DETECTING TUNNELS AND UNDERGROUND FACILITIES USING DIFFRACTED P-WAVES

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Abstract

Numerous near surface geophysical techniques have been applied to the tunnel detection problem. Thus far, successful techniques require differentiating tunnel signature from noise, or a priori knowledge of tunnel location for optimized data acquisition and processing. We demonstrate a seismic method for locating tunnels that requires minimal interaction with the data and no a priori knowledge of tunnel location. The principle assumption of our processing algorithm is that every point in the subsurface potentially contains a tunnel. Two seismic reflection datasets were processed using the proposed algorithm – one synthetic dataset and one acquired over Moffat Tunnel in Winter Park, Colorado. Each dataset were corrected for diffraction moveout in both the source domain and receiver domain, assuming that all receivers were located directly above a tunnel. The result of this processing algorithm is a 2D profile with a seismic amplitude anomaly at the lateral location and zero-offset traveltime correct for the tunnel. The amplitude of the tunnel anomaly is 26.6 dB and 14.4 dB greater than the background on the synthetic and Moffat Tunnel datasets, respectively. This study indicates that this method could possibly be used as part of a semi-automated procedure for tunnel detection.

Introduction

The ability to rapidly and accurately locate tunnels over a large area is of interest to both law enforcement and military operations (Steeples, 2001). Comparison of the many geophysical techniques used for tunnel detection shows that seismic methods are the most sensitive to changes in velocity and density of subsurface materials associated with the presence of a tunnel (Miller et al, 2004). A surface wave technique incorporating SASW, MASW, and CMP methods successfully enhanced Rayleigh-wave diffractions to delineate voids (Ivanov et al, 2003). Traditional seismic reflection techniques have been used to interpret voids as amplitude anomalies on common midpoint (CMP) stacked sections (Miller and Steeples, 1988; Miller and Steeples, 1991). However, these methods only allow indirect detection of tunnels by interpretation, rather than by direct imaging. Khaidukov et al (2004) directly detect subsurface scattering objects by muting focused reflection energy on synthetic shot gathers and migrating the remaining P-wave diffractions to image small scattering objects in modeled seismic data. This method requires muting some diffraction energy along with focused reflections to enhance diffractions on shot gathers, which decreases the amplitude of the diffraction.

The objective of this study is to demonstrate a seismic method for locating tunnels that requires minimal interaction with the data and no a prior knowledge of the tunnel location. The traveltime equation for a tunnel of unknown depth is developed for diffraction moveout from a tunnel with an assumed lateral location. This equation is the basis for a processing algorithm designed to enhance a diffraction apex on common shot gathers and common receiver gathers. Two datasets are presented in which three tunnels were successfully detected using the proposed algorithm.

Theory and Method

The traveltime equation for a compressional wave (P-wave) diffraction is a function of the P-wave velocity (v_p), lateral distance from the source to the tunnel (x_s), lateral distance from the tunnel to an active receiver (v_r), and depth of the tunnel (h):

$$t_d = \frac{1}{v_p}\left[\sqrt{x_s^2 + h^2} + \sqrt{x_r^2 + h^2}\right] \qquad \text{Eq. 1}$$

When the active receiver is directly over the tunnel, depth can be rewritten:

$$h = \frac{t_0^2 v_p^2 - x_s^2}{2 \cdot t_0 v_p} \qquad \text{Eq. 2}$$

Substituting Eq. 2 into Eq. 1 results in the traveltime equation for P-wave diffraction from a tunnel of unknown depth:

$$t_d = \frac{1}{v_p}\left[\sqrt{x_s^2 + \left(\frac{t_0^2 v_p^2 - x_s^2}{2 \cdot t_0 v_p}\right)^2} + \sqrt{x_r^2 + \left(\frac{t_0^2 v_p^2 - x_s^2}{2 \cdot t_0 v_p}\right)^2}\right] \qquad \text{Eq. 3}$$

This equation is hyperbolic and unique to diffractions on both common shot gathers (when x_s is constant) and common receiver gathers (when x_r is constant). These observations were used to develop an algorithm to enhance the diffraction apex on each shot gather and correct for diffraction moveout on receiver gathers.

