Estimating the location of a tunnel using interferometric times of Rayleigh-wave scattering

A. Kaslilar[1]*, U. Harmankaya[1], K. Wapenaar[2], D. Draganov[2]

[1] Department of Geophysical Engineering, Faculty of Mines, Istanbul Technical University, 34469, Istanbul, Turkey

[2] Sec. Applied Geophysics and Petrophysics, Dept. of Geoscience & Engineering, Delft University of Technology, The Netherlands

Main objectives:

We show a technique inspired by seismic interferometry and use it to estimate the location of a buried scatterer by correlation and inversion of scattered Rayleigh waves.

New aspects covered:

We demonstrate the efficiency of the method when applied to seismic field data. We obtain good estimations for the location of a tunnel.

SUMMARY

Inspired by a technique called seismic interferometry, we estimate the location of a scatterer using scattered waves. We isolate the scattered wavefield and evaluate the result of correlating scattered waves at different receiver locations. The cross-correlation eliminates the travel path between a source and a scatterer, making the estimation of the scatterers' locations dependent only on properties between the receivers and the scatterer. We illustrate the potential of this method by locating a tunnel from seismic field data, recorded along a line with multiple source and receiver locations. As near-surface scatterers are potential weak zones and may pose risk for the environment, to mitigate geo- and environmental hazards, this method can be an efficient alternative in detection of such structures.

Introduction

The Earth's subsurface contains heterogeneities at different scales. These heterogeneities may scatter seismic waves when the dominant seismic wavelength is close to the size of the heterogeneities. Scattered waves can be used for locating and characterizing near-surface structures in engineering, exploration and global seismology (*e.g., Grandjean and Leparoux,* 2004*; Xia et al.,* 2007*; Harmankaya et al.,* 2013; *Snieder and Nolet,* 1987; *Rickers et al.,* 2012). In our method, we use correlations of scattered arrivals to estimate the location of scatterers, but we only correlate isolated scattered waves due to one source at the surface. In terms of seismic interferometry, correlation of scattered fields using a single source only retrieves non-physical (ghost) arrivals (*Mikesell et al.,* 2009*; Harmankaya et al.,* 2013, *Meles and Curtis,* 2013). In our case, the scattered waves are body waves, caused by the incident Rayleigh waves. We apply the method to seismic field data and successfully estimate the location of a buried tunnel (*Kaslilar et al*., 2013).

Estimation of the Tunnel Location by Cross-correlation of Scattered Waves

The method proposed by Harmankaya et al. (2013) is applied to seismic field data collected above an a priori known tunnel by BRGM (Bureau de Recherche Géologique et Minière) at Jargeau site, Loiret, France (Leparoux et al., 2000). The data consists of multiple shot gathers recorded along a 63-metre-long profile with 24 channel receivers. The nearest offset, shot and receiver-group intervals, and temporal sampling are 5 m, 1 m, 1 m, and 1 ms, respectively. The tunnel's walls are of masonry, with its upper surface at a depth of 3 m. The tunnel is 2 m by 1.5 m in height and width, respectively (Figure 1). For the shot gathers, the dominant frequency is about 40 Hz. The Rayleigh wave velocity is calculated as 180 m/s from the slope of the direct Rayleigh wave arrival in Figure 2a. Using the velocity and the dominant frequency, the dominant Rayleigh wavelength is calculated as 4.5 m, which is comparable to the size and the depth of the scatterer. Due to the buried tunnel, we record converted S body waves from the scattering of the incident Rayleigh waves. Therefore, for estimating the location of the scatterer, we use S-wave velocity (V_S) of 200 m/s, calculated using the relation $V_R \approx 0.9 V_S$, .

