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'Mapping the Underworld': recent developments in vibro-acoustic techniques to locate buried infrastructure

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A major UK initiative entitled Mapping the Underworld (MTU) is seeking to address the serious social, environmental and economic consequences arising from an inability to locate – accurately and comprehensively – buried utility service infrastructure without resorting to extensive excavations. MTU 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, and a number of different vibro-acoustic methods for detecting buried infrastructure have been investigated. The latest developments in the vibro-acoustic location research are presented here. Three complementary methods are described, one of which involves direct excitation of the buried asset and the other two require no such direct access. All involve measurement of the ground surface vibration as a result of the excitation, whether of the ground or of the buried asset directly. Together, these techniques constitute a substantial step change in the way buried infrastructure can be detected using vibro-acoustic methods.

KEYWORDS: buried structures; dynamics; in situ testing; pipelines; vibration

INTRODUCTION

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 buried utility infrastructure exists beneath roads and therefore any excavation is likely to disrupt the traffic. A recent UK study estimated that street works cost the UK £7 billion annually, comprising £5·5 billion in social and indirect costs and £1·5 billion 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 are carried out by specialist contractors. Controlled trials carried out by UK Water Industry Research (Ashdown, 2000) have shown that, even when sophisticated detection techniques are employed, detection rates are often poor and, as a result, far more excavations are carried out than would otherwise be necessary for maintenance and repair. While 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. In particular, no commercial system that can detect and locate plastic pipes is yet available.

In response to this, a large multi-centre programme, dating back to 2004 and called Mapping the Underworld (MTU, 2013), is being undertaken in the UK to research a range of technologies that could 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. The current phase of the programme is nearing completion; a number of novel vibro-acoustic techniques have been developed and show considerable promise.

At this stage, the work sits firmly in the research arena. The authors do not claim that the techniques in their present form could be integrated into a device that could be deployed successfully in an urban environment – rather, the intention is to demonstrate their potential and reveal the underlying physical processes in play. The techniques are described in detail in separate publications (Muggleton *et al.*, 2011, 2012a, 2012b, 2013), to which the interested reader is referred. In this paper, the major advances that have been made in this area under the MTU umbrella are summarised and future areas of research are highlighted.

BACKGROUND

The principle behind all of the vibro-acoustic techniques that have been explored in MTU is that when one part of the pipe/soil structure is mechanically excited in a controlled manner, waves will propagate away from the excitation point, interact with the surrounding structure or fluid and be subsequently measurable at some remote location(s) on the ground surface. By analysing the nature of the measured response(s) at the surface, the location of the buried pipe(s) can then be inferred.

Three complementary vibro-acoustic techniques for locating buried services have been developed in MTU: one involves direct excitation of the asset and the other two require no such direct access.

Pipe excitation method

This method, which has its origins in water leak detection, is applicable when a buried pipe can be accessed from the surface (e.g. a fire hydrant). Historically, water leaks have

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been detected using a listening rod in contact with the ground in the vicinity of the leak; the leak noise propagates through the soil to the ground surface where it can be picked up by the human ear at the end of the listening rod (Fuchs & Riehle, 1991; Liston & Liston, 1992).

The exposed pipe is mechanically excited at low frequencies (<1 kHz) resulting in waves that propagate along the pipe and in any fluid contained within the pipe. The energy of these waves then radiates to the ground surface where it is measured, using geophones, and from which the location of the remainder of the pipe can be inferred. Current detection systems operate on this same principle but employ only one ground vibration sensor; furthermore, only the amplitude information is taken into account. Significantly more information can be gleaned by using an array of sensors but, more importantly, taking account of the phase information in the measured signals. Herein lies the novelty of the MTU approach, further details of which are given by Muggleton *et al.* (2011, 2012a).

