Journal of Applied Geophysics 106 (2014) 164–172

Contents lists available at ScienceDirect

Journal of Applied Geophysics

journal homepage: www.elsevier.com/locate/jappgeo

A shear wave ground surface vibration technique for the detection of buried pipes

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ARTICLE INFO

Article history:
Received 18 December 2013
Accepted 25 April 2014
Available online 9 May 2014

Keywords:
Shear wave
Buried pipe
Ground vibration
Mapping the Underworld
Time domain stacking

ABSTRACT

A major UK initiative, entitled 'Mapping the Underworld' aims to develop and prove the efficacy of a multi-sensor device for accurate remote buried utility service detection, location and, where possible, identification. One of the technologies to be incorporated in the device is low-frequency vibro-acoustics; the application of this technology for detecting buried infrastructure, in particular pipes, is currently being investigated. Here, a shear wave ground vibration technique for detecting buried pipes is described. For this technique, shear waves are generated at the ground surface, and the resulting ground surface vibrations measured. Time-extended signals are employed to generate the illuminating wave. Generalized cross-correlation functions between the measured ground velocities and a reference measurement adjacent to the excitation are calculated and summed using a stacking method to generate a cross-sectional image of the ground. To mitigate the effects of other potential sources of vibration in the vicinity, the excitation signal can be used as an additional reference when calculating the cross-correlation functions. Measurements have been made at two live test sites to detect a range of buried pipes. Successful detection of the pipes was achieved, with the use of the additional reference signal proving beneficial in the noisier of the two environments.

1. Introduction

There is a requirement to be able to detect object buried at a shallow depth, typically 1–2 m, in the ground. Typical target objects of interest include buried infrastructure (Royal et al., 2011), such as water and gas pipes, archaeological artefacts and buried ordnance. The problems associated with inaccurate location of buried pipes and cables have been serious for many years and are getting worse as a result of increasing traffic congestion in the UK's major urban areas. The problems primarily derive from the fact that the vast majority of the buried utility infrastructure exists beneath roads and therefore any excavation is likely to disrupt the traffic. A recent UK study estimated that streetworks cost the UK £7 bn annually; comprising £5.5 bn in social and indirect costs and £1.5 bn in direct costs (McMahon et al., 2005). The location techniques that are currently commercially available are either simple (yet strictly limited in their ability to detect the wide variety of utilities) and carried out immediately prior to excavation by site operatives or are more sophisticated and carried out by specialist contractors. Controlled trials carried out by the UK Water Industry Research have shown that, even when sophisticated detection techniques are employed, detection rates are often poor (Ashdown, 2000) and, as a result, far more excavations are carried out than would otherwise be necessary for maintenance and repair. Whilst a variety of techniques using different technologies are available, all suffer from the same essential drawback that, when deployed alone, they will not provide an adequate solution to the problem; moreover, all have their own specific limitations.

Much of the technological focus on the detection of such objects utilises electromagnetic phenomena (Linford, 2006). These technologies have limited ability to detect non-metallic or interfacing with weakly contrasting permittivity/permeability. In addition, those technologies featuring electromagnetic wave propagation, such as ground penetrating radar and metal detectors, suffer from high attenuation in wet or conductive media, resulting in limitations on their performance. Currently a large multi-centre programme, Mapping the Underworld (see www.mappingtheunderworld.ac.uk), is being undertaken in the UK to assess the feasibility of a range of potential technologies that can be combined into a single device to accurately locate buried pipes and cables. The potential technologies include ground penetrating radar, low-frequency quasi-static electromagnetic fields, passive magnetic fields and low frequency vibro-acoustics and significant advances have already been made (Royal et al., 2010, 2011). Vibro-acoustic techniques offer performance in media in which electromagnetic alternatives struggle and, furthermore, have the potential to image differences in mechanical, rather than electromagnetic, impedance. Vibro-acoustic techniques are thus worthy of development as they have the potential to complement the more mature existing imaging technologies.

Previous work (Muggleton and Brennan, 2008; Muggleton et al., 2011) addressed the detection of plastic water pipes in situations where access to some part of the pipe could be gained at the ground

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http://dx.doi.org/10.1016/j.jappgeo.2014.04.021

surface. Although successful, the access requirement limits the wider potential of this technique. A prior feasibility study, however (Muggleton and Brennan, 2006), also identified a second deployment strategy — direct excitation of the ground. When the ground is mechanically excited, waves will propagate away from the excitation point. Depending on the form of excitation, different wave types will be excited in the ground and these waves can be detected, depending of course on the frequency. Furthermore, they will be scattered by objects, such as pipes and cables, whose mechanical properties are different from the soil, even if they are buried several metres deep, provided that the object is larger than about half a wavelength. Detection and analysis of the scattered waves, in principle, allow the pipes/cables to be accurately located.

Acoustic imaging in the ground is historically associated with hydrocarbon exploration. This application has been successful in deep imaging of geological layers to reveal the location of hydrocarbon deposits. The imaging methods are usually based on the common depth point (CDP) stack technique (Schnieder, 1984), which employs time domain stacking. An impulsive source is used along with multiple sensors whose time histories are summed, after accounting for propagation delays, to form an image. However, these methods cannot be directly scaled to shallow depths due to a variety of problems. These include the much shorter separation time between the waves propagating directly from sources to sensors over the ground's surface and those reflected from buried surfaces, the requirement for higher frequencies, and the possibility of substantial near surface variations in wavespeeds (Miller and Xia, 1998).

