Near surface tunnel detection using diffracted p-waves: a feasibility study

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Summary

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 data acquisition and processing. We propose a seismic method that has the potential to minimize interaction with the data and requires no a priori knowledge of tunnel location. Synthetic fixed receiver spread data is processed first in the common source domain then in the common receiver domain, resulting in a final gather than contains a relatively large-amplitude, low-frequency wavelet from which the depth and lateral location of the tunnel can be determined. 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). Many non-invasive near surface geophysical techniques have been used to detect tunnels, with varying degrees of successs. Spiegel et al (1980) created an electrical resistivity anomaly model for elongated 3D voids, which could be used to aid the interpretation of field data. Butler (1984) measured gravity and interpreted residual gravity anomalies to detect a 10 m deep air-filled cavity system; data were acquired over a period of several days and required the necessary corrections to produce a final residual gravity map. Verification drilling sometimes resulted in interception of clay-filled cavities as opposed to air-filled voids. Surface borehole methods have been successful at determining an approximate location, but require multiple passes to accurately locate the tunnel (Moran et al, 1993).

Seismic techniques show substantial promise. Shallow, high-resolution seismic reflection has been successfully used to detect voids in a 1 m thick, 7 m deep coal seam (Miller et al, 1991). Landa and Keydar (1998) detect scattering objects by analyzing diffraction curves and concentrating signal from diffractions on a seismic section. Miller et al (2004) have developed a prototype system to scan the subsurface and detect anomalies unique to underground facilities by processing data using a variety of methods designed to focus on specific aspects and components of the seismic wavefield. Khaidukov et al. (2004) developed a method of diffraction enhancement by focusing shallow reflections in a shot gather to a point, muting focused reflections, and defocusing the residual wavefield so all that remains are other usual portions of the wavetrain (e.g. ground roll, air wave) and diffractions for imaging. Diffraction of Rayleigh waves has been used to successfully detect both modeled and real near surface voids (Xia et al, 2006).

This study uses synthetic seismic data to determine the feasibility of locating tunnels based on diffracted p-waves. Diffractions are corrected for receiver offset and enhanced, while noise and other seismic energy are suppressed in the common source domain. Data are resorted into the common receiver domain, then manipulated and collapsed into one trace for each receiver station. The result is a single gather containing wavelets at the lateral location and depth of the tunnel. This method, coupled with complementary seismic tunnel detection methods describe above, could feasibly be used to rapidly and accurately locate tunnels.

Theory and Method

Seismic energy that encounters a tunnel in the near surface will return as diffracted energy. The two-way traveltime of energy diffracted from a tunnel, derived from the relationship between the tunnel, source, and receiver locations is:

$$t_d = (1/V_p)\{(x_s^2 + h^2)^{1/2} + (x_r^2 + h^2)^{1/2}\} \qquad (1)$$

where V_p is the seismic p-wave velocity of the layer in which the diffractor is located, h is the depth of the tunnel, and x_s is the lateral distance from the tunnel to the source, and x_r is the lateral distance from the tunnel to a receiver. When x_s is constant, the traveltime equation of a diffraction event describes the shape of the diffraction on a common shot gather. The apex of the hyperbola will always be located at the minimum x_r, the receiver closest to the tunnel. When x_r is constant, the traveltime equation (1) describes the shape of the diffraction on a common receiver gather. The apex of the hyperbola will always be located at the minimum x_s, the source station closest to the tunnel. Based on these observations, we have developed a method for processing seismic data that contains diffraction events from a tunnel.

The first step is to enhance diffraction events on common source gathers. A single shot gather is replicated so that the total number of gathers equals the number of receiver stations in the gather, and a geometry assigned to duplicate gathers assuming each point in the subsurface contains a scattering object (i.e. tunnel). The source station is assigned to the n^{th} receiver station of the n^{th} duplicate gather. Because a diffractor acts as a point source, when the source station is assigned to the receiver station above the tunnel, the diffraction will flatten when corrected for normal moveout, using a normal moveout velocity (V_{NMO}) approximately equal to half the seismice p-wave velocity (V_p) (Sheriff and Geldart, 1982). Duplicate gathers are corrected for normal moveout using $V_{NMO} \approx ½V_p$, where V_p is derived either from a refracted arrival or a reflection. Traces from each duplicate gather are then horizontally stacked, resulting in one trace per duplicate gather. Only the gather to which the receiver above the tunnel was assigned the source station will properly move out, and result in a high-amplitude wavelet at the time corresponding to t_0, the traveltime of the diffraction apex. These traces are then resorted into one diffraction-enhanced shot gather.