When making frequency response measurements relating vibrational velocity on the ground surface to the input excitation, both magnitude and phase information were found to be informative, with phase being the more important measure: the phase encapsulates the relevant time delay information as waves travel from the input to the measurement location and is much more robust in the presence of noise; magnitude information can supplement this and may be particularly useful in identifying discontinuities where reflections can occur, for example a bend in the pipe, a change in pipe material or dimensions or, indeed, a leak. Limits on the coherence were also defined (Muggleton *et al.*, 2011), below which phase unwrapping would no longer be successful, thus setting an upper bound on how much noise can be tolerated.

Furthermore, by examining the gradients of the unwrapped phase (the rate of change of unwrapped phase with frequency, independent of frequency for non-dispersive waves) and thus inferring the wavespeed, it may be possible to glean further information about the location of the pipe and indeed some of its properties. Figure 1 depicts the unwrapped phase gradients along a line directly above a medium-density polyethylene (MDPE) mains water pipe. This 180 mm diameter pipe was buried at a depth of approximately 1 m, so is therefore typical of the type of MDPE water pipe and burial depth found across the UK. The soil in which the pipe was buried was a mixture of gravel, sand and clay, again typical of many installations. The ground surface was grass, which – while clearly not common in urban areas – provided a useful starting point for measurements and allowed the burial matter to be considered homogeneous. The plot consists of three approximately straight sections: the first comprises the first three data points close to the vibration source; the second is also approximately straight and contains the most of the data directly above the pipe; the final section is beyond the pipe end. Fitting a straight line to the first three data points gives a phase speed of approximately 120 m/s; this most likely corresponds to the directly excited Rayleigh surface wave, which will dominate in the near-field before decaying as $1/r^{1/2}$. A least-squares fit over the second straight line section gives a phase speed of approximately 373 m/s; this corresponds to the fluid-dominated, axisymmetric wave in the pipe as anticipated, measured previously on the same pipe as 365 m/s (Muggleton & Brennan, 2008). At these ranges, this wave dominates over the directly excited wave as it will suffer no geometric attenuation along the pipe. The data in the final section correspond to locations at and beyond the end of the pipe and indicate a significant decrease in the wavespeed measured on the surface; this is a convincing indicator of the end of the pipe. Computing the wavespeed from the final two measurement points gives a figure of approximately 80 m/s, which again most likely corresponds to the Rayleigh surface wave as the wave in the pipe is no longer propagating. If the pipe material and/or dimensions were not already known, knowledge of the wavespeed above the pipe could aid in determining these parameters.

The pipe excitation technique has been found to be very successful for locating both plastic and metal water pipes, laid under grass and under tarmac. Figure 2 shows an example result at a single frequency for the same MDPE water pipe. When using magnitude information alone, only the excitation point (at (0, 0) m) and the pipe end (at (0, 18) m) can be seen; the unwrapped phase clearly reveals the entire run of the pipe. Figure 3 shows an example result for a cast iron pipe laid under a combination of grass and tarmac, where excitation is again at (0, 0) m. The pipe dimensions here are unknown as the burial records do not

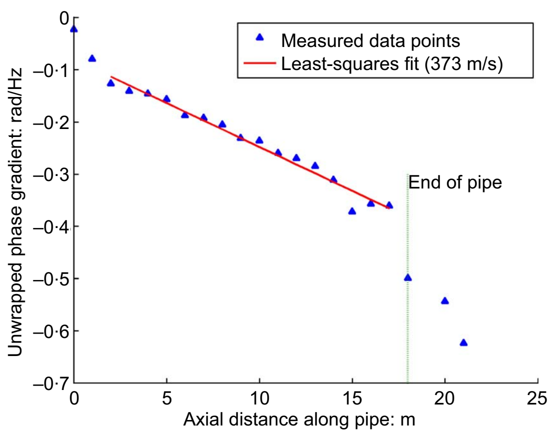

Fig. 1. Unwrapped phase gradients along the ground above an MDPE water pipe (the location of the pipe end is shown)

