0-000  SHALLOW IMAGING WITH SCATTERED SEISMIC SURFACE WAVES

XANDER CAMPMAN\textsuperscript{1}, CHRISTINA DWI RIYANTI\textsuperscript{1} and GÉRARD HERMAN\textsuperscript{2,1}

\textsuperscript{1}Delft Institute of Applied Mathematics, Delft University, P.O. Box 5031, 2600 GA Delft, The Netherlands
\textsuperscript{2}Shell International E&P

Summary
We have developed an imaging method for scattered surface waves to obtain spatial images of near-surface heterogeneities. We test our method on ultrasonic data from a laboratory test and investigate its resolution on synthetic data. The images, thus obtained, show that this method has potential to locate near-surface heterogeneities.

Introduction
It is widely recognized that surface waves provide valuable information about the near subsurface. For instance, they can give insight in the vertical structure of the Earth through modal analysis — a technique well-established in global seismology. In engineering geophysics, this technique has become known as spectral analysis of surface waves (SASW). Owing to its simple field implementation, this method has become a popular tool in geotechnical near-surface studies to produce depth-dependent shear velocity profiles. In these methods, scattered surface waves cause artifacts in the result of dispersion analysis and remain a source of noise in most seismic near-surface studies (Gucunski et al., 1995). Park et al. (1999) introduce multichannel analysis of surface waves (MASW), combining the ideas of SASW with reflection seismic methods to obtain more reliable dispersion curves. Multichannel records of surface waves can also be used to detect and locate heterogeneities in the shallow subsurface. Park et al. (1998) use the fact that heterogeneities cause a different phase velocity and attenuation in a linear ground roll event to identify heterogeneities. Leparoux et al. (2000) apply the same type of processing, but also try to bring out the scattered Rayleigh wave, to use it as a direct indicator of heterogeneity. In Behboodian et al. (1999), a processing method is developed to obtain spatial images of land mines which are in some way related to the intensity of the scattered field. Herman et al. (2000) image heterogeneities, close to a receiver line, by spatial and temporal deconvolution of scattered surface waves. In this paper we investigate an imaging algorithm to obtain spatial images of near-surface heterogeneities under an areal receiver array. The method is based on iterative inversion of an approximate integral representation for the vertical component of velocity where we assume that scattering takes place at the surface. In this way, we obtain a spatial distribution of the heterogeneity, proportional to the density contrast.

Method
Our goal is to image surface waves, scattered close to the Earth’s surface. Although upcoming body waves in reflection seismic surveys may also excite surface waves when they impinge on near-surface heterogeneities, we consider the case of surface wave-to-surface wave scattering here only. In practice, this means that we select a time-window around the Rayleigh wave, including scattering and use only this event to derive the image. We assume that we only measure the vertical component of particle velocity \( v \). We decompose the field measured at the geophones as follows:

\[
v(x, y, z_0) = v^0(x, y, z_0) + v^1(x, y, z_0),
\]
where \( v^0 \) is the field that would have been measured when the near-surface were homogeneous and \( v^1 \) is the field due to local heterogeneity. The image is obtained by iteratively updating the impedance function that minimizes a cost function, consisting of the squared difference between the observed scattered Rayleigh wave (\( v^1 \)) and the modeled scattered Rayleigh wave. The cost function, \( F \), is defined as:

\[
F = \frac{||v^1 - K\sigma||^2}{||v^1||^2} + \lambda||\sigma||^2,
\]

where \( \lambda \) is a stabilization parameter and \( K \) is an operator defined through (Campman et al., 2003)

\[
\{K\sigma\}(x, y, z, \omega) = \int_{\text{Surface}} u^G(x - x', y - y', \Delta z, \omega)\sigma(x', y', z_1, \omega)v(x', y', z_1, \omega)dA.
\]

Here, \( u^G \) is the displacement of the elastic medium due to an impulsive vertical point force. In deriving \( u^G \), we assume that the interaction between the horizontal and vertical components of the wave field can be neglected. Horizontal position is denoted by \( x, y \) and depth with \( z \); \( \omega \) is angular frequency and \( \Delta z = z_0 - z_1 \). The impedance function is denoted by \( \sigma \). Because it is evaluated at the surface, we allow the impedance function to depend on frequency to account for variation in the actual depth of the heterogeneities. We assume that the scattering takes place close to the surface (\( z_1 \approx z_0 \)), and replace the field at the scattering depth with the field measured at the surface. In this way, the only unknown in Eq. (3) is the impedance function.