For every shot gather, one duplicate gather is created for each trace in the record. The lateral tunnel location is assigned to the first trace of the first duplicate, the second trace of the second duplicate, etc. Duplicate gathers are corrected for diffraction moveout using the P-wave velocity determined from first arrivals (Figure 1) and stacked. Diffraction moveout will be properly corrected and stack

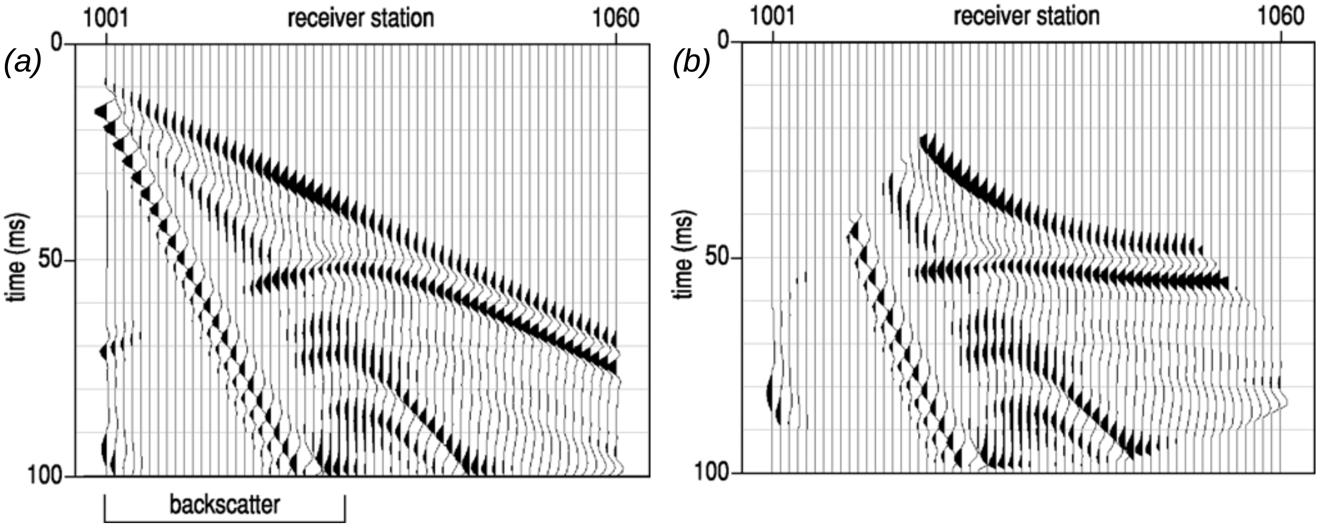

Figure 1. Duplicate shot gather from source station 1000 (a) before, and (b) after correction for diffraction moveout. The bracket indicates the portion of the diffraction that is backscattered toward the source in (a). Assumed tunnel location for this duplicate gather is 1029.

coherently only when the source station is correctly assigned to the receiver above the tunnel. The resulting stacked traces are assembled into a modified shot gather, in which each receiver station was assumed to be over the tunnel. The tunnel apex is enhanced and other wavefield components are attenuated (Figure 2).

Modified shot gathers are sorted into common receiver gathers (Figure 3). The location of a diffraction apex on a receiver gather always corresponds to coincident source and receiver stations. Therefore, the lateral tunnel location is assumed to be the receiver station of each receiver gather. The gathers corrected for diffraction move-out and stacked into one trace per receiver station. The resulting traces are assembled into a cross-sectional format for the final gather – a profile indicating lateral tunnel location and two-way zero-offset traveltime.

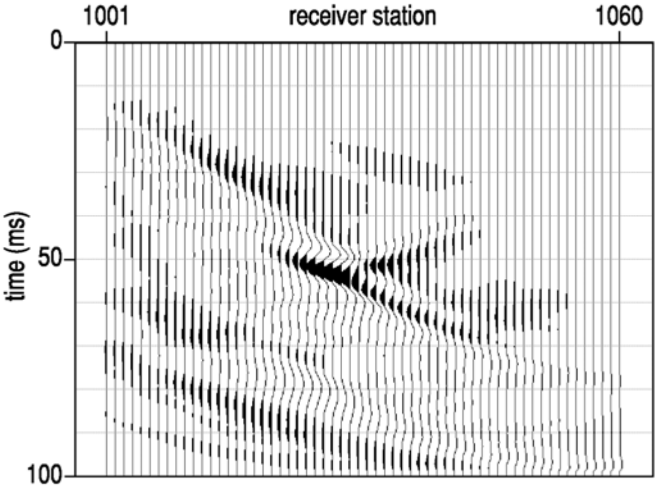

Figure 2. Modified shot gather from source station 1000 (shot gather from Figure 1a after diffraction apex enhancement).