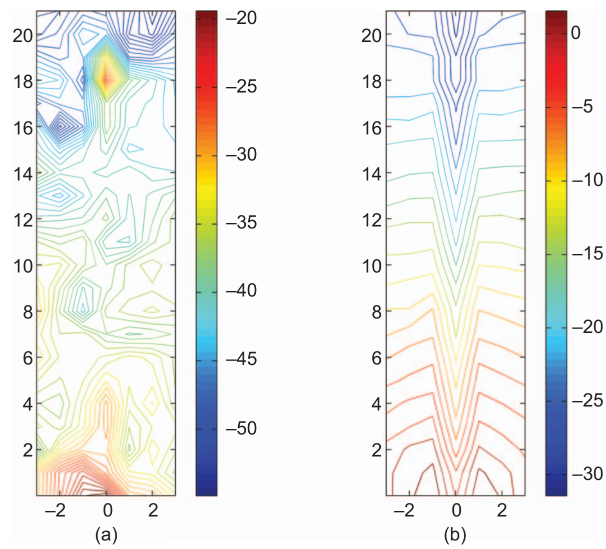

Fig. 2. Contour plots of magnitude and phase of frequency response at 62 Hz. (a) Magnitude of velocity in dB relative to velocity measured by geophone adjacent to excitation point, scaled by the square root of the distance from excitation point to measurement point. (b) Spatially unwrapped phase in radians. The *x*- and *y*-axes are in metres relative to the excitation location; the pipe runs up the centreline in each plot

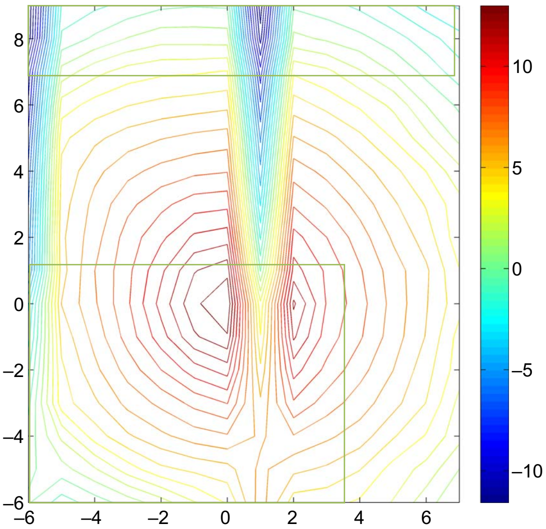

Fig. 3. Contour plots of unwrapped phase of frequency response at 35 Hz for a cast-iron pipe laid under a combination of grass and tarmac. The two green rectangles indicate the grass areas. The x- and y-axes are in metres relative to the excitation location

contain that information. Here too, the run of the pipe is clearly evident, with no change in behaviour apparent over the tarmac compared with the grass areas (also shown in Fig. 3). The presence of multiple surfaces does not affect the technique since the phase delay due to propagation in asphalt is negligible compared with the overall phase delay. Furthermore, in this plot, the waves radiating cylindrically out from the excitation point are also apparent.

Vibration excitation applied at the ground surface (shear wave method)

This method is applicable when the general vicinity of a buried service is known but attachment of an exciter is not possible. At present, there is no commercially available detection system of this sort. Directional shear waves are generated at the ground surface and the subsequent reflections arriving at the ground surface are detected and analysed. Cross-correlation functions between the measured ground velocities and a reference ground velocity measurement adjacent to the excitation are used to generate a cross-sectional image of the ground using a time domain stacking approach (Papandreou *et al.*, 2011; Muggleton *et al.*, 2012b). Figure 4 depicts a typical experimental setup. A typical distance between geophones is 0·5 m. A series of measurements is carried out with the exciter adjacent to each geophone in turn.

