Tunnel detection using near-surface seismic methods

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Summary

Geophysical detection of near-surface voids caused by mining, tunnels, karst features, etc., is a persistent problem that has not been solved either consistently or across multiple geologic settings. Multiple methods have been used with varying degrees of success. We present shallow seismic data collected at a test site with a 9.1-m deep tunnel in unconsolidated sediments similar to geologic settings found along the southwest US border. Test results demonstrate the capability of using P-wave diffraction and surface wave backscatter techniques to detect a purpose-built subterranean tunnel. Data were processed blindly by remote personnel, who were not aware of the target location, and results are in excellent agreement with the ground truth. These methods show promise for both efficient, production-scale data acquisition and real-time automated data processing.

Introduction

Clandestine tunneling is a relatively obscure but persistent problem around the globe that has been around for centuries, primarily for military applications. Areas of interest in recent decades have included Vietnam, the Korean Peninsula, the Israel-Gaza and Egypt borders, and the United States-Mexico border. Although borders are the most common areas of interest, smaller perimeters are also vulnerable, including secure facilities and prisons. Tunnels pose a range of threats including covert attacks and illegal transportation of drugs and/or weapons. More than 75 cross-border tunnels have been discovered in the United States alone since 2007 while hundreds are thought to exist along the Gaza Strip. Efforts at detecting these clandestine tunnels have ranged from new applications of old techniques to the novel, with degrees of success having a similar span. Although the contrast between an air-filled void and surrounding geologic media should provide a robust target, in practice tunnel detection has proven to be a complex problem in general and becomes increasingly so when the wide range of geologic settings and depth of interest are taken into account.

In this paper we will discuss using seismic diffractions and backscattered surface waves to detect a 1.5 x 1.2 m horizontally dug tunnel in unconsolidated sediments at a site representative of a southwestern desert environment. It is emphasized that this tunnel is horizontally dug and was not excavated using cut and fill or other methods so that the overlying material has not been disturbed and is representative of an actual clandestine tunnel that may be used to infiltrate or circumvent legal channels of entry or exit.

Multiple geophysical techniques have been applied to near-surface void detection, including electrical methods, ground-penetrating radar (GPR), gravity, and magnetic. Seismic methods have demonstrated some success to date for identifying subsurface voids (Belfer et al., 1998; Branham and Steeples, 1988; Sloan et al., 2011). Belfer et al. (1998) applied refraction tomography and seismic diffractions to locate a 25-m deep industrial tunnel. Branham and Steeples (1988) used near-surface seismic reflection methods to locate water-filled voids nine meters deep in Kansas. Walters et al. (2009) detected a seven-by-five meter railroad tunnel in Winter Park, Colorado, using P-wave diffractions. Peterie et al. (2009) demonstrated the advantages of diffraction imaging over reflection imaging to image shallow voids in coal seams for improved localization. Other examples of the application of diffractions and backscattered surface waves are described by Sloan et al. (2011).

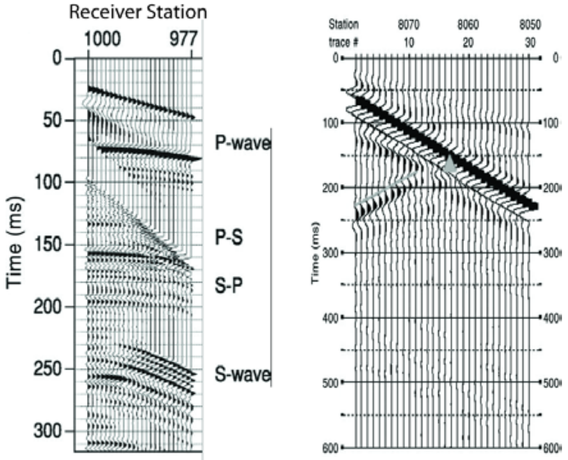

Figure 1. Synthetic shot gathers displaying various diffraction modes (P, P-S, S-P, and S) on the left and backscattered surface waves on the right.

Recent examples have applied near-surface refraction tomography methods (Hickey et al., 2009; Riddle et al., 2010) to identify various voids at depths of 0.6 and 6 m.

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Nolan et al. (2011) demonstrated the use of multichannel analysis of surface waves (MASW) and refraction tomography to image a 3-m deep horizontally dug tunnel. Tomography velocity plots were not definitive by themselves, but ray coverage plots and MASW were both successful and in agreement.

Seismic methods have shown promise, most likely due to the large contrast in properties that is typical of an air-filled void (335 m/s) and the typically higher velocity and density of the surrounding material. However, seismic methods are also sensitive to ambient noise levels and subsequent decreased S/N. Noise sources may include natural sources such as wind or rain, or anthropological such as vehicle traffic, industrial noise, power lines, air traffic, etc.