Case Study I: Synthetic Dataset

Data Acquisition

A synthetic dataset was created to simulate data acquisition over a tunnel, test the diffraction enhancement algorithm, and test the effectiveness of several additional steps. A 2×1 m tunnel is 10 m deep in a half space with a P-wave velocity of 1000 m/s. A fixed spread of 60 receivers with 1 m station spacing is located above and perpendicular to the tunnel, which intersects the line of receivers at the 29th station. The source wavelet is a 150-Hz Ricker wavelet. The source starts 1 m off-end and is walked through the spread at approximately 10 m intervals. A bandpass filter and AGC were applied to remove source-generated noise and adjust amplitudes. Each shot gather has a bulk static shift of +4 ms.

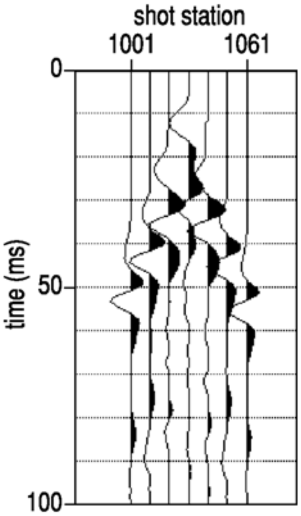

Figure 3. Common receiver gather corresponding to receiver station 1029.

Data Analysis

The diffraction apex enhancement algorithm was performed as outlined above on each of the sixty shot gathers. The result is a 2D profile with an amplitude anomaly associated with the tunnel within the 15 to 40 ms interval on traces from receiver stations 1026-1033 (Figure 4). The reference amplitude of background energy not associated with the tunnel was determined from the amplitude spectrum calculated for the 15 to 40 ms interval on a trace containing no energy from the diffraction. The amplitude of the tunnel anomaly was determined from the amplitude spectrum calculated for the same interval of the trace from station 1029.

To test the effectiveness of additional steps in the algorithm, each of three steps was individually included and the amplitude of the resulting tunnel anomaly was compared to the reference amplitude. First, to attenuate energy not associated with the diffraction prior to stacking, a horizontal-pass *f-k* filter was applied to moveout-corrected duplicate shot gathers and receiver gathers. Second, to minimize stacking of traces with little or no recorded diffraction energy that decrease the post-stack amplitude of the diffraction apex, only a window of traces surrounding the assumed tunnel location on moveout-corrected gathers were stacked. Third, because the linear portion of the diffraction hyperbola propagating away from the seismic source has the same slope as the first arrival energy on duplicate shot gathers, this energy will coherently stack after moveout correction. To reduce the amplitude of the first arrival on post-stack traces, only traces that potentially contain diffraction energy backscattered in the direction toward the source were stacked (Figure 1b).

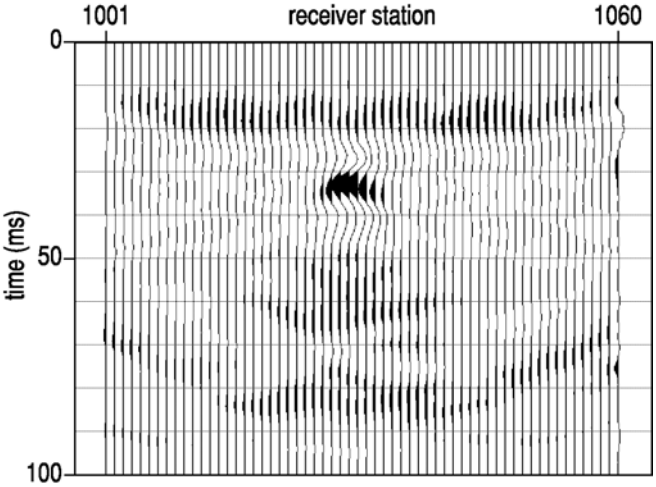

Figure 4. Final profile with an amplitude anomaly at the lateral location and two-way zero-offset traveltime correct for the tunnel.

