A novel method for the remote condition assessment of buried pipelines using low-frequency axisymmetric waves

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Abstract. "Mapping the Underworld" is a large multi-disciplinary, multi-university research programme taking place in the UK, which aims to revolutionize the way we undertake streetworks. Within this programme, a number of vibration-based techniques for remotely detecting and locating buried pipes have been developed. Relying either on the direct excitation of a pipe as it comes up to the surface or excitation of the ground in the vicinity of a buried pipe, mapping the ground surface vibration response allows information to be gathered concerning the pipe's exact position. However, contained within this surface response is often information which could, if utilized appropriately, provide insights into the condition of the pipe as well as its location. Furthermore, critical information regarding the condition of the ground in which a pipe is buried could, in some circumstances, be gleaned. In this paper, how this additional information might be extracted, used and eventually exploited is explored. Providing the basis for work currently being undertaken in a new programme, "Assessing the Underworld", example results are presented which demonstrate the immense potential of the proposed methods.

1. Introduction

The manmade network of underground utilities that serves our towns and cities is almost unparalleled in its complexity, and yet it is one that is invisible from the ground surface. It is thus one that, for the most part, goes unnoticed unless it fails in some manner. Consequently, the task of locating this buried infrastructure in the absence of comprehensive and accurate maps, and, moreover, determining its condition, is highly problematic. The complexity of the underground utilities networks derives from the many types of utility services being supplied and the materials of the pipelines and conduits through which they are delivered, their interconnectedness, their different ages and their different sensitivities to disturbance.

The different utility service lines include water pipes, gas pipes and electricity cables; sewers and storm water drainage; telecommunication cables; and street lighting and traffic lighting cables [1]. It is widely appreciated that the type and quality of materials have varied through the decades, and occasionally centuries, over which these pipelines and cables have been installed, even in the case of the same utility; for example for water distribution pipelines alone, a wide range of materials can be found, including cast iron, MDPE, HDPE and PVC. Moreover, even within a nominally single material, the chemical and physical properties can vary considerably from one pipe to another, due either to differences in the initial manufacturing process or changes over time.

In response to the aforementioned difficulties associated with locating and assessing the condition of our buried infrastructure, a large, UK-based, multi-university, multi-disciplinary research programme, “Mapping the Underworld” (MTU) [2] is underway. This programme aims to revolutionize the way in which we undertake streetworks by developing a range of different technologies which can be used in intelligent combination to remotely map buried utilities without resorting to extensive excavations [3]. 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 [4] 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.

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 [1]. It is hoped that by adopting the MTU approach, these huge direct, social and environmental costs can, to a large extent, be mitigated.

More recently, a follow-on research programme, “Assessing the Underworld” (ATU) [5], has commenced, seeking to extend the capabilities of the technologies developed under MTU to remotely assess the condition of buried assets and their surroundings, in addition to their mapping and location [6,7].

Of the four main technologies developed in MTU, the emphasis here is on the methods which exploit vibration in some form, particularly for water pipes. 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 [8]. In addition to location information, however, contained within this surface response is often information which could, if utilized appropriately, provide insights into the condition of the pipe as well as its location. Moreover, critical information regarding the condition of the ground in which a pipe is buried could, in some circumstances, be obtained. In this paper, possibilities for how this additional information might be extracted, used and eventually exploited, is explored.

In general, in buried water pipes, acoustic energy propagates at relatively low frequencies [9]. Of the four main energy carriers, three of them are axisymmetric (n=0) waves including a predominantly fluid-borne (s=1) wave, a compressional shell (s=2) wave, and a torsional (s=0) wave. Much of the present authors’ previous work has involved both theoretical and experimental investigations into the s=1 waves [10-14] and this is again the focus here. The present paper is arranged as follows: in section 2, the pipe excitation technique developed in MTU, and its rationale, is briefly outlined to familiarize the reader with the basic concepts; these ideas are taken forward in section 3 where it is shown how information beyond that of simple mapping could be acquired; in section 4 conclusions are summarized and a way forward presented.