The methods described here utilize diffracted P-waves and backscattered surface waves. Seismic diffractions can occur as a result of subsurface point-like objects, such as tunnels, pipes, mine workings, etc., that act as a secondary energy radiation point to produce a hyperbolic seismic signature. Backscattered surface waves occur as a result of forward-propagating surface waves meeting a lateral velocity/density boundary that scatters a portion of the energy back towards the source. Both the backscattered and diffracted energy lend themselves to enhancement processing due to their unique and distinguishable properties relative to their surroundings, ie they are uniquely different from other types of seismic responses. Figure 1 shows synthetic common-source gathers with seismic diffractions and backscattered surface waves.

Site Description

The test site is representative of a dry desert environment similar to those in the Middle East and the southwest US border. The site is comprised of unconsolidated sand, silt, and clay with very little soil moisture. Soils mostly consist of loose to very dense clayey sands and hard to very hard sandy clays. Only the upper few feet of soils were loose; the remaining soils were typically dense to very dense or hard to very hard. There is no groundwater within the upper 90 m at the site. The tunnel roof is 9.1-m (30-ft) deep. It is 1.5 m tall and 1.2 m wide and structurally supported by wooden shoring with fully enclosed walls, roof, and floor (Figure 2).

Methods

Data were acquired using an accelerated weight drop as the source and a 24-station land streamer that included 4.5- and 40-Hz geophones at 1.22-m spacing pulled by a tow vehicle. Five shots were acquired and stacked for each source location. Data were recorded by Geometrics Geode seismographs with 24-bit A/D conversion, 2-s trace lengths, and a 0.5-ms sampling interval. Data were post-processed to produce enhanced diffraction and backscatter sections by reducing coherent noise and increasing the signal-to-noise ratio. Data processing routines are described in more detail by Walters et al. (2007) and Sloan et al. (2011).

Results & Discussion

Figures 3 and 4 show the enhanced diffraction (top) and surface wave backscatter (bottom) sections for two different lines collected at the site. Line 1 was collected 40 m from the vertical access shaft and Line 2 was collected 30 m away from the shaft. Lines were collected farther away from the shaft to avoid interference with energy reflecting off of the vertical shaft that could be misinterpreted as being from the horizontal shaft. The diffraction data in figure 3 shows a high-amplitude anomaly at station 1057 that is significantly higher than anything else in the plot. A two-wave traveltime of approximately 30 ms, combined with a diffraction moveout velocity of 670 m/s, yields an estimated depth of 10 m, which is within 10% of the known target depth. The backscattered surface wave plot for line 1 shows a coherent, high-amplitude event right around station 1056 that also corresponds with the diffraction section.

Figure 2. Photograph of the inside of the tunnel displaying the wood shoring, rail tracks, ventilation pipe, and electrical lighting.

The diffraction data in figure 4 shows a similar high-amplitude event as that in figure 3, located at station 1056. A two-wave traveltime of approximately 28 ms, produces an estimated depth of 9.4 m, which is within 3% of the

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known target depth. The backscattered surface wave plot for line 1 shows a coherent, high-amplitude event right around station 1056 that also corresponds with the diffraction section. The corresponding backscatter section also displays a high-amplitude, coherent backscatter event at station 2056. The known target location is station 1057/2057 for both lines.

The diffraction sections do exhibit other high-amplitude events besides those corresponding with the target location; however, they do not display the same geometry. Test results from this site have produced roughly circular, bulls-eye shaped signatures associated with the tunnel location. The other anomalies have not been drill-confirmed, but are interpreted to be resultant of geologic anomalies such as pinch-outs, which have been observed in other data collected at the site. These anomalies tend to be either lower amplitude or elongated in shape, helping to reduce the number of false positives with the method.

The surface wave backscatter sections tend to contain very few signatures that match those from the known feature: high-amplitude, moderately sloping, coherent events. As with all geophysical methods, those presented here can also suffer from non-uniqueness with similar signatures produced by natural anomalies. However, the multi-method combination of the backscatter and diffraction techniques helps to reduce false alarms and increase confidence in the interpretation by processing and interpreting each data set independently.

Conclusions

Tunnel detection continues to be a challenging geophysical problem; however, the methods presented here show promise in being capable of identifying subsurface anomalous events of interest. Data acquisition and processing can be accomplished quickly and efficiently, relative to conventional seismic techniques, at production rates. The methods also show potential for semi-automation to enable near real-time data processing. The data presented demonstrate that a subterranean void can be detected using near-surface seismic methods, including seismic diffractions and backscattered surface waves, in this type of geologic setting. Future work includes improving processing parameter selection and acquisition geometries to further enhance the signatures of interest.

