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Using near-surface seismic refraction tomography and multichannel analysis of surface waves to detect shallow tunnels: A feasibility study

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ABSTRACT

Near-surface seismic refraction and surface wave data were collected at a site to determine the feasibility and limitations of using these seismic methods to detect and localize a shallow tunnel in unconsolidated sediments. Data sets were collected both before and after the construction of the tunnel. We were able to detect the air-filled cavity using multichannel analysis of surface waves. The refraction tomography results showed the tunnel location in the raypath coverage plots, but only small velocity variations were observed. In tandem the two methods would reduce false positives, but individually the false alarm rate would likely be high due to non-uniqueness of the results. In this geologic setting, these methods are not the best choice of geophysical methods to detect clandestine tunnels and should be combined with other geophysical techniques to improve and constrain interpretations.

1. Introduction

Illegal tunnels pose a threat to several nations around the world for various reasons including narcotic trafficking (USA–Mexico border), unregulated trade (Egypt–Gaza border), and attacks (Israel–Gaza border), to name a few. Research using geophysical methods to detect these tunnels has been ongoing for multiple decades with much of the early work focusing on large and deep targets in hard rock environments on the Korean peninsula (Ballard, 1982; Rechtien et al., 1995) and more recent work looking at shallower features in unconsolidated sediments (Llopis et al., 2005; Tucker et al., 2007). Despite the volume of previous studies, no individual technology or method has been identified or developed that can detect and localize clandestine tunnels efficiently, consistently, and across a variety of geological settings. Whereas one method, such as GPR, may work great at a particular site, it may not work at all at another depending on subsurface properties such as clay content, and dielectric permittivity, or target parameters (depth, size) and the same can be said for all geophysical methods, not just GPR. As with most geophysical studies, appropriate methods are chosen based on the goal of the study and properties of the site to be surveyed. The study presented here focuses on the use of seismic refraction tomography and multichannel analysis of surface waves (MASW) to determine the potential of the two methods for tunnel detection at shallow depths.

Multiple examples of different geophysical techniques have been applied to tunnel detection (Cho et al., 2006; Choi and Ra, 1999; Greenfield et al., 1991; Llopis et al., 2005; Mahrer and List, 1995; Rechtien et al., 1995; Sloan et al., 2011), including seismic, electromagnetic, and radar, among others. Near-surface seismic methods in particular have been used for both general void detection (Branham and Steeples, 1988; Dobecki, 1988; Inazaki et al., 2005; Peterie et al., 2009) and tunnel detection (Belfer et al., 1998; Llopis et al., 2005; Rechtien et al., 1995; Sloan et al., 2011; Tucker et al., 2007; Walters et al., 2007, 2009). From a theoretical standpoint, seismic methods would be a good choice for void detection due to the drastic change in seismic properties from a geologic medium to an air-filled void (Sloan et al., 2011).

Sheehan et al. (2005) describe an example of locating an interpreted water-filled void in a karst environment using seismic refraction tomography at a depth of approximately 20 m. The cavity in this case was much larger than a typical tunnel, but did exhibit noticeable variations in the P-wave velocity profile. More recent examples have applied refraction tomography methods to detect voids at depths of 0.6 and 6 m. Hickey et al. (2009) buried a plastic pipe at 0.6 m depth using cut-and-fill and subsequently completed a seismic refraction survey orthogonal to the buried pipe. The authors noted reduced P-wave velocity (V_P) around and above the pipe; however, the method of emplacement also disturbed the overlying material, which would be expected to produce a similar result. Riddle et al. (2010) used refraction tomography to detect a concrete tunnel 1 m × 1.6 m in size approximately 6 m deep. Their results show subtle changes in raypath coverage and V_P compared to the surrounding material. The main difference between past studies and the work presented here is that an actual tunnel is used that was constructed in a similar fashion to illegal cross-border

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tunnels, providing a more representative target and removing extraneous influences such as overburden that has been disturbed by target emplacement. This study is the first that we are aware of to use an actual tunnel in a controlled environment for research purposes.

The objective of the research presented here was to determine the feasibility and limitations of using near-surface seismic refraction traveltime tomography and MASW methods to detect and locate a small-diameter, shallow tunnel in an environment comprised of dry unconsolidated materials. Baseline data were collected prior to the construction of the tunnel and are compared with coincident data collected after the tunnel was completed. Results of this study show that these methods can be used to detect voids in the right geologic setting; however, individually the results of one method alone may be inconclusive and would be best used by combining with other seismic or geophysical methods to reduce uncertainty and increase confidence in the results. This work was done as part of an undergraduate senior research project.