The above procedure is repeated for the remaining shot gathers. Once all shot gathers have been diffraction-enhanced, all traces are resorted into common receiver gathers, which contain diffraction hyperbola as previously described. A similar procedure is used to enhance the diffraction as was used for shot gathers. A single receiver gather is replicated so that the total number of duplicate gathers equals the number of shot stations in the gather, and a geometry assuming every point in the subsurface contains a scattering object is assigned to each duplicate gather. The source station is assigned to the m^{th} receiver station of the m^{th} duplicate gather, and duplicate gathers are corrected for normal moveout using approximately half the seismic p-wave velocity. All traces associated with the receiver station are then stacked into one trace. This is repeated for the remaining common receiver gathers. Traces are then resorted into one gather with a total number of traces equal to the total number of receiver stations. A relatively high-amplitude, low-frequency wavelet exists at the time corresponding to the two-way traveltime from the source station closest to the tunnel to the receiver station closest to the tunnel on traces corresponding to the lateral location of the tunnel.

Synthetic Example and Discussion

To determine the feasibility of this method, it was tested on a synthetic dataset modeling seismic acquisition over a tunnel using a fixed receiver spread (Figure 1). To suppress undesirable portions of the wavefield (i.e. ground roll), data were bandpass filtered. Resulting shot gathers contain diffraction hyperbola with apexes recorded by the receiver above the tunnel (Figure 2). Using the procedure described above, shot gathers were duplicated, assigned the previously-described geometry, and corrected for normal moveout. Only duplicate gathers in which the source station was assigned to the receiver station above the tunnel properly moved out and resulted in a large-amplitude wavelet after horizontal stacking (Figure 3). Diffraction-enhanced shot gathers were resorted into common receiver gathers, duplicated, assigned a geometry, corrected for normal moveout, and horizontally stacked (Figure 4). Traces, one per receiver station, were resorted into one gather that contains a relatively large-amplitude, low-frequency wavelet associated with the tunnel (Figure 5). The wavelet associated with the receiver directly above the tunnel has the largest amplitude and arrives at the time corresponding to the shortest traveltime of diffracted energy (recorded by the receiver directly above the tunnel when the source was directly above the tunnel). Later wavelets of comparable amplitude are caused by diffraction multiples that would not occur in the real world, but are a product of our model.

Conclusion

Processing synthetic shot gathers modeling fixed-spread seismic data acquired over a tunnel with the proposed method results in large-amplitude, low-frequency wavelets, relative to residual signal, at the traveltime corresponding to and lateral location of the tunnel. This procedure could be used to process real seismic data acquired over a tunnel to determine accurate lateral location and depth of the tunnel.

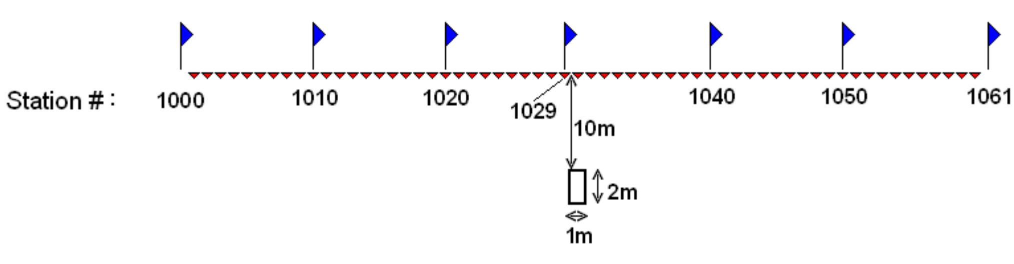

Figure 1: Model fixed receiver spread configuration above a tunnel. Receiver spacing (receiver stations are denoted by a red triangle) is 1 m, source spacing (source stations are denoted by a blue flag) is 10 ± 1 m. The 2 × 1 m tunnel is located 10 m beneath the midpoint between stations 1029 and 1030.

