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A theoretical study of the fundamental torsional wave in buried pipes for pipeline condition assessment and monitoring

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ABSTRACT

Waves that propagate at low frequencies in buried pipes are of considerable interest in a variety of practical scenarios, for example leak detection, remote pipe detection, and pipeline condition assessment and monitoring. Whilst there has been considerable research and commercial attention on the accurate location of pipe leakage for many years, the various causes of pipe failures and their identification, have not been well documented; moreover, there are still a number of gaps in the existing knowledge. Previous work has focused on two of the three axisymmetric wavetypes that can propagate: the $s=1$, fluid-dominated wave; and the $s=2$, shell-dominated wave. In this paper, the third axisymmetric wavetype, the $s=0$ torsional wave, is investigated. The effects of the surrounding soil on the characteristics of wave propagation and attenuation are analysed for a compact pipe/soil interface for which there is no relative motion between the pipe wall and the surrounding soil. An analytical dispersion relationship is derived for the torsional wavenumber from which both the wavespeed and wave attenuation can be obtained. How torsional waves can subsequently radiate to the ground surface is then investigated. Analytical expressions are derived for the ground surface displacement above the pipe resulting from torsional wave motion within the pipe wall. A numerical model is also included, primarily in order to validate some of the assumptions made whilst developing the analytical solutions, but also so that some comparison in the results may be made. Example results are presented for both a cast iron pipe and an MDPE pipe buried in two typical soil types.

1. Introduction

The condition assessment of underground utilities is of paramount importance for engineers working in the realms of buried infrastructure and, indeed, for the society that they serve; quite apart from the essential services which the utilities provide to support 21st century ways of life, certain catastrophic accidents result directly from gas pipe leaks or broken water mains. In recent years there has been a move towards more remote and non-intrusive methods of condition

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assessment, alongside developments in continuous monitoring techniques. If the condition of the buried infrastructure is routinely assessed and monitored, proactive warning of impending failure might be achieved and thus the probability of the serious consequences of accidents caused by deterioration of the utility network can be effectively reduced.

Traditionally, for example, sewer surveys were carried out by sending out inspectors to ‘see and touch’ the defects inside those man-entry pipes along the network. However, this method, although highly effective at revealing the internal condition and providing certain clues about the external condition, suffers from inefficiency in terms of manpower, and it is obviously impractical for the majority of pipes and cables that make up the network.

Moreover, modern legislation restricted this approach of direct inspection by operators for health and safety reasons [1]. Remote (i.e. non-manual) techniques were developed to overcome this concern and greatly increase the inspection efficiency.

Over the past decade, much attention has been paid to remotely detecting buried pipes and cables in all ground conditions without the need for excavation, under the umbrella of a major UK initiative entitled “Mapping the Underworld” (MTU) [2]. A new research project, entitled “Assessing the Underworld” (ATU) [3], building on the highly successful outcomes from MTU, has recently commenced to take the research into a new sphere. This programme aims to use geophysical sensors deployed both on and beneath the ground surface to remotely determine the condition of these urban assets. Vibro-acoustics, as one of the four essential technologies in the MTU, has been proven to be suitable and highly successful for locating buried water pipes [4,5]. In the ATU phase, some of the vibro-acoustic techniques developed in MTU will be extended from detecting pipes to assessing their condition. It is within this framework that the work presented here has been undertaken.

Failures in aging water mains are a serious problem for all water distribution systems. Whilst there has been considerable research and commercial attention on the accurate location of water leakage for many years [6–8], the various causes of pipe failures and their identification, have not been well documented; moreover, there are still a number of gaps in the existing knowledge. One mode of failure, about which there is very little in either the academic or industrial literature, is spiral fracture, occurring, for the most part, in cast iron pipes [9]. Beyond the obvious case of a spirally welded pipe, it is not altogether clear what mechanism might underlie such a failure. Steverding [10], investigating helical cracks in cylinders suggested that the spiral was caused by self-radiation of the moving crack, with the pitch being determined by the crack speed, this, in turn, being linked to the ductility of the fracture process. It is also possible that some kind of torsional excitation might initiate a spiral failure; although it is difficult to envisage how that could occur in practice, differential soil movement either side of the pipe might play a part.

Perhaps more tractable and undoubtedly of more relevance to the present study is the link between spiral failure (however initiated) and the wave motion set up within the pipe in consequence. There is a desire, particularly within the gas industry, to be able to detect and locate fracture events as they occur and, if possible, remotely confirm the likely mode of failure. For a vibro-acoustic technique to be effective, the acoustic characteristics of the dominant wave mode(s) associated with particular types of pipe failure must be known *a priori*. Furthermore, how these waves may radiate to the ground surface, where than can potentially be detected, is of