Results and Discussion

The reference amplitude calculated from background energy on the profile generated with the diffraction enhancement algorithm with is 1.1. The wavelet with the largest amplitude occurs on trace 1029 with an amplitude of 22.1 dB greater than the background. The arrival time of the wavelet is approximately 24 ms, a time consistent with the two-way zero-offset travel time for a 10 m deep tunnel in material with a velocity of 1000 m/s.

The horizontal-pass *f-k* filter effectively attenuates energy not associated with the diffraction on duplicate shot gathers. The amplitude of the tunnel anomaly on trace 1029 of the resulting final profile is 22.1 dB greater than the background. Therefore, the filter does not improve the result, and stacking sufficiently attenuates energy that is not horizontal after correction for normal moveout.

The optimal windows for stacking traces in duplicate shot gathers and receiver gathers are 25 and 7, respectively. Stacking fewer traces on duplicate shot gathers reduces the number of traces in the stack that either destructively stack with the diffraction or constructively stack at a different time. This results in a final profile that more clearly indicates the tunnel location, and a tunnel anomaly with an amplitude of 27.1 dB greater than the background.

Stacking only traces that correspond to receivers that would record backscattered energy from the tunnel did not improve the final profile. The absolute amplitude of the tunnel anomaly is reduced to 21.8 dB greater than background, ajnd other recorded energy does not sufficiently attenuate, thereby increasing the difficulty of interpretation of the tunnel location.

Case Study II: Moffat Tunnel (Winter Park, CO)

Data Acquisition

Moffat tunnel is a 7×5 m man-made railroad tunnel in ryolitic granite that cuts through the continental divide. Seventeen meters to the south of the railroad tunnel is a smaller water tunnel (Miller and Steeples, 1988). Two surveys were acquired 19 and 86 m (Lines 1 and 2, respectively) above and perpendicular to Moffat Tunnel in Winter Park, Colorado. The survey acquired at Line 1 was a roll-along style survey with the source 9.1 m off-end from the nearest of 24 active receivers. The seismic source was a surface .30-06 rifle and receivers were 100-Hz geophones with 1.2 m station spacing. Two shots were recorded separately at each station, and the source and receivers were rolled 0.6 m. The survey acquired at Line 2 was a walk-away style survey with a fixed spread of 24 active receivers directly over the railroad tunnel. The seismic source was a downhole .50-caliber rifle and receivers were 100-Hz

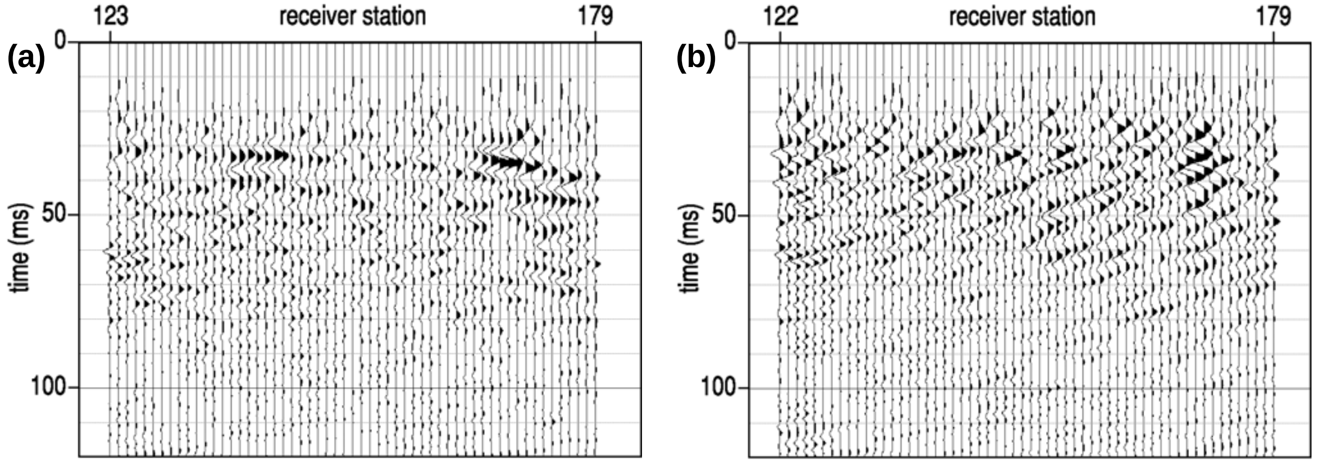

Figure 5. (a) Line 1 profile resulting from the diffraction enhancement algorithm. (b) Resulting profile when only backscattered energy is stacked.

geophones with 1.2 m station spacing. Five shots were recorded separately and stacked at each of 7 stations. The nearest source station was 53.6 m and source station spacing was 7.3 m.