2. Site description

The tunnel used for this study was dug using a 6 m by 6 m vertical shaft for entry, exit, and spoil removal. Digging was done using mechanical hand tools similar to those discovered in recent tunnel seizures along the southwest US border, such as hammer drills, to accurately represent the target of interest. Overlying and surface material was not disturbed during construction. The roof of the tunnel is located at 3 m depth and the tunnel has a size of 1.25 m width and 1.25 m height (Fig. 1). The tunnel is shored using wooden beams and the walls and ceiling are also lined with wooden boards.

The site of investigation is located in the northeastern portion of the Great Basin near the Great Salt Lake, a sub-province of the Basin and Range province in the United States. The area of investigation is underlain by a thin layer of Holocene-age eolian sheet-sand deposits overlying Pleistocene-age lacustrine deposits related to the former existence of Lake Bonneville. Drilling at the site yielded 0.5–1.0 m of eolian sheet sands across the entire site, underlain by fine-grained lacustrine deposits. The eolian deposits consist of fine-grained, loose to medium-dense silty sand and sandy silt. The lacustrine deposits are comprised of alternating layers of silt, sandy silt, and silty sand, overlying gravelly sands and clayey sand toward the bottom of the borings.

3. Methods

Multiple shallow seismic data sets were collected at the site including refraction tomography (P and S), and MASW over a three day period in July and again in November of 2010 (Fig. 2). Each survey was conducted along a coincident line with similar acquisition geometries

Fig. 1. Picture of the tunnel used in this study during construction.

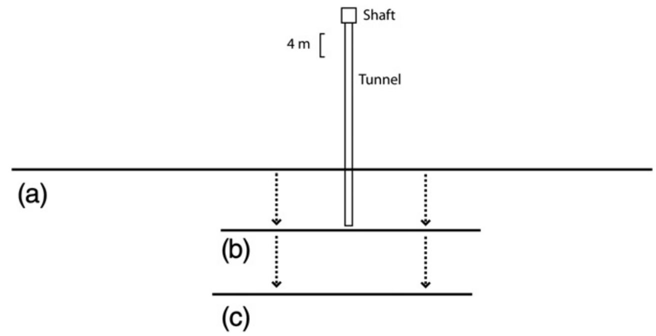

Fig. 2. Illustration depicting the layout of the surface wave line (a), S-wave lines (b), and P-wave lines (c). Note that all data sets were collected along the same coincident line (a), but have been spread out for illustration purposes as indicated by the dashed arrows.

and parameters (Table 1). Data sets were acquired both before and after construction of the tunnel, besides the MASW data set which was acquired only after. The pre-construction P-wave seismic refraction data were collected using 144 100-Hz vertical-component geophones with 0.25 m spacing. The source was a 1.36 kg (3 lb) hammer struck on a steel plate with 0.5 m spacing. The first shot point was 5 m away from the first geophone and the last shot point was 5.25 m beyond the last geophone. Ninety-three source locations were occupied over a total distance of 46 m. Data were recorded using six 24-channel seismographs with 24-bit A/D conversion, 0.25-ms sampling interval, and 256-ms trace lengths. Post-construction data were acquired using 144 40-Hz vertical-component geophones with 0.25 m spacing due to equipment availability constraints, but the other acquisition parameters remained the same.

Shear-wave refraction data were also acquired using the same parameters with the exception that 14.5-Hz horizontal-component geophones were used, with the same hammer impacting a horizontal shear block for the source. The source and receivers were oriented to collect horizontally polarized (SH) data. Each data set was collected during the same visit for both pre- and post-construction surveys. However, the post-construction S-wave data proved too noisy to reliably pick first breaks due to wind noise and required another return visit one year later in the fall of 2011. Surface wave data were collected using 96 4.5-Hz vertical-component geophones spaced at 1-m intervals. An accelerated weight drop provided the input energy every 1 m. The first source location was 20 m in front of the first geophone and ended 8 m past the last geophone. This resulted in a total of 124 shot locations.

Seismic refraction tomography methods typically utilize a grid of either fixed or variable sized cells to represent the subsurface. Forward modeling methods, such as a finite difference method, are used to predict ray paths and travel times between source locations and receivers. Cell velocities are iteratively adjusted until the misfit between the observed and predicted travel times is within some acceptable range. In this case the wavepath eikonal traveltime (WET) inversion scheme is used (Schuster and Quintus-Bosz, 1993).

Table 1
Summary of the seismic acquisition parameters for the different lines collected.

Seismic acquisition parameters					
Seismic line	Receiver spacing	Source spacing	Channels	Geophone	Source
Pre-construction					
Refraction (P)	0.25 m	0.5 m	144	100-Hz	Hammer
Refraction (S)	0.25 m	0.5 m	144	14.5-Hz	Hammer
Post-construction					
Refraction (P)	0.25 m	0.5 m	144	40-Hz	Hammer
Refraction (S)	0.25 m	0.5 m	144	14.5-Hz	Hammer
MASW	1 m	1 m	96	4.5-Hz	Weight drop