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Seismic interferometry as a tool for improved imaging of the heterogeneities in the body of a landfill

L.A. Konstantaki [a,*], D. Draganov [b], R. Ghose [b], T. Heimovaara [a]

[a] Section of Geoengineering, Dept. of Geoscience and Engineering, Delft University of Technology, The Netherlands
[b] Section of Applied Geophysics and Petrophysics, Dept. of Geoscience and Engineering, Delft University of Technology, The Netherlands

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ABSTRACT

It is challenging to image and characterize the body of a landfill. High-density areas that act as obstructions to fluid flow are of specific interest to the landfill operators (e.g., for improvement of treatment technologies), and thus their imaging is important. In seismic reflection sections, such areas manifest themselves as sources of scattered energy. The heterogeneities inside the landfill, in addition to the surface-wave energy which is difficult to remove, add to the complexity in the seismic data. We propose to make use of seismic interferometry (SI) not only as a tool to improve the imaging of the scatterers, but also as a tool to remove the undesired surface-wave energy. We investigate the results obtained from application of SI to field seismic reflection data recorded at a landfill. We show that the data, retrieved by SI, image the scattered energy better than the seismic reflection data when the latter is processed in a conventional way. The increased stacking power of SI and its implicit consideration of multiple scattering result in a better illumination of the scatterers. We also use SI to predict the surface-wave energy and remove it from the original seismic reflection data using an adaptive subtraction method. The result from the adaptive subtraction when compared to the reflection data, processed in a conventional way, shows improved imaging, especially of layers in the landfill. Combined interpretation of the stacked reflection sections together with the velocity fields obtained from the three different datasets (conventional seismic reflection, SI and adaptive subtraction) leads to an improved interpretation.

1. Introduction

Using seismic interferometry (SI) it was previously shown that the imaging of near-surface (very shallow) scatterers in synthetic reflection seismic data was improved (Konstantaki et al., 2013). Compared to the data of conventional reflection seismic survey (CRSS), the results retrieved by SI were found to be less affected by errors that occur during data acquisition and processing, e.g., due to incorrect positioning of sources in time-lapse measurements or incorrect top muting. First goal of this research, is to test the previous numerical findings by applying SI to field reflection data recorded over a landfill. Both ambient-noise recordings (Campillo and Paul, 2003; Shapiro and Campillo, 2004; Draganov et al., 2007, 2009) and controlled-source recordings (Schuster, 2001; Wapenaar et al., 2002; Schuster et al., 2004) can be used in SI. Here we use controlled-source reflection recordings for SI.

In our application of SI, we cross-correlate common-receiver gathers recorded by two receivers – one at location A and another at location B – and then sum the correlation result along the sources with the aim of retrieving the reflection response at B from a virtual source at position A (e.g., Wapenaar and Fokkema, 2006; Wapenaar et al., 2010a). For a correct retrieval of the reflection response, the sources must surround the receivers. Nevertheless, it was found that even with sources and receivers only at the surface (as is the case for seismic reflection data acquisition on a landfill), the reflection response could still be retrieved (van Wijk, 2006; Halliday et al., 2007). In this case, however, non-physical arrivals might be retrieved as well (Snieder et al., 2006; Draganov et al., 2012; King and Curtis, 2012). Such non-physical arrivals would be suppressed when significant multiple scattering occurs in the subsurface (Wapenaar, 2006). In such cases, objects scattering seismic energy can be regarded as secondary (Huygens) sources that illuminate the receivers also from below.

Typically, a landfill is an extremely heterogeneous body which is full of localized objects responsible for scattered seismic energy in the reflection recordings. The presence of scattered energy in reflection data poses extra requirements to the acquisition and processing of data, thus making seismic imaging of landfills a challenging task. On the other hand, the presence of significant secondary scattering in the landfill makes the application of SI advantageous.

Backscattered or reflected body-wave seismic energy from the very near-surface objects is usually overlain by dispersive surface waves

* Corresponding author at: Stevinweg 1, PO-box 5048, 2628 CN Delft/2600 GA Delft, The Netherlands.
E-mail addresses: l.a.konstantaki@tudelft.nl (L.A. Konstantaki), d.s.draganov@tudelft.nl (D. Draganov), r.ghose@tudelft.nl (R. Ghose), t.j.heimovaara@tudelft.nl (T. Heimovaara).

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generated by an active source at the surface. Thus, an important challenge in imaging shallow scatterers through reflection seismics is the elimination of the surface waves. This is a difficult task. Surface waves from other sources can also be recorded (e.g., anthropogenic traffic noise or noise from gas/water pipes in the subsurface) and interfere with the active recordings. More critically, the surface waves often have a similar velocity and frequency content to those of the investigated signal (reflections and scattering events), making it difficult to remove them by conventional methods like bandpass or frequency-wavenumber (f-k) filtering (Konstantaki et al., 2015). Slightly incorrect use of the parameters in the f-k filter may result in artifacts due to signal distortion and spatial correlation of the background noise thus lowering further the quality of an obtained image. In the synthetic data of Konstantaki et al. (2013), surface waves were not present. In field data, however, surface waves are usually present, and they typically obscure the imaging of the near-surface scatterers (Konstantaki et al., 2015). The second goal of our study is thus to investigate the use of SI for removal of surface-wave energy.

Prediction of surface waves with SI and their adaptive subtraction (AS) from the seismic reflection data is a way to remove the surface waves. SI can be used to predict surface waves without the need for a near-surface velocity model. After the prediction, the surface waves retrieved by SI can be subtracted from the original reflection data using an adaptive filter (Dong et al., 2006; Halliday et al., 2010). Halliday et al. (2010) specifically mention the difficulties of removing scattered surface-wave energy from the reflection data by conventional processing and show the advantages of AS after prediction with SI. We test the use of SI to predict the unwanted surface waves and remove them from the reflection data with the goal to improve the imaging of the landfill.