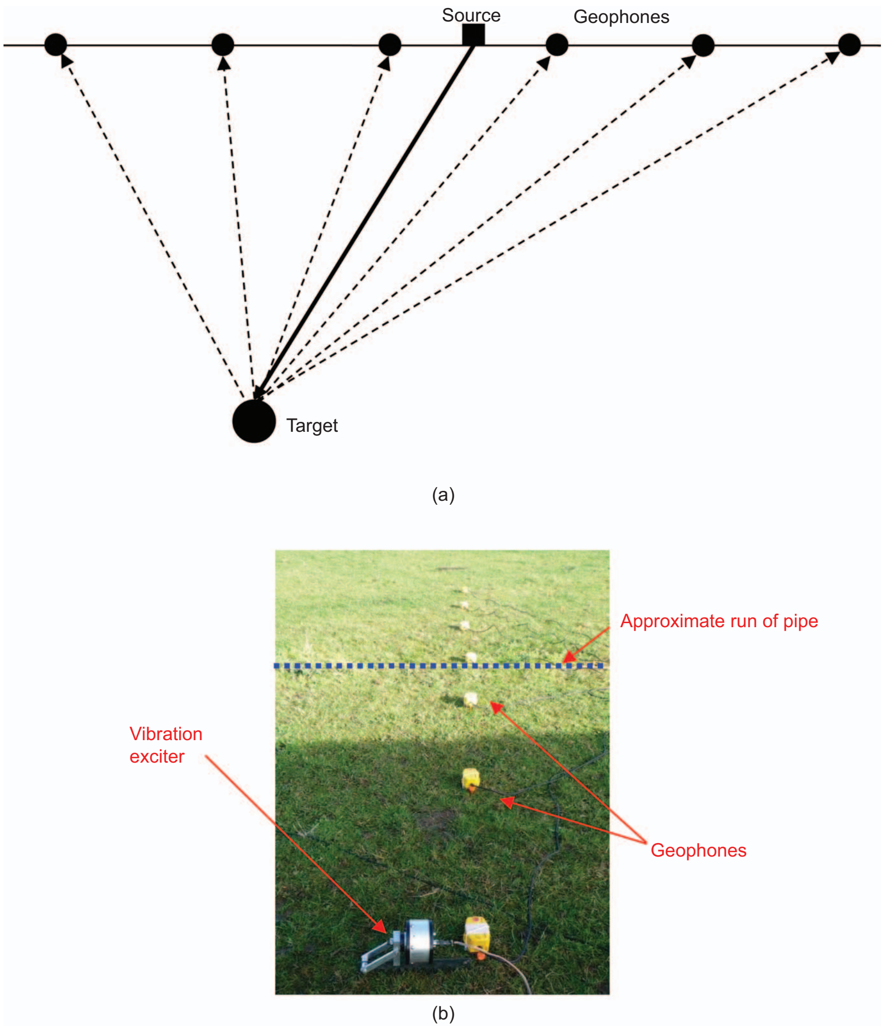

Fig. 4. Arrangement of shaker and geophones for ground excitation measurements using shear waves: (a) sectional view; (b) view on the ground

A recent improvement has been obtained using a modified version of the smoothed coherence transform (SCOT) (Muggleton *et al.*, 2012b), which is more effective in noisy environments, and given by

$$R_{riV_{\mathrm{ref}}}(\tau)=\int_{-\infty}^{\infty}\psi_{rV}(f)\psi_{iV}(f)S_{rV}(f)S_{iV}^{*}(f)\mathrm{e}^{2\pi i f t}\,\mathrm{d}f$$

where $S_{rV}(f)$ is the cross-spectral density between the reference velocity measurement (r) and the voltage input to the shaker (V), $S_{iV}(f)$ is the cross-spectral density between the ith velocity measurement and the voltage input to the shaker, * indicates the complex conjugate, ψ are the respective SCOT weighting functions and f is frequency. The SCOT weighting functions effectively pre-whiten the signals and then weight by the respective coherence functions; the additional voltage reference means that extraneous signals received by both the reference geophone and the measurement geophone but not correlated with the shaker input signal (such as might be arise from other proximal noise sources in the environment) are effectively removed.

The shear wave method has been successful at detecting both plastic and metal water pipes and air-filled metal pipes. The first results of this kind (Fig. 5), shows an example image above a live MDPE water main, with the dark red area indicating the presence of the pipe.

Vibration excitation applied at the ground surface (point measurement method)

This method is also applicable when no direct access to the pipe is available. Here, vertical excitation is applied at the ground surface at several points along a line and accelerance (acceleration/force) is measured at each point.

