Authors

U. Harmankaya¹, A. Kaslilar¹, B. Verstraeten², S. Creten², C. Glorieux², K. Wapenaar³, D. Draganov³

¹ Department of Geophysical Engineering, Faculty of Mines, Istanbul Technical University, Istanbul, Turkey

² K.U.Leuven Laboratorium voor Akoestiek en Thermische Fysica, Leuven, Belgium.

³ Sec. Applied Geophysics and Petrophysics, Dept. of Geoscience and Engineering, Delft University of Technology, The Netherlands

Title

Locating cavities using ghost scattered waves in a scale-model experiment.

Abstract

The investigation and detection of near-surface structures (cavities, caves, tunnels, mineshafts, buried objects, archeological ruins, water reservoir, etc.) is important to mitigate geo- and environmental hazards. We use a method inspired by seismic interferometry to estimate the location of a cavity in a scaled ultrasonic experiment, representative for geophysical field problems. We use only one source at the surface and retrieve ghost scattered waves by evaluating the correlation of scattered waves at different receiver locations. As an exploitation of the ghost arrival information, the ghost travel times are determined and combined to estimate the location of a cavity with good accuracy.



Introduction

Near-surface structures such as cavities, caves, tunnels, etc., may pose risk during and after the construction of buildings, transportation ways (roads, highways, railways) or power plants (wind, solar, etc). Detecting and monitoring these near-surface structures is important to mitigate the potential hazards. We use ghost scattered waves retrieved by seismic interferometry (SI) to estimate the location of a near-surface scatterer. In our method, we use active-source SI and only one source at the surface (Harmankaya et al., 2013). Retrieving the complete Green's function requires boundary sources to enclose the receivers (Wapenaar and Fokkema, 2006). In our case, the receivers are not fully illuminated, thus non-physical arrivals appear in the SI result (Snieder et al., 2006; Halliday and Curtis, 2009, Halliday et al., 2010). As it is essential to validate a new method's effectiveness in a controlled environment (Kaslilar 2007; Bretaudau et al., 2011), in the following we test the proposed method on data from an ultrasonic laboratory experiment.

Method

We use a method inspired by SI, but we consider only one source and an array of receivers. As an isolated scattered wavefield is required, the scattered wavefield is isolated from the total wavefield at the receivers by filtering and muting all other arrivals (Harmankaya et al., 2013). On the isolated scattered wavefield a reference receiver, at which would be the virtual source (VS) position, is selected and all traces on this record, including the reference trace, are cross-correlated with the trace at the virtual-source position. In this way the common travel path from the real source to the scatterer is eliminated, and the estimation of the scatterers' locations becomes dependent only on the properties between the receivers and the scatterer. This results in the retrieval of ghost scattered waves. To estimate the location of the scatterer, the following theoretical ghost travel-time relation is used:

$$t = \frac{1}{V} \left\{ \left[\left(x_i^r - x \right)^2 + \left(z_i^r - z \right)^2 \right]^{1/2} - \left[\left(x_{vs} - x \right)^2 + \left(z_{vs} - z \right)^2 \right]^{1/2} \right\}.$$
 (1)

The relation calculates model ghost traveltimes between the virtual source, the scatterer and the receivers. In Eq. (1), V is the wave velocity, i is the index for the receiver numbers, vs denote the virtual source and x and z are the horizontal and vertical location parameters, respectively.

The traveltime relation (Eq. 1) and the traveltimes obtained for each virtual source location from the data are used in an inversion to find the unknown model parameters (the x and z location of the object). The nonlinear problem is solved iteratively. The system of equations for the forward problem is denoted as $\Delta \mathbf{d} = \mathbf{G}\Delta \mathbf{m}$. The difference between the observed t_{obs} (retrieved), and the calculated

 t_{calc} ghost scattered data is given by $\Delta \mathbf{d} = t_{obs} - t_{calc}$, the unknown model parameters - the x and z location of the object - are denoted by the vector $\Delta \mathbf{m}$, while the Jacobian matrix is represented by \mathbf{G} . The inverse problem is solved by using damped singular value decomposition and the uncertainties of the estimations are obtained by the model covariance matrix using a coverage factor 2, which provides a confidence level of 95%.

Estimation of the Location of a Cavity from Ultrasonic Data

To confirm the validity of the proposed method, an ultrasonic experiment is designed at the Laboratory of Acoustics and Thermal Physics in KU Leuven. The experimental setup is shown in Figure 1.

A 4-milimetre-wide hole was drilled into an aluminum block of size 100 mm \times 100 mm \times 80 mm (Figure 1a). This cavity extends 25 mm in the horizontal direction (Figure 1b). A Nd:YAG laser is used to generate ultrasonic waves with a bandwidth of about 1 MHz. The wave field is recorded with a laser Doppler vibrometer for 16 µs, at a sample rate of 500 MS/s, using receiver positions indicated





Figure 1 (a) Schematic side view of the aluminum block, with the locations of the laser spot source (star), receivers (triangles) and scattering cavity (circle). (b) Top view: the dashed rectangle represents the drilled hole.

by triangles in Figure 1. A total of 60 receiver positions with 0.5 mm spacing were used. To increase the signal-to-noise ratio, the source excitation was repeated 128 times at 10 pulses per second for each receiver position and the recordings were averaged. The recorded wave field is shown in Figure 2a. High-frequency noise in the record is suppressed using a weighted average smoothing and a 2-D median filter, results of which are given in Figure 2b.