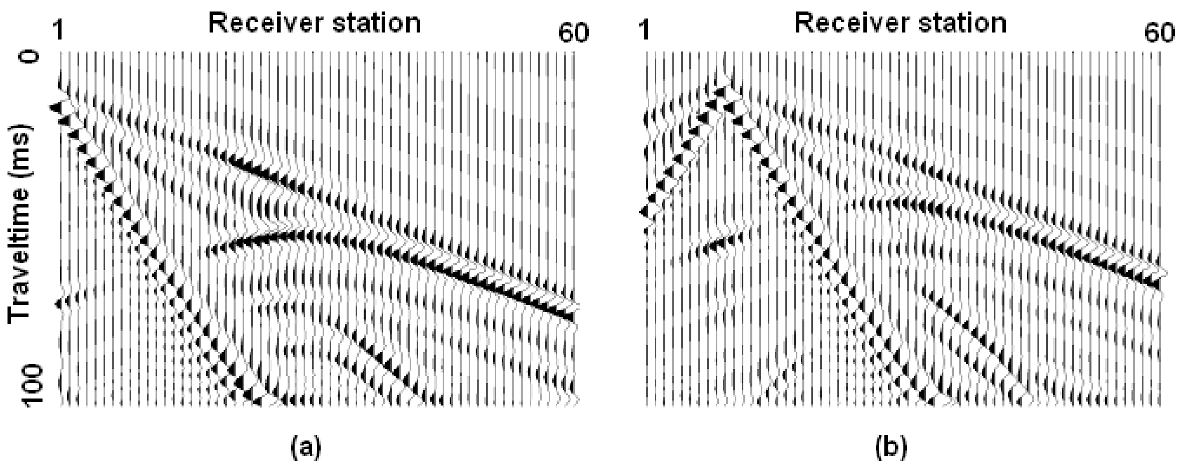

Figure 2: Bandpass filtered synthetic shot gathers containing diffraction hyperbola, caused by the tunnel. The source in (a) is at station 1000; the source in (b) is at station 1010. The apex of the hyperbola is laterally located at the same station in both gathers.

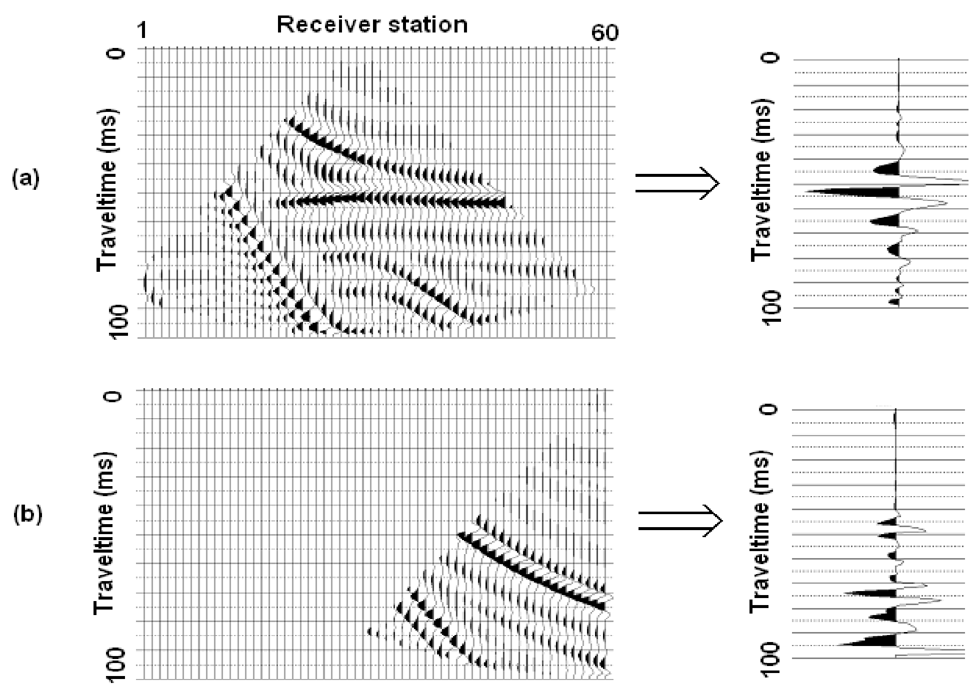

Figure 3: NMO corrected duplicate shot gathers associated with source station 1000, and resulting traces after horizontal stacking. The source was assigned to station 1029 in (a) and station 1060 (b). Only the traces in gather (a) properly moved out and flattened, resulting in a high-amplitude wavelet.