At low frequencies, the ground behaves as a single-degree-of-freedom system with a well-defined resonance, the frequency of which will depend on the density and elastic properties of the soil locally. Changes in resonance frequency can be used to detect the presence of a buried object close to the surface (Muggleton *et al.*, 2013); expressions for the expected mass and stiffness components have been presented and how these might alter in the presence of a shallowly buried object discussed.

This technique has been used successfully to detect a number of shallowly buried services. Figure 6 depicts two example point accelerance measurements in the vicinity of an air-filled MDPE pipe. Here, the resonance frequency is seen to reduce by a factor of about 3 directly above the buried pipe. Figure 7 shows the results from a typical line traversing the pipe, with the minimum value measured directly above the pipe.

This method could serve as a useful adjunct to the more conventional methods of buried object detection, such as ground penetrating radar, for example. A particular advantage of the method is that the measurements are relatively quick to make and analyse; furthermore, they are straightforward to interpret. Importantly, modelling suggests that the detection depth depends on the excitation contact radius, so that greater detection depths could be achieved by using increased contact with the ground surface.

CONCLUSIONS AND THE WAY AHEAD

The results for all three techniques are extremely promising. Together, the three techniques constitute an innovative and powerful tool and a substantial step change in the way buried infrastructure can be detected using vibro-acoustic methods. More conventional methods may then be paired with the vibro-acoustic approaches to improve overall detection efficiency. In particular, the techniques presented here have been shown to be successful in detecting plastic as well as metal pipes. This represents a crucial step forward as, to date, none of the other technologies have been found to be capable of detecting plastic infrastructure.

However, there is clearly much work to be done before these techniques can be used in earnest outside the research arena. The issue of traffic noise and background vibration is undoubtedly a concern when transferring to an urban environment. However, all three techniques utilise a method in which the cross spectrum between one of the measured signals and the signal output from the shaker is calculated (Muggleton *et al.*, 2011, 2012a, 2012b, 2013). This means that any part of the measured signal not correlated with the input signal is effectively removed, thus minimising the effects of external sources of vibration. The layered and very often quite disturbed ground that is

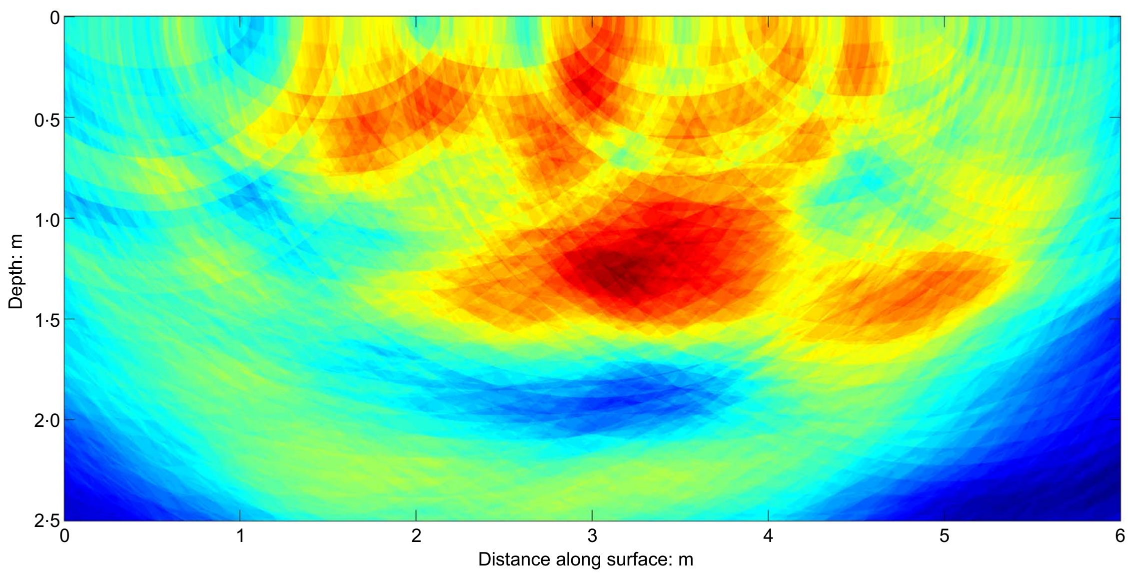

Fig. 5. Cross-sectional stacking image; the dark red region identifies the pipe location