Data Analysis

A final profile was generated for each line using the diffraction apex enhancement algorithm described above. Each of the additional methods described for the synthetic dataset were tested to further enhance the diffraction apex. In addition, both an air-coupled wave mute and first arrival mute prior to diffraction apex enhancement were tested on shot gathers from Line 1.

Results and Discussion

On Line 1, the background amplitude within the 25 to 40 ms interval of a trace containing representative amounts of noise is 4.5. The absolute amplitude of the railroad and water tunnel anomalies within the same time interval on traces 168 and 141 are 13.2 dB and 11.0 dB greater than the background, respectively (Figure 5a). The horizontal-pass *f-k* filter did not significantly improve the final profile. Optimal stacking windows for duplicate shot gathers and receiver gathers of 19 and 16, respectively, improved the amplitudes of the railroad tunnel anomaly to 20.4 dB and the water tunnel anomaly 17.8 dB greater than the background, while sufficiently attenuating other recorded energy. Air-coupled wave and first arrival mutes did not improve tunnel anomaly amplitudes, and reduced destructive stacking of other recorded wavefield components and noise. Likewise, stacking only backscattered energy reduces tunnel anomaly amplitudes and significantly increases the difficulty of distinguishing tunnel anomalies from other recorded energy (Figure 5b).

On Line 2, the background amplitude within the 60 to 100 ms interval of a trace containing representative amounts of noise on the final profile is 9.0. The absolute amplitude of the railroad tunnel on trace 348 is 15.4 dB greater than the background (Figure 6). The

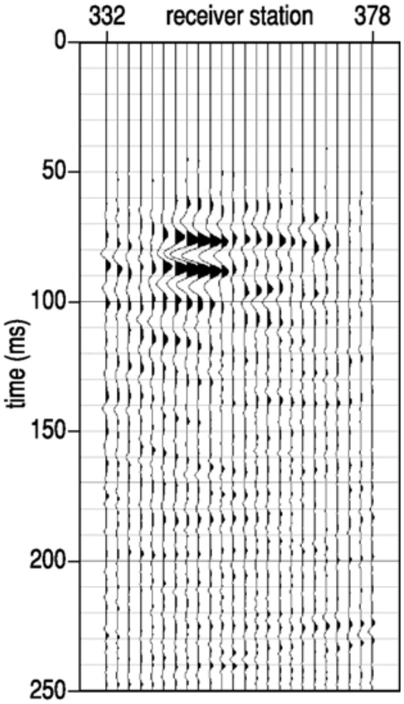

Figure 6. Line 2 profile resulting from the diffraction enhancement algorithm.

horizontal-pass *f-k* filter had little effect on attenuation of other recorded energy and did not improve the amplitude of the railroad tunnel anomaly. Use of a stacking window or stacking only backscattered energy decreases the amplitude of the tunnel anomaly and increases the difficulty of distinguishing the tunnel anomaly from other recorded energy.

Conclusions

The diffraction enhancement algorithm successfully enhances the diffraction apex on shot gathers and produces a final profile with a seismic amplitude anomaly at the lateral location and zero-offset traveltime correct for a tunnel. The amplitude of the tunnel anomaly on the final profile of synthetic seismic data is 22.1 dB greater than the background. The amplitudes of the railroad and water tunnel anomalies on the final profiles from the Moffat Tunnel dataset are 17.7 dB, on average, and 11.0 dB greater than the background, respectively. Use of a stacking window improves the amplitude of the tunnel anomaly with respect to other recorded energy on final profiles of synthetic and field data by 4.5 dB, on average. Based on these results, this method has potential for use in a semi-automated procedure for tunnel detection.

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