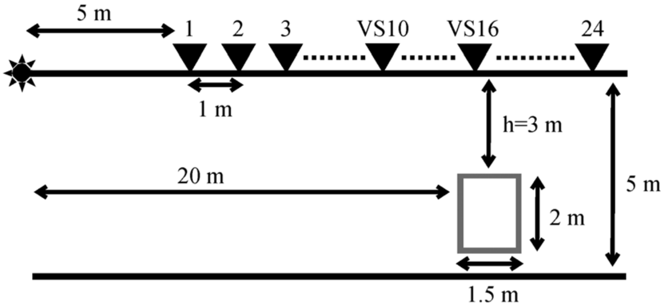

Figure 1*. Sketch of the tunnel (the rectangle) and the acquisition geometry at the surface (not to scale). The star represents the source, the triangle-receivers, and VS10 and VS16 indicate two selected virtual–source positions.*

Estimating the horizontal (x) and vertical (z) coordinate of the tunnel requires an isolated scattered wavefield. In this case, we take advantage of having several shot gathers. Each shot gather represent a recording at 24 receivers from a source 5 m to the left of the leftmost receiver. We select two shot gathers, one above and the other away to the left (not above) of the tunnel. Since one of the shot gathers is away from the tunnel, it can be considered as the incident wavefield due to the background medium without a scatterer (Figure 2a), while the one above the tunnel is the total wavefield, containing both incident and scattered wavefields (Figure 2b). Ideally, taking the difference of the assumed total and incident wavefields (Figures 2b and 2a) would result in a scattered wavefield, provided that the medium properties are not changing in the lateral direction. In our case, only a part of the incident wavefield is suppressed, but this is sufficient to improve the interpretability of the scattering due to the tunnel (Figure 2c). For the first estimation of the scatterer location, we chose the hyperbola with the least distorted waveforms (marked as S1 in Figure 2c), which is due to the right corner of the tunnel. The remnants of the direct arrivals (i.e., incident wavefield) and other unnecessary arrivals are muted out to obtain a clean scattered wave hyperbola (Figure 3a).

In our method, inspired by seismic interferometry, a reference trace is chosen at a virtual-source (VS) location, and is correlated with all the traces on the isolated scattered wavefield. This correlation eliminates the common travel path from the actual source to the scatterer and results in the retrieval of ghost (non-physical) scattered body or surface waves. The scatterer location parameters (x and z) are estimated by inverting for the following ghost travel-time relation:

$$t = \frac{1}{V_S}\left\{\left[\left(x_i^r - x\right)^2 + \left(z_i^r - z\right)^2\right]^{1/2} - \left[\left(x^{VS} - x\right)^2 + \left(z^{VS} - z\right)^2\right]^{1/2}\right\}, \tag{1}$$

where i is the index for the receiver numbers and the superscript VS indicates the parameters of the virtual source.