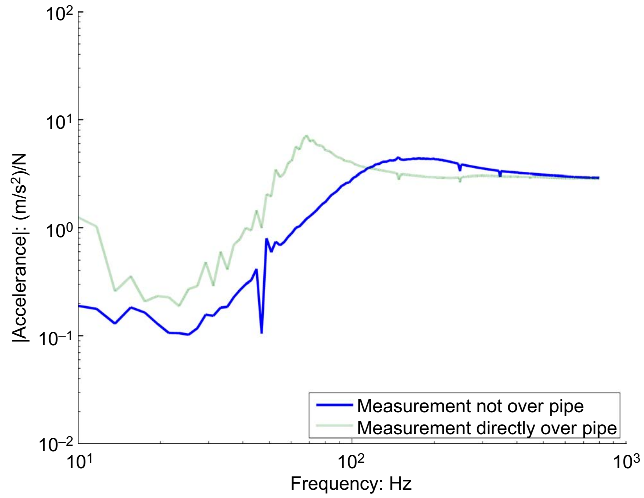

Fig. 6. Two point accelerance measurements in the vicinity of an air-filled MDPE pipe buried at a depth of 30 cm

typical in an urban environment is also of concern – the ground on which measurements have been taken to date has been relatively homogeneous and undisturbed. Work is currently under way to look at different surfaces and the effect of layering and inhomogeneities in the ground beneath. Likewise, the pipe configurations tested to date have been extremely simple (limited to one pipe). How the techniques perform when multiple, possibly crossing, pipes and cables are present is also the subject of ongoing tests.

MTU has access to numerous test sites and, in particular, the MTU centre of excellence (www.construction-skills-academy.co.uk/mtuce; MTU, 2013), which incorporates a number of test bays with a wide range and complexity of utility layouts. Furthermore, since testing of the techniques described here, the equipment required for vibro-acoustic testing has been incorporated into a multi-sensor trolley along with the equipment for the three complementary technologies (MTU, 2013). This 'mobile laboratory' is much more suited to making measurements on urban streets, particularly as the geophone array is mounted on a moveable arm, making their placement on the ground faster and more accurate.

The MTU programme is now seeking to move beyond simply the detection and location of buried infrastructure,

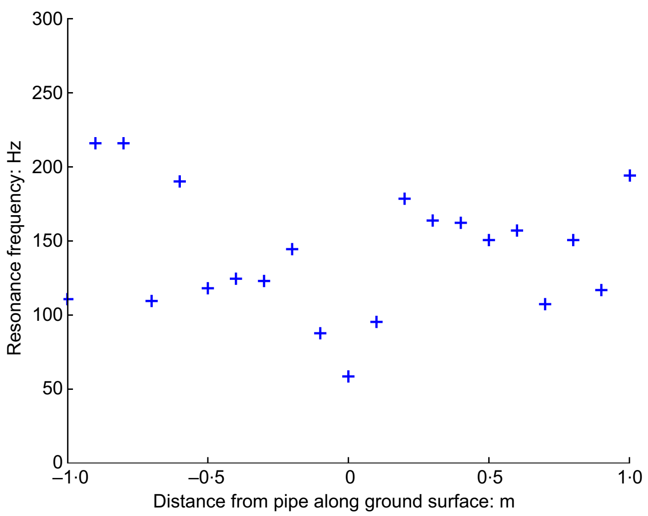

Fig. 7. Variation of resonance frequency along a line traversing an air-filled MDPE pipe buried at a depth of 30 cm

and a new programme of research to build on the many advances made in MTU is starting imminently. Entitled 'Assessing the Underworld', this new programme aims to use geophysical sensors deployed both on the surface and inside water pipes to remotely determine the condition of buried assets.

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