2. A pipe vibration method for pipeline location and mapping

2.1. Background to the 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. at a fire hydrant). Historically, water leaks have 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 [15,16). Currently available acoustic pipe location systems operate on the principle that acoustic signals in the pipe will propagate to the ground surface where they can be detected and the location of the pipe inferred. In this case, however, the acoustic signal is not a leak, but is injected into the pipe deliberately by some means at a known location, for example, using a ‘chatter’ valve or a single frequency tone; this results in waves that propagate along the pipe and in any fluid contained within the pipe. The excitation frequency is sometimes tuned to exploit possible resonant behaviour in the pipe, and again this is determined empirically. The signal is detected at the ground surface using an electronic ‘listening rod’, consisting of a single transducer at the end of a rod in which the acoustic signal can be heard via headphones, and possibly seen on a simple amplitude meter. The listening rod is gradually moved away from the sound source, following local maxima in signal strength; it is assumed that the run of the pipe lies directly below this path.

However, if the pipe is mechanically excited using an electrodynamic shaker, more control can be exerted over the precise excitation frequency range and signal content (two example excitation configurations are shown in Figures 1a,b). Moreover, significantly more information can be gleaned by using an array of sensors and, more importantly, taking account of the phase information in the measured signals. Herein lies the novelty of the MTU approach [17].

(a) (b)

Figure 1

Example excitation configurations

(a) shaker placed directly onto standpipe; (b) shaker bolted onto modified hydrant cap

2.2. A theoretical basis

Consider a pipe buried in the ground at a depth, *d*, as shown in figure 1. A low-frequency (typically <1kHz) excitation is applied to the pipe at some known location (x=0) where the pipe is accessible from the surface. For plastic pipes, whether the excitation is applied to the pipe wall (either via some intermediate arrangement, such as a hydrant, or directly) or directly into the fluid, it is the fluid-borne (s=1), axisymmetric (n=0) wave that will be predominantly excited and thence propagate along the pipe. The energy radiates as conical shear and, under some circumstances, compressional waves into the surrounding ground, which then propagate(s) towards the ground surface [18,19]. Recent work undertaken by the authors has shown that, directly above the pipe, the axial dependence of the ground surface response mirrors the axial dependence of the waves propagating within the pipe [20].

However, in addition to the waves radiated from the pipe, the source applied to the pipe will also tend to excite waves directly in the ground. These directly-excited waves will radiate cylindrically over the surface from the source location and thence a portion of these will also reach the measurement points.

The interaction between the waves will be complex and which one of the wavetypes will dominate at any given surface location will depend on both the proximity to the source and to the axis of the pipe:

- close to the source, at a distance less than the first conical wave intersection with the ground surface, the source waves will dominate;
- at lateral distances far from the pipe axis, again the source waves are likely to dominate, as the waves radiated from the pipe will have undergone significant damping whilst propagating through the soil;
- directly over the pipe are the waves radiated from the pipe likely to dominate as here the soil losses will be small

When measuring at the ground surface, potentially both magnitude and phase information will be useful, although to visualize the wave fields described above, phase is likely to be the more important measure. Lines of constant phase represent wavefronts, encapsulating the relevant time delay information as waves travel from the input (via the pipe or otherwise) to the measurement location; moreover, unwrapped phase extremely robust in the presence of noise. It has been shown [17] that, dependent on the number of averages employed in calculating the frequency response functions, extremely low levels of coherence can be tolerated in the phase unwrapping process.

Figure 2 shows unwrapped phase contours for vertical ground vibration measurements made on a cast iron water pipe buried in soil beneath a combination of grass and tarmac. In this figure, the waves radiating cylindrically from the excitation location are clearly seen. Up the centerline of the figure, the distortion of the wavefronts due to the pipe-radiated waves are also evident, betraying the run of the pipe. Here, the differences in ground surface finish do not have a perceptible effect.

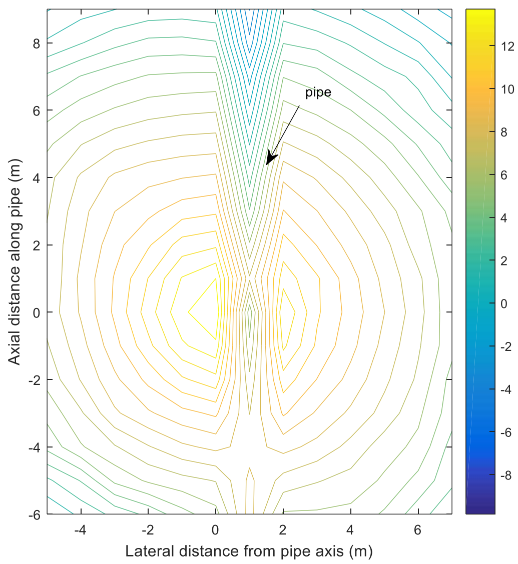

Figure 2
Ground surface response: unwrapped phase contours reveal both the run of the pipe and the waves spreading cylindrically from the source