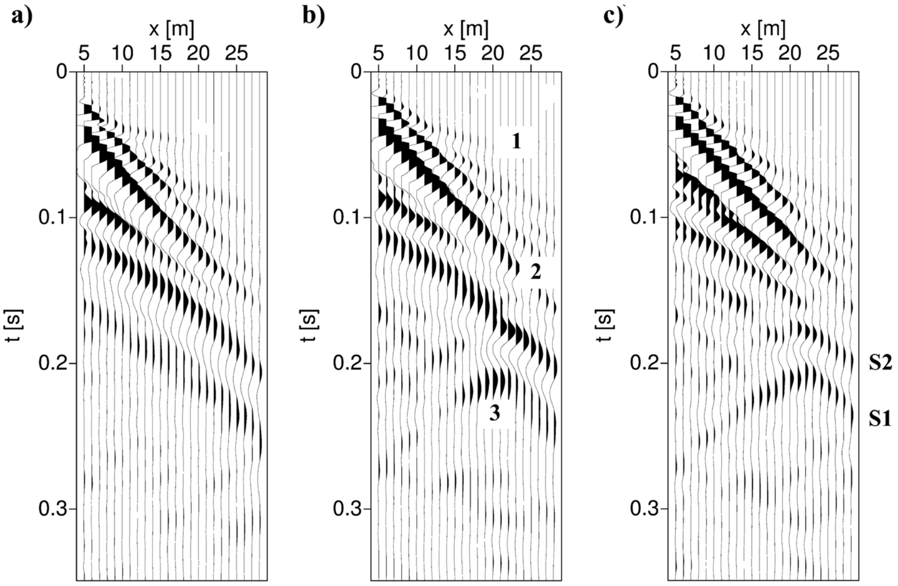

Figure 2. *(a) Common shot gather for shot 10 representing assumed incident field. (b) Common shot gather for shot 19 representing assumed total wavefield. The direct and refracted body waves, direct Rayleigh waves, and scattered waves are labeled by 1, 2 and 3 respectively. (c) The resulting wavefield obtained from the difference of the gathers in Figure 2a and 2b. Diffractions from the right and left corners of the tunnel are indicated with S1 and S2, respectively.*

For the shot gather above the tunnel, we choose the receivers 10 and 16 as the VS locations, i.e., VS10 (14 m) and VS16 (20 m) in Figure 1, and set the the active-source position as the origin of the coordinate system. For each VS location, we cross-correlate the trace at the VS receiver with the other traces on the muted scattered wavefield (Figures 3a). In this way, the ghost scattered body waves are retrieved (Figure 3b-c).

The inversion is performed for the picked travel times of the retrieved ghost arrivals (dots in Figure 4a). We solve the inverse problem using damped singular value decomposition. The system of equations is given as $\mathbf{\Delta d} = \mathbf{G\Delta m}$. The difference between an observed ghost arrival time, t_{obs}, and a calculated one, t_{calc} is given by the vector $\mathbf{\Delta d} = t_{obs} - t_{calc}$. The unknown model parameters – the coordinates x and z of the scatterer – are denoted by the vector $\mathbf{\Delta m}$, while the Jacobian (sensitivity) matrix is denoted by $\mathbf{G}$. Uncertainties of the estimations are calculated using the model covariance matrix, considering a coverage factor 2, which provides a confidence level of 95%.

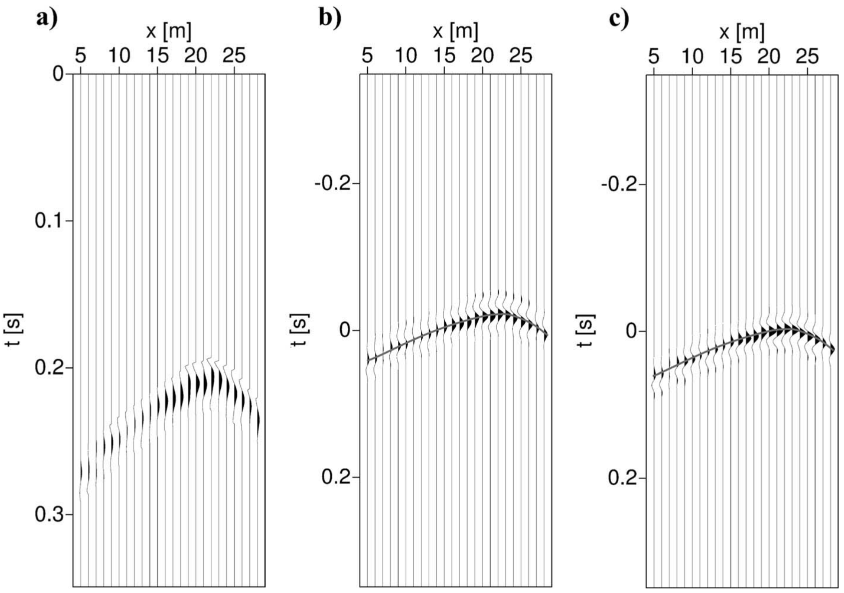

Figure 3. *(a) Isolated scattered wavefield for the S1 arrivals. Ghost-scattered arrivals retrieved by cross-correlation applied to scattered wavefield for the virtual sources at (b) VS10 and (c) VS16. Picked travel times are shown with gray lines.*