The detection of objects buried at a shallow depth has had comparatively little attention. Notable attempts to detect buried objects at very shallow depths (<10 cm) using Rayleigh waves have been made, chiefly with the aim of landmine detection (Sabatier and Gilbert, 2000; Scott et al., 2001). Whilst these methods are capable of achieving good results for targets just under the surface of the ground they are not applicable to the slightly more deeply buried targets of interest in this paper because of the rapid attenuation of the Rayleigh wave with depth. However, Sugimoto et al. (2000) have adapted the time domain stacking technique for the detection of objects buried at more shallow depths. More recently, the signal stacking method has been further modified by using time extended signals, an alternative excitation method and additional signal processing techniques (Papandreou, 2011; Papandreou et al., 2009, 2011) and has been used with some success to detect concrete pipes and slabs. It is this technique which is adapted here and employed with the aim of detecting a range of buried pipes.

At this stage the work sits firmly in the research arena. The authors do not claim that the technique in its present form could be integrated into a device which could be deployed successfully in an urban environment; rather, it is our intention to demonstrate its potential and reveal some of the underlying physical processes in play. The paper is organised as follows: Section 2 gives a description of the fundamentals of the experimental method, the signal processing adopted along with an enhancement for use in noisy environments; in Section 3 the imaging experiments are described and the results presented; finally, Section 4 presents the conclusions and makes recommendations for further work.

2. Description of the method

2.1. Fundamentals

The basic experimental method used in this publication has been previously documented (Papandreou, 2011; Papandreou et al., 2011), and consequently only a brief synopsis is provided here. It is an active method that produces a cross-sectional two-dimensional image through the ground. A seismic source produces a time-extended signal to illuminate the buried object. Reflections are then measured using an array of surface sensors. The experimental setup is shown in Fig. 1.

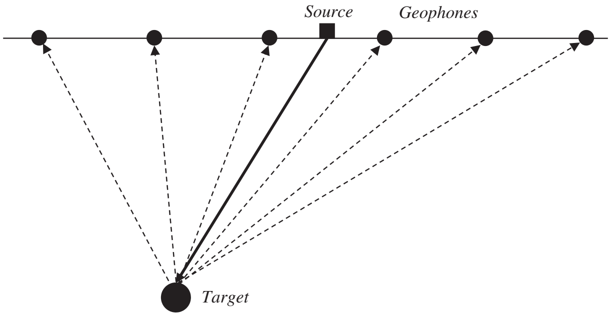

Fig. 1. Diagram of the experimental setup used for the imaging method. The circles on the surface denote geophones and the square on the surface denotes the source.

To form an image the distances from the source to sensor locations via each pixel on the image plane are first calculated. These are related to times of flight by the speed of the wave which is assumed to reflect from the target and propagate to the sensors. Due to high variability of the wavespeed between locations and with soil conditions an estimate of the wavespeed is required.

If an impulsive source has been used (e.g. hammer strike) then the measured time histories will contain a peak at the time of flight of a reflected signal. Thus by making the pixel value equal to the amplitude of the measured signal at this time, the reflection is mapped from the time domain to the image plane, with each peak in the time domain generating an elliptical curve. Repetition of this procedure for each of the geophones and summation of the resultant images will, provided that the wavespeed has been accurately estimated, produce a peak in the image that indicates the location of a target. The signal to noise ratio can be improved by moving the source, repeating the method, and summing the resultant image. This also reduces the impact of anomalous dead-patches or regions of high heterogeneity.

As discussed previously, the method has been adapted by using time extended signals rather than impulses. This enables both greater control of the frequency content of the input signal and, moreover, the ability to input larger amount of energy without resorting to input amplitudes that produce a non-linear response in the ground. In order to incorporate time-extended signals into the imaging method cross-correlation functions are used.

A form of the cross-correlation function useful for practical implementation is given by Bendat and Piersol (1993)

$$R_{xy}(\tau) = \int_{-\infty}^{\infty} S_{xy}(f) e^{2\pi i f t} df \qquad (1)$$

where $S_{xy}(f)$ is the cross-spectral density between a reference signal (provided by a geophone located close to the source at x) and the yth measurement sensor and f is the frequency. Eq. (1) is a statement that the cross-correlation function is equal to the inverse Fourier transform of the cross-spectral density. Numerical implementation of the cross-correlation functions uses the relation of Eq. (1) to exploit the computational efficiency of the fast Fourier transform. This also allows for generalisations to the cross-correlation function that are now discussed.

2.2. Smoothed coherence transform

It is desirable to minimise the width of peaks in the cross-correlation functions prior to application of the imaging algorithm. The reason for this is two-fold: firstly, if the cross-correlation peaks are too wide then multiple peaks in the cross-correlation domain due, for example, to the propagation of multiple wave types, may coalesce; secondly, if the peaks are very wide, then a cross-correlation function with a single peak will produce an image where all regions have a high value with