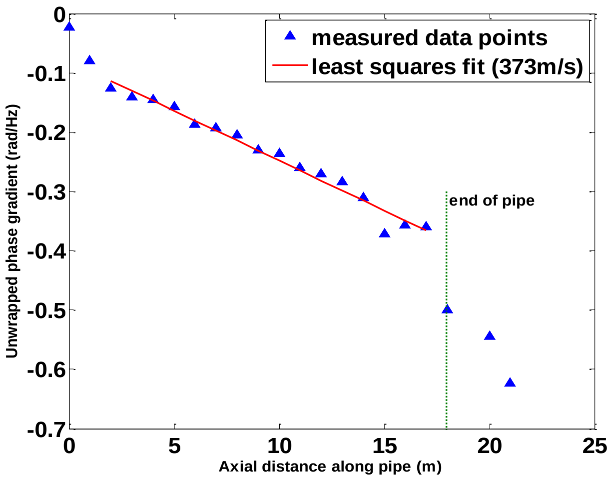

Figure 3
Ground surface response: unwrapped phase gradients directly above an MDPE water pipe (first shown in [17])

Figure 3 depicts the unwrapped phase gradients as a function of axial distance along the pipe (the rate of change of unwrapped phase with frequency, independent of frequency for non-dispersive waves) along a line directly above an MDPE mains water pipe. For each measurement location directly above the pipe, the gradient of the unwrapped phase line was found by performing a least squares fit over a continuous straight line section of the frequency-unwrapped phase plot for that location. The variation in this gradient with axial distance along the pipe was then analyzed. The plot can be seen to consist of three sections: the first is approximately straight and comprises the first three data points from 0m to 2m from the vibration source at the pipe end; the second is also approximately straight and contains the bulk of the data, from 2m to 17m from the source (barring one stray data point at 15m), i.e. to the far end of the pipe; and the final section comprising the last three measurement locations (excluding that directly over the manhole at 19m), one just at the end of the pipe, at 18m, and the two beyond the manhole at 20m and 21m respectively. Fitting a straight line to the first three data points gives a phase speed of approximately 120m/s, which decreases to around 110m/s if only the first two points are used. This most likely corresponds to the directly-excited which will dominate in the nearfield. A least squares fit over the second straight-line section gives a phase speed of 373m/s; this corresponds to the fluid-dominated, axisymmetric wave in the pipe as anticipated (measured previously as 365m/s) [17]. 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, corresponding to locations at and beyond the end of the pipe suggest a significant decrease in the wavespeed measured on the surface, and is a convincing indicator of the end of the pipe. Computing the wavespeed from the final two measurement points gives a figure of approximately 80m/s which again most likely corresponds to the Rayleigh surface wave as the wave in the pipe is no longer propagating.

3. Possibilities for condition assessment and monitoring

The pipe location method, outlined in the previous section also has the potential to reveal the condition of a pipe or its surroundings. Whereas the phase of the ground surface vibrational response is particularly useful for locating a pipe, magnitude information can supplement the phase data 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, a leak, or, indeed, a change in the soil in which the pipe is buried. The ways in which the magnitude information can be exploited are described in the following sub-sections.

3.1. Detection of holes and cracks

We have seen in the preceding paragraphs that waves propagating along a pipe will, in general, radiate to the ground surface where they can be measured; furthermore, that the axial dependence of the waves in the pipe is directly mirrored at the ground surface. For the most part, waves will propagate in the ground at a different phase speed to those in the pipe. Any damage to the pipe wall will disrupt the waves propagating in the pipe and this disruption will be reflected in the ground surface response. In the extreme, if a pipe is damaged or cracked to such an extent that the structural connection between two sections of pipe is completely lost (as can happen with severely deteriorated cast iron pipes in clay soil, for example), then the wave in the pipe may no longer propagate. In this instance, it will appear as if the pipe has ended and a response such as that seen at the pipe end in Figure 3 may be observed. In less extreme cases, where a small crack or hole has appeared, a proportion of the energy propagating along the pipe will be reflected back along its length, whilst some energy is still transmitted past the defect. In this case, it may be that the magnitude of the surface response is more revealing. Figure 4 shows the magnitude and unwrapped phase of the surface response (relative to the input excitation) for the same MDPE pipe as discussed earlier.