**Test on ultrasonic data**

To test our algorithm, we applied it to data of surface waves, scattered at the surface of an aluminum block (Campman et al., 2003). The wave field is excited by a pulsed infrared laser, focused on a line to create a line surface wave source. This wavefront is scattered by a cylindrical cavity with a diameter of 2 mm and a depth of about 3 mm, which is also roughly the size of a Rayleigh-wave length. Vertical velocity is measured at the surface of the aluminum block, using a scanning laser interferometer. Traces are recorded at .25-mm intervals, which is about 10 times per wavelength. In Fig. 1(a), a top view of the wavefield is shown. The position of the cavity is slightly left and down from the center of this figure. We selected the direct Rayleigh wave, as shown in a cross-
Figure 2: (a) Top view (constant time) of the scattered field in the first model. The contours indicate the actual locations of the scatterers. (b) Image at the surface, at $t = 0$. (c) The actual scatterer distribution. (d) Cross section of the image at $t = 0$ through the line A-B in (c). Both the image and the actual scatterer distribution have been normalized to their maximum values.

section along a vertical line through 9.25 mm, in Fig 1(e). Then, we separate the near-surface scattered field from the Rayleigh wave as expressed by Eq. (1). Here, we have used that the Rayleigh wave can be approximated by a plane wave and hence that it will be mapped to a line in the wavenumber-frequency domain, while the perturbations due to local scattering will be mapped over the entire wavenumber-frequency space. Aided by the dense sampling, we use a narrow, one-pass, wavenumber frequency domain filter to estimate the incident field, shown in Fig. 1(b). Subtracting this from the field in Fig. 1(a) then gives the near-surface scattered field, shown in Fig. 1(c). Observe that most of the coherent event has been removed. The same procedure is shown for cross sections of the same Rayleigh wave in Figs. 1(e)-(g). In field data, the Rayleigh wave may be complicated by propagation effects from the source to the scattering domain and more sophisticated filtering techniques may be required. Having obtained the near-surface scattered field, we use this as the input for our imaging scheme. After inversion, we obtain the image shown in Fig. 1(d). We have focussed the energy at the actual location of the scatterer. In addition, in the upper and lower right corners, two ‘dots’ appear, which represent focussed energy from scattering from surface disturbances smaller than the cavity (difficult to see in the scattered data of Fig. 1(c)).

Test on synthetic data

To test if our algorithm can distinguish between different scatterers, we have applied it to data from two models. In both tests, the wavefield was calculated at 1-m intervals, while the source was excited at the surface with a dominant frequency of about 20 Hz. In both models, the shear velocity of the background medium is 1000 m/s and its density is 1500 kg/m$^3$. A top view of the wavefield in the first model, at 40 ms is shown in Fig. 2(a) and for the second model at 70 ms in Fig. 3(a). The actual location of the scatterers is shown by the contour lines. The source is located at position $x = -80, y = -80, z = 0$— outside the imaging domain. The size of the heterogeneities is 10 by 10 m, while the vertical extent is 20 m. The top of the heterogeneities is 5 m below the surface of an otherwise homogeneous elastic half space. The data were modeled using a 3-D, elastic integral equation method (Riyanti and Herman, 2003). In principle, scattered surface waves can be observed directly on the record. The location of a scatterer can then be inferred from the top of the apex of the diffraction. But, it may be hard to interpret these diffractions when they interfere with diffractions from other scatterers. Then, imaging can increase the lateral resolution and individual objects may be distinguished. This is shown in Fig 2(b), here we have imaged 3 scatterers. The heterogeneities are resolved and are imaged at their actual location. This is even more clear if we look at a crossection of the image through the line A-B (Fig. 2(d)). Here, we have plotted the actual distribution scaled to its maximum value and the estimated distribution, also scaled to its maximum value. The scaling is necessary because the image we obtain does not give the actual value of the contrast but a value that is proportional to the difference in density of the scatterer and the background medium. For accurately locating the scatteerr, this is, however,
not important. Finally, we image a domain in which 36 scatterers of 10 $m^3$ are present, all with different properties, chosen from a normal distribution. From Fig. 3, it is clear that the scatterers can not be found by inspection of the scattered field, due to interference of the scattering from the different scatterers. The image is shown in Fig. 3(b). We have increased the spatial resolution of the scattered energy. The individual scatterers can be identified, while the strength of the scatterers is proportional to the actual strength of the scatterer.

**Discussion and conclusions**

We show on ultrasonic and synthetic data, that it is possible to obtain spatial images of near-surface heterogeneities using scattered surface waves. These images allow one to accurately locate individual scatterers, even when many scatterers produce interfering scattered surface waves.

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**References**