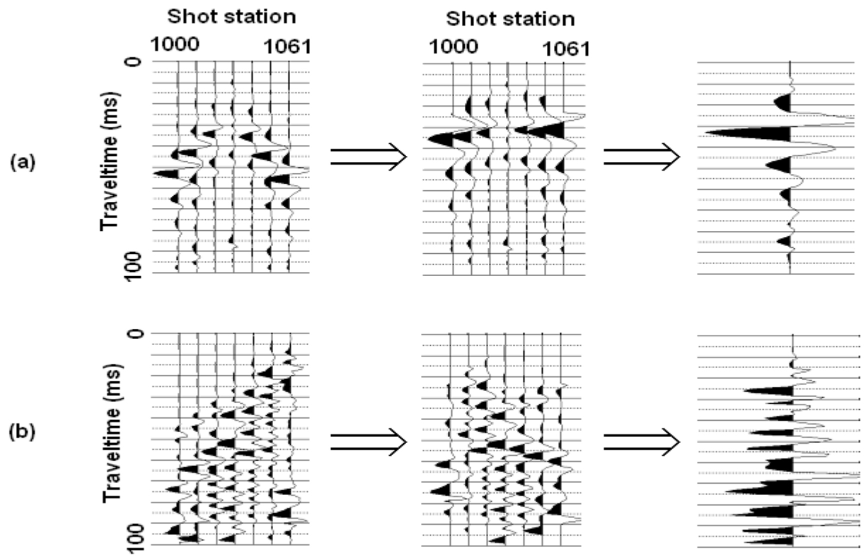

Figure 4: Common receivers prior and subsequent to normal moveout correction, and resulting stacked trace. (a) The common receiver gather for the receiver above the tunnel contains a diffraction hyperbola that is properly moved out and horizontally stacked, resulting in a large-amplitude wavelet. (b) The common receiver gather for the receiver at station 1060 contains no visible diffraction hyperbola, does not flatten, and results in a noisy trace.

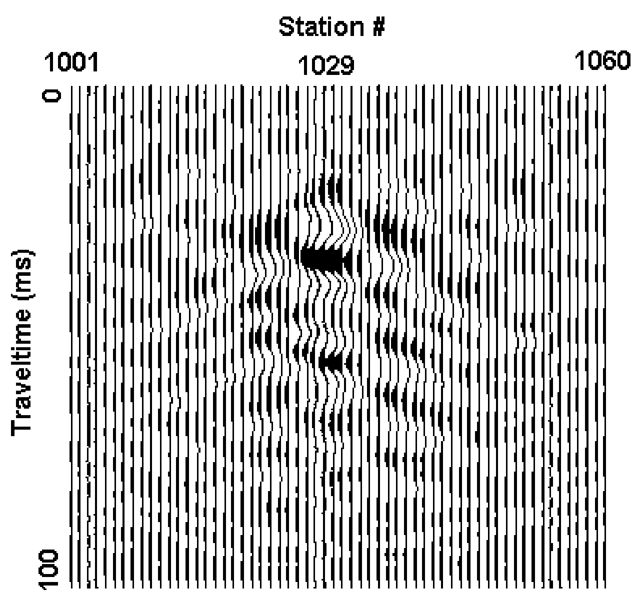

Figure 5: Resulting traces from NMO correction and horizontal stacking in the receiver domain. The relatively large-amplitude wavelets resulting from the tunnel are clearly visible on traces corresponding to stations 1027 through 1032 at roughly 24 ms, the time corresponding to the shortest two-way traveltime when the source was directly over the tunnel.

EDITED REFERENCES

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