Figure 2 (a) Recorded ultrasonic wave field. (b) Smoothed wave field after applying a moving average filter and 2-D median filter. Symbols P_D , S_D , R_D , PWS, SWS, RWS, and SR denote the direct P-waves, direct S-waves, direct Rayleigh waves, P-wave scattering, S-wave scattering, Rayleigh-wave scattering and side reflections, respectively. (c) Direct wave field obtained after frequency-wavenumber filtering. (d) Scattered wave field, obtained by subtracting the direct wave field in (c) from the full wave field in (b).

The proposed method for estimating the scatterer's location requires an isolated scattered wave field, so the elimination of the direct waves is needed. For this purpose, an f-k (frequency-wavenumber) filter is used. Using this filter, the direct wave field (Figure 2c) can be separated, and the scattered wave field (Figure 2d) can be obtained by subtracting the direct wave field (Figure 2c) from the total wave field (Figure 2b). After muting out the early arrivals in the scattered wave field (Figure 3a), SI is applied to the remaining scattered waves by cross-correlating the selected trace at the VS location with all traces on the isolated scattered wavefield. Figure 3b-d shows the retrieved interferometric ghost scattered waves for three separate VS locations: 13, 23 and 31 (16, 21 and 25 mm). The ghost traveltimes are picked from the maximum amplitude of the retrieved ghost scattered waves (grey curves on Figure 3b-d). After f-k filtering, it is observed that direct arrivals and forward-scattered



wave field are eliminated together, as they have similar slope and frequency content. For this reason, travel times on the right branch are extrapolated by taking the symmetry of the back-scattered (left) branch. It is also important to note that, in case of disturbed wavefields as seen in Figure 3b-d, the apex of the scattered arrivals can be used to determine the apex in the interferometric panels. In Figure 2b, the apex of the scattered arrivals can be visually observed from PWS or RWS arrivals. The remnants of the S-wave scattering are indicated with arrows in Figure 3b-d.



Figure 3 (a) The scattered wave field after muting out arrivals other than the scattered waves in Figure 2d. (b), (c) and (d) show the retrieved ghost scattered waves obtained by applying seismic interferometry to (a) for virtual source locations 13, 23 and 31 (16, 21 and 25 mm), respectively. The grey lines show the picked travel times. The arrows represent the remnants of S-wave scattering.

To find the location of the scatterer, the traveltime relation and the traveltimes obtained for each virtual-source location are used in the inversion. The best fit between the observed and calculated traveltimes of the ghost scattered waves for virtual sources 13, 23 and 31 (16 mm, 21 mm and 31 mm) are given in Figure 4a. The initial model parameters and the updated parameters are given in Figure 4b. After six iterations, the model parameters - the horizontal and vertical location of the scatterer - converge to the actual values. In Figure 4c, the estimated parameters and their 95% confidence intervals, obtained by Eq. (4), are shown for each virtual-source location. The error bars for the average values are calculated by error propagation and the blue lines are the lateral and vertical bounds of the scatterer. The estimated locations are within the boundaries of the real location of the cavity, thus confirming the validity of the method.

Conclusion

A method proposed for obtaining the location of a near-surface scatterer by using traveltimes of ghost (non-physical) scattered waves is applied to data from an ultrasonic experiment. Using only one surface source, the traveltimes of ghost scattered waves are used in an inversion to find the location of a buried cavity. It is observed that the location of the cavity is correctly estimated.

Acknowledgements

This work is supported by The Scientific and Technological Research Council of Turkey with the project TUBITAK CAYDAG110Y250 titled "Detecting Near-surface Scatterers by Inverse Scattering and Seismic Interferometry of Scattered Surface Waves". We gratefully acknowledge this financial support. The research of D.D. is supported by the Division for Earth and Life Sciences (ALW) with financial aid from the Netherlands Organization for Scientific Research (NWO, VIDI grant 864.11.009). C.G. acknowledges KU Leuven for financial support (OT/11/064). B.V. is grateful to



FWO and SCK (research scholarship ZKC1026). The authors thank Werner Neefs (Laboratory of Acoustics and Thermal Physics, KU Leuven) for his technical support when performing the experiment. We also thank the Colorado School of Mines for providing the Seismic Un*x (Cohen and Stockwell, 2012) package as open source software.



Figure 4 (a) Observed (dot) and calculated (solid line) traveltimes; (b) Estimated horizontal and vertical locations of the cavity scatterer for virtual sources 13 (blue, 16 mm), 23 (brown, 21 m) and 31 (red, 25 m). The values for the zeroth iteration correspond to the initial parameters for the inversion. (c) Estimated model parameters and their 95% confidence limits, blue lines illustrate the lateral (left) and vertical (right) bounds and the midpoint of the scatterer.

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