The travel-time inversion is performed for VS10 and VS16 for arrival S1. In Table 1, we compare the estimated coordinates of the right corner of the tunnel to the corner's actual location. The third row in Table 1 shows the average value of the estimated parameters. Figure 4a shows the picked (observed) ghost travel times and the calculated times using the model parameters from final iteration, while Figure 4b shows the updates of the model parameters after each iteration. Good agreement between the observed and the calculated travel times (Figure 4a) and also between the actual and the estimated locations (Table 1) is observed. The normalized percentage errors for the travel time and the estimated model parameters are calculated and given in Table 1 as well.

The same procedure is also applied for arrival S2 in Figure 2c, which is the scattering from the left corner of the tunnel. Since the left branch of the scattered wavefield S2 has distorted waveforms, we chose the VS trace from the right branch of S2, VS20, and obtain also an estimation of the location of the left corner of the tunnel (S2 in Table 1).

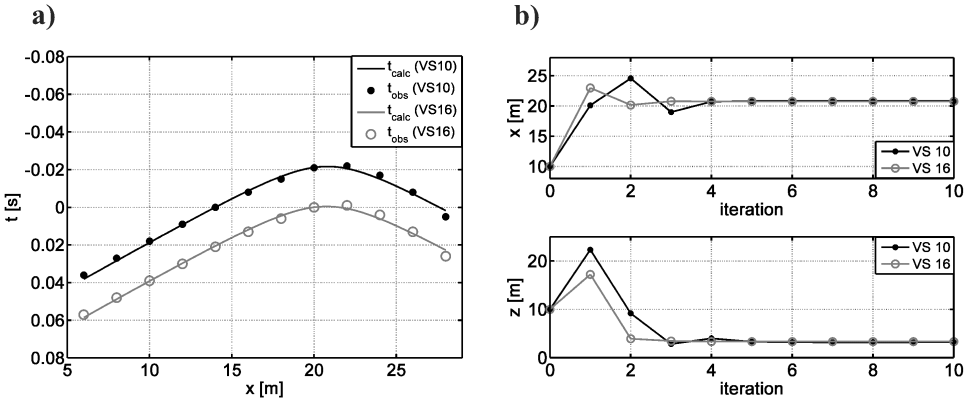

***Figure 4**. (a) Travel times for arrival S1: observed (dots) and calculated (solid line); (b) Estimated x and z coordinate of the tunnel's right corner for the virtual sources 10 (black) and 16 (gray). The initial parameters of the inversion are shown as the zeroth iteration.*

Conclusions

We applied our method, which uses principles of seismic interferometry and inversion, to successfully estimate the location of a tunnel. We used recordings from two active sources (above and away from the tunnel) to isolate scattered arrivals, which were afterwards correlated. The retrieved non-physical travel times were inverted to estimate the locations of the corners of the tunnel. With this application, we showed the potential of the method at geotechnical scale. When the scattered wavefield can be isolated in another way, our method would allow estimating the location of a scatterer with recordings from a single active source. An important advantage is that the method is independent of the wave propagation from the source to the scatterer.

Table I. *The estimated model parameters for each virtual-source (VS #) location for the configuration given in Figure 1. The listed values are actual location of the scatterer (AL), the estimated locations (x and z) with their 95% confidence levels (1.96 σ), percentage errors on the travel times (E_t), and model parameters (E_m).*

	VS #	**AL [m]** **x / z**	**$x \pm \sigma_x$ [m]**	**$z \pm \sigma_z$ [m]**	**Et [%]**	**Em [%]** **x / z**
	S1					
	10	21.5/3.0	20.80±0.11	3.18±0.39	0.64	3.6/6.0
	16		20.76±0.13	3.34±0.19	0.26	3.4/11.3
Average			20.78±0.12	3.26±0.31		3.3/8.6
	S2					
	20	20.0/3.0	19.98±0.08	3.15±0.18	0.16	0.1/5.0

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