Reliable characterization and imaging of the heterogeneities inside a landfill are becoming increasingly important. Definition of the aftercare period, prediction of the emission potential, and improvement of the treatment technologies are lately important topics for the landfill operators. One of the goals is to minimize the aftercare period (e.g., Scharff, 2005; van Vossen, 2010). For that purpose, a good understanding of the processes occurring inside the landfill body (e.g., preferential flow paths, biogeochemical processes, settlement) is essential. Many of these processes depend strongly on the heterogeneity distribution inside the landfill. Konstantaki et al. (2015) proposed a new approach involving CRSS and electrical resistivity methods to image and characterize a landfill in detail. The third goal of this study is to investigate the possibility to improve the characterization of a landfill when interpreting together the results from the CRSS, SI and AS methods.

In the following sections, we discuss the application of SI to the CRSS data acquired at a very heterogeneous landfill site. We investigate if the causal part, the acausal part, or a combination of both parts of the retrieved wavefield from SI is best for the acquisition geometry that we have used. We compare the result of SI with that of CRSS. Next, we present the results after AS of surface waves as predicted by SI. Finally, we characterize the landfill by joint interpretation of the results of CRSS, SI and AS.

2. Data acquisition and processing: conventional reflection seismic survey

In the summer of 2013, we acquired CRSS data on a landfill in Wieringermeer, The Netherlands. We used 10-Hz horizontal-component geophones as receivers and a high-frequency, electrodynamic horizontal (shear-wave) vibrator as the source (Ghose et al., 1996; Brouwer et al., 1997; Ghose, 2012). The horizontal geophones are oriented in the crossline direction; the shear-wave vibrator is used in an SH mode, which is achieved by orienting it in the crossline direction as well. In such a way, we ensure that we generate and record SH waves. Compared to impulsive seismic sources, high-frequency vibrators are often more suitable for resolving the heterogeneities in a very heterogeneous shallow subsurface (e.g., Ghose et al., 1996; Ghose et al., 1998). We have used shear (S) waves because in low-velocity soft soils S waves generally offer higher resolution than P waves due to the much lower velocity for S waves, and more importantly because S-wave velocity is directly linked to the elastic rigidity of the subsoil and S waves are more sensitive to the subtle changes in the soil type (e.g., Ghose, 2003; Ghose and Goudswaard, 2004). We used 48 geophones planted along a straight line with a 0.5 m spacing between the geophones. We kept the geophone array fixed and moved only the source. We shot at 33 locations, starting 4 m before the first geophone and finishing 4.5 m after the last geophone using a source spacing of 1 m. The noise from the nearby gas pipes and the work at nearby industrial buildings resulted in a relatively low signal-to-noise (S/N) ratio in the data. Further details about the acquisition parameters together with a detailed description of the processing of the CRSS data can be found in Konstantaki et al. (2015).

The main processing steps we applied to the CRSS were as follows: (1) vibroseis source-signature deconvolution to compress the raw vibrograms for each shot seperately in order to correct for shot-to-shot variation (Ghose, 2002); (2) vertical stacking of shots at every source location; (3) bandpass filtering (4–10–160–200 Hz); (4) top, bottom and surgical muting for removing the unwanted surface waves; (5) iterative velocity analysis; (6) normal moveout (NMO) correction and stacking; we also applied (7) prestack-depth migration.

3. Processing for seismic interferometry

3.1. Processing steps

To investigate if we can improve the results of CRSS at a landfill, we apply SI to the CRSS data. For this purpose, we perform the following steps. First, we compensate for intrinsic losses (dissipation) by multiplying the raw CRSS data by exp.$(1.3 * t)$, where t is the time. With this, we aim to boost the latter arrivals for the correlation process. Then we top-mute the direct arrivals and sort the data to common-receiver gathers (CRG). After that, we cross-correlate the CRGs and sum each correlation result along the sources. As a final step, we apply a bandpass filter (5–35–95–110 Hz) to remove low- and high-frequency noise and a notch filter to remove the 50-Hz powerline noise. The latter noise is present in the CRSS data, and the cross-correlation process amplifies it. Therefore, we need to suppress it. Once the virtual common-source gathers are retrieved by SI, we apply the same processing steps 4) to 6) as described in Section 2. To obtain stacked images of the landfill from the SI data, we use retrieved common-midpoint (CMP) gathers with a CMP fold ≥6. We apply post-stack automatic gain correction (AGC) with a 30 ms window to the stacked images for a better visualization. We finally apply a post-stack bandpass filter (10–35–95–110 Hz) to remove the low- and high-frequency noise that is boosted by the correlation process. After the stacking, we perform a time-to-depth conversion using a smoothed version of the stacking velocity field.

3.2. Using parts of the causal and acausal retrieved results

Using SI by cross-correlation requires illumination from all sides. When the illumination is homogeneous, physical arrivals will be retrieved equally well in the causal and acausal part of the wavefield (Wapenaar, 2004; van Manen et al., 2005; Wapenaar et al., 2010b). The causal part refers to times later than the zero time (positive time) and the acausal part to times earlier than the zero time (negative time). In such a case, the final retrieved result can be taken only from the positive times, only from the negative times, or even from their summation, where the latter might result in improved S/N ratio. In case when the illumination is not homogeneous from all sides (e.g., when one-side illumination occurs or gaps in the illumination are present) then parts of the physical energy can be retrieved at