly distort the recorded data.

Comparison with damped harmonic oscillator model

We investigated whether the obtained receiver terms are consistent with the damped-harmonic oscillator model. This model is widely used to describe the geophone-ground coupling response, and is characterized by a resonant frequency f_c and a corresponding damping factor η_c (Hoover and O'Brien, 1980; Krohn, 1984):

$$R_c = \frac{1 + i\,(f/f_c)\,\eta_c}{1 - (f/f_c)^2 + i\,(f/f_c)\,\eta_c}. \tag{3}$$

Since the receiver terms obtained only describe relative perturbations, we cannot compare these directly to the absolute response given by the coupling model. Therefore, we compared *ratios* of receiver responses obtained to *ratios* of the response of two damped-harmonic oscillators. Due to the nonlinearity of the inverse problem to determine the resonant frequencies and damping factors of each geophone, solving the full inverse problem was not feasible: The solution obtained was inherently dependent on the chosen starting model. Therefore, convergence to the global minimum could not be guaranteed. Instead, we investigated each ratio independently. For each ratio, we determined the optimum combination of resonant frequencies and damping factors using a grid search technique. This procedure was re-

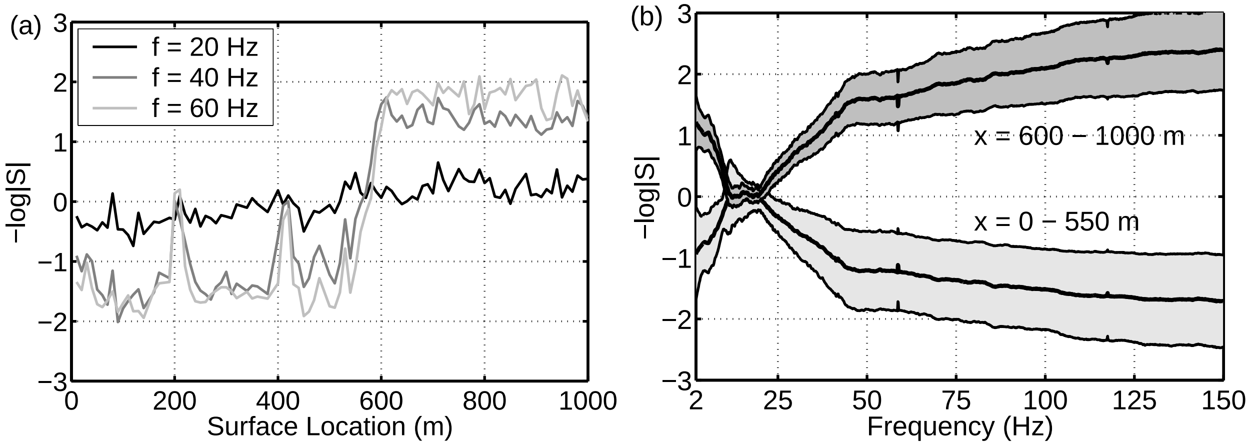

Fig. 2: Characteristics of source corrections: (a) lateral variation in source corrections for the frequencies 20, 40, and 60 Hz, and (b) frequency dependency for source corrections. Shown are the average source corrections between surface location intervals 0 - 550 m and 600 - 1000 m. The gray areas indicate the one-sigma uncertainty interval. On the y-axis, log denotes the natural logarithm.

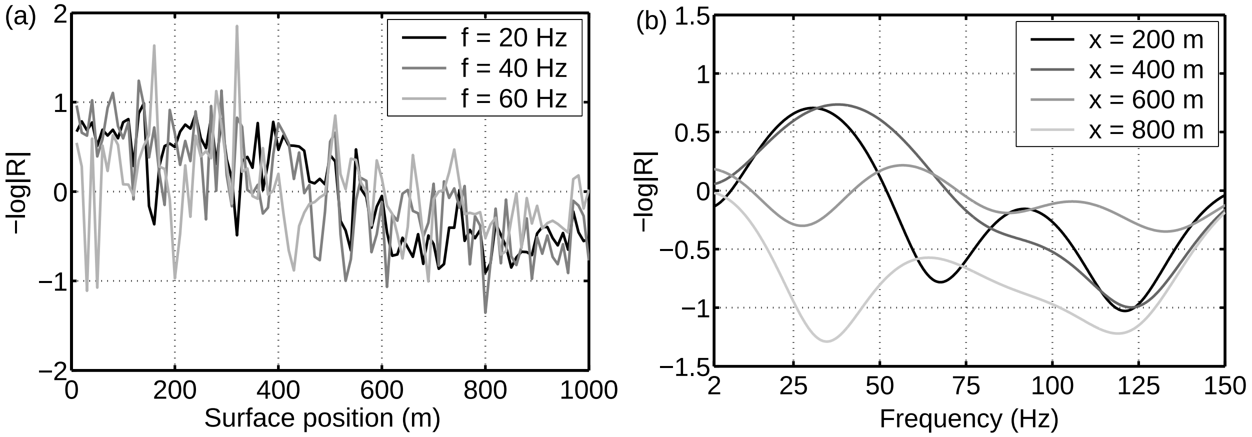

Fig. 3: (a) Receiver corrections at 20 Hz, 40 Hz, and 60 Hz for the different surface locations, and (b) shows the amplitude response at surface locations 200, 400, 600, and 800 m as a function of frequency.

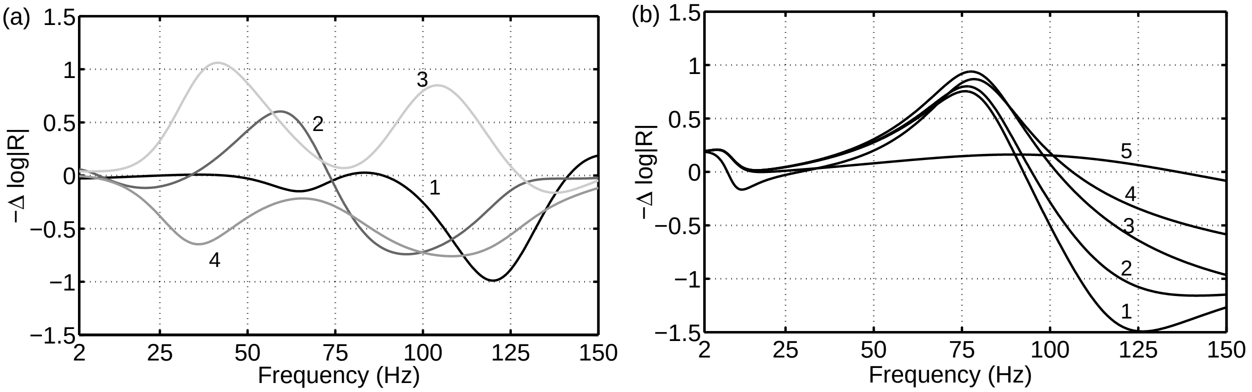

Fig. 4: (a) Ratios of receiver corrections obtained. The labels refer to the receivers used to compute the ratios: (1) is the ratio between receivers positioned at 200 and 210 m, (2) at 400 and 410 m, (3) 600 and 610 m, and (4) 800 and 810 m. (b) Ratios of the damped harmonic oscillator curves. The resonant frequencies and damping factors for each curve are given in Table 1.

	$f_c^{(1)}$ (Hz)	$\eta_c^{(1)}$	$f_c^{(2)}$ (Hz)	$\eta_c^{(2)}$
1	80	0.3	120	0.3
2	80	0.3	120	0.5
3	80	0.3	120	1.0
4	80	0.3	90	1.0
5	120	1.1	180	1.5

Table 1: Resonant frequencies and damping factors used for the ratios of the damped-harmonic oscillator shown in Figure 4b.

peated for each ratio in order to be able to test the consistency of the results. We used the following misfit function:

$$L_{ij} = \left\{ \frac{\int_{f_{min}}^{f_{max}} \left[\tilde{m}_{ij}(f) - m_{ij}(f)\right]^2 \mathrm{d}f}{f_{max} - f_{min}} \right\}^{1/2} \quad (4)$$

where the subscripts i and j refer to the geophone responses which are investigated:

$$\tilde{m}_{ij}(f) = \log|R_i(f)| - \log|R_j(f)| \quad (5)$$

and

$$m_{ij}(f) = \log\left|R_c^{(i)}\right| - \log\left|R_c^{(j)}\right| \quad (6)$$

We determined for each ratio $i = 1, \ldots, 99$ and $j = i + 1, \ldots, 100$ the misfit in the frequency band between 2 and 150 Hz for different values of the resonant frequencies and damping factors using a grid search technique, allowing the resonant frequencies to vary between 50 and 200 Hz with 5 Hz intervals, and the damping factors between 0.2 and 1.8 with steps of 0.1. Thus, for each ratio we determined the optimum combination of resonant frequencies and damping factors.

In order to test whether the damped-harmonic oscillator model can be used to explain the observed receiver amplitude responses, the first indicator is the misfit L_{min} corresponding the best fitting model for each ratio of receiver responses. We found that the average minimum misfit $\bar{L}_{min} = 0.36$, which is rather large. Second, we also investigated the consistency of the resonant frequencies and damping factors obtained for each individual receiver. We found that the average standard deviations in the obtained resonant frequencies and damping factors are 39 Hz and 0.45, respectively. The average resonant frequency obtained is 91 Hz, and the average damping factor 0.68. Thus, both the minimum misfit and the inconsistency in of the inversion results for a single geophone indicate that the damped-harmonic oscillator response does not explain the receiver amplitude responses obtained. This is also confirmed by Figure 4. Figure 4a shows four ratios of the retrieved receiver terms, and Figure 4b shows ratios of damped-harmonic oscillators with resonant frequencies and damping factors given in Table 1. The large values below 60 Hz in Figure 4a cannot be explained with the damped-harmonic oscillator model, since resonant frequencies for a vertical geophone are reported to be higher than 100 Hz (Krohn, 1984).

Concluding remarks

We discussed the characteristics of source and receiver amplitude perturbations which were retrieved from single-sensor data acquired in Manistee County, Michigan.

- Source strength variations are strongly correlated to the moisture content of the sediments in the near-source region. This controls the amount of energy transmitted into the ground by explosive sources, and we observed energy differences up to a factor 100 along the acquisition line.
- Despite that receiver perturbations are smaller in amplitude than source perturbations, these are still significant. The receiver terms vary rapidly along the acquisition line, indicating that the coupling of an individual geophone to the ground is dominant. We cannot explain the observed receiver responses with the generally accepted damped-harmonic oscillator model. This implies that this model may need to be revised for future land seismic applications.
- Corrections for both source and receiver perturbations are therefore essential for imaging subsurface structures. In the accompanying paper (Van Vossen et al., 2005), we show that compensating these data for these source and receiver perturbations significantly improves the signal-to-noise ratio on both prestack and poststack data.

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