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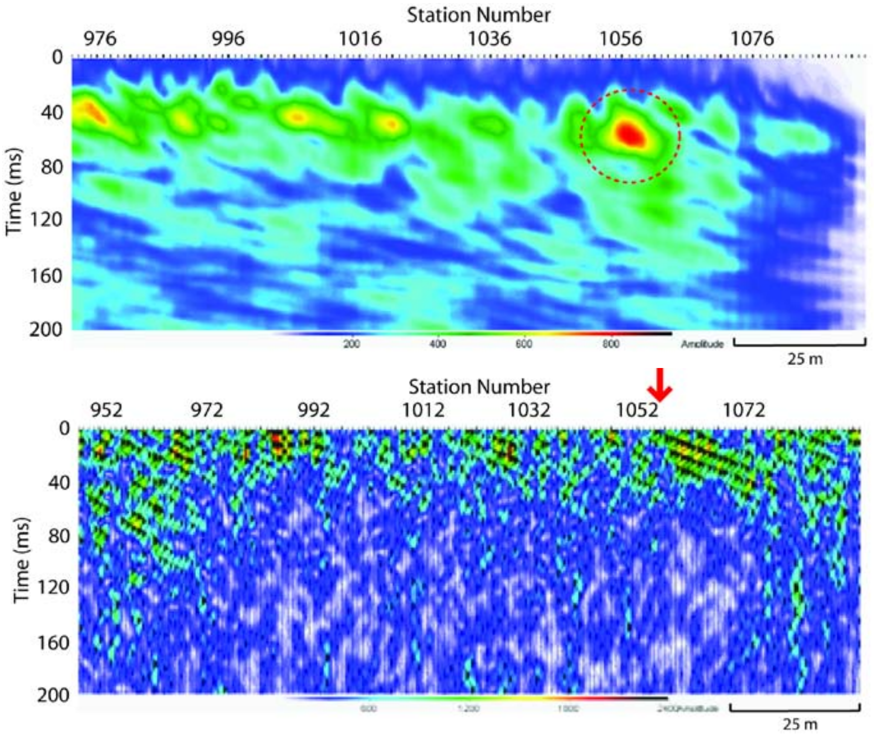

Figure 3. Enhanced diffraction section (top) and backscattered surface wave section (bottom). The target is indicated by the red-dashed circle in the upper plot and by the red arrow in the lower plot.

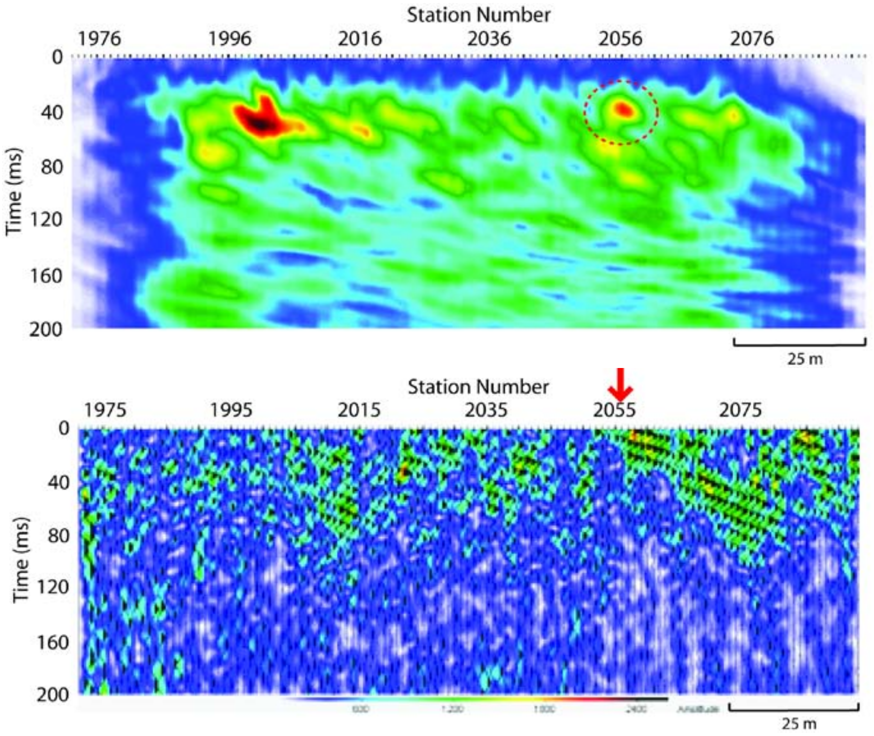

Figure 4. Enhanced diffraction section (top) and backscattered surface wave section (bottom). The target is indicated by the red-dashed circle in the upper plot and by the red arrow in the lower plot.

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