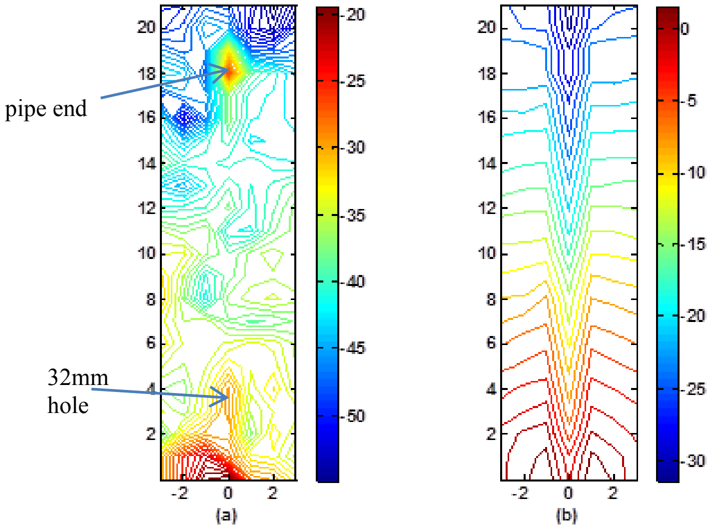

Figure 4

Ground surface response above an MDPE water pipe: (a)magnitude; (b) phase

Whilst the phase is extremely useful for determining the run of the pipe, and the magnitude is not, the magnitude reveals additional information. The far end of the pipe is very clearly seen (identified in the figure), revealed by a clear increase in response; moreover, an additional location where the response is evidently increased (approximately 4m from the excitation source, and also identified in the figure), was found to be the site of a 32mm hole. Although these two ‘defects’ are somewhat larger than might be always seen in practice, the detection potential is clear. Perhaps more promising is the notion that, if repeated measurements were made over long periods, then it would be possible to monitor *changes* rather than *absolutes*, which might be more straightforward to interpret.

3.2. Deterioration of the pipe wall.

As described in section 2, it has been shown previously that it is possible to measure the wavespeed of the dominant mode of wave propagation in a buried pipe from measurements of the ground surface vibration directly above the pipe [17]. For the n=0 (axisymmetric), s=1 (fluid-dominated) wave, this wavespeed is highly dependent on the elastic properties of the pipe wall, and largely independent of the soil type in which the pipe is buried. At low frequencies, a simple analytic expression can be adopted [10,13,14] to calculate this wavespeed, c_p, which is given by

$$c_p = c_f \left(\frac{1}{\sqrt{1 + \frac{2B_f a}{E_p h}}} \right) \tag{1}$$

where, c_f is the freefield wavespeed in the contained fluid, B_f, is the bulk modulus of the contained fluid and E_p is the elastic modulus of the pipe wall material, and a and h are the, radius and wall thickness of the pipe respectively.

Rearranging equation (1) gives alternative forms

$$E_p h = \frac{2B_f a}{\left(\frac{c_f}{c_p}\right)^2 - 1} \text{ or } E_p = \frac{1}{h} \frac{2B_f a}{\left(\frac{c_f}{c_p}\right)^2 - 1} \text{ or } h = \frac{1}{E_p} \frac{2B_f a}{\left(\frac{c_f}{c_p}\right)^2 - 1} \tag{2}$$

These equations show that if the wavespeed can be measured and the pipe radius is known, then the product of the pipe wall elastic modulus and thickness can be inferred. For a metal pipe, either one of these parameters may change due to the effects of ageing or corrosion; for a plastic pipe, the wall thickness is unlikely to alter but the elastic modulus may change, as a result of embrittlement, for example. The fact that the wavespeed expression contains a square root means that significant changes might need to occur in the modulus-thickness product before a change in the wavespeed may, in practice, be detectable, particularly from measurements made at the ground surface. Such circumstances are not, by any means, unknown, as, for example, in the case of cast iron pipes in clay when the cast iron pipe has corroded completely and what contains the water is the clay around the original pipe form.

As for detecting holes and cracks it is likely that monitoring changes over time will be more fruitful than a single standalone measurement.

3.3. The condition of the soil

It is not only discontinuities in the pipe which can result in wave reflections seen at the ground surface. Changes in the condition of the soil itself can cause the ground surface response to alter, with abrupt changes giving rise to much of the wave energy being reflected. Such alterations in the soil condition could include: changes in soil type, possibly subsequent to back filling; lack of any soil at all, as in the presence of a sink hole; changes in saturation as a pipe passes through/under a water course or above/below the water table; or simply natural soil boundaries . Some of these changes in the soil may be either clearly visible from the ground surface or already identified, but some may not. Figure 5 shows two measurements of the magnitude of the ground surface response due to exciting a pipe at a test facility.

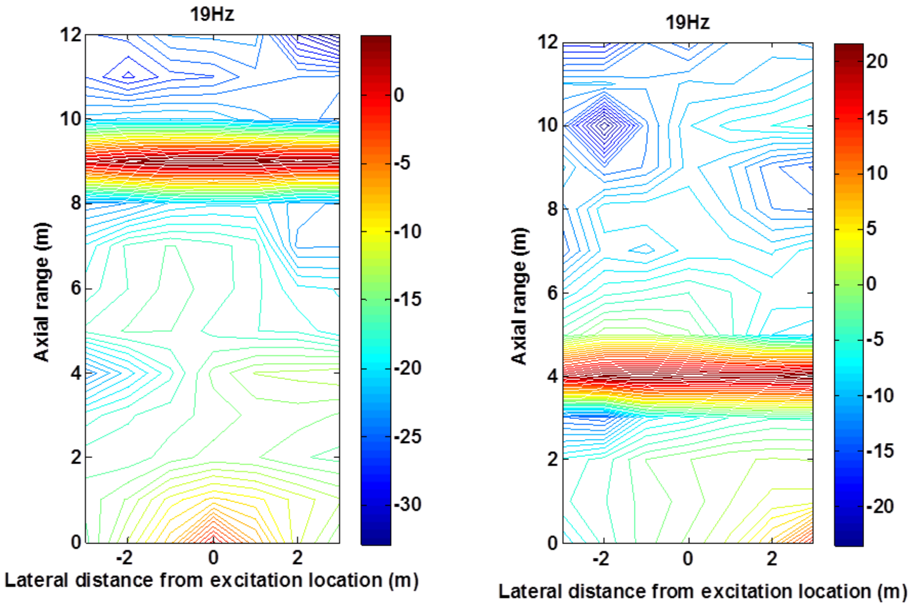

Figure 5
Magnitude of ground surface vibration response

Here, the boundaries between the 'bays' containing different soil types are clearly visible in the response. The pipe, in this instance, is acting as a waveguide which, in turn, excites the soil, thus providing information regarding the soil rather than the pipe itself. It is conceivable that this approach could be adopted to interrogate other soil variations, the advantage being that the pipe will naturally guide the energy in a direction parallel to its axis and any geometric attenuation will thus be minimised.

Interactions between buried infrastructure and the soil/ground in which the infrastructure is buried are complex and degradation in one part may initiate deterioration or failure in the other. Being able to use the buried infrastructure to interrogate the surrounding soil could be a powerful way to gain more immediate access to hitherto difficult areas to probe and may also provide a forewarning of incipient failure in one or other system.

4. Discussion and Conclusions

How these ideas can be taken forward in practice has yet to be determined. Experiments on leakage test beds have been planned which should enable the feasibility of the suggested approach to evaluated more fully. As part of the wider *Assessing the Underworld* programme, deterioration models are being developed which will aid in establishing how pipes (both metal and plastic) degrade and how the wall properties (thickness and elastic modulus) will alter over time. Likewise, this work aims to examine the complex interactions between ground, surface infrastructure and buried infrastructure such that all can be maintained or protected in the most effective manner. The possibility of being able to interrogate buried pipes and the ground in the ways described in this paper could provide additional pieces in the jigsaw aimed at characterising and, ultimately, safeguarding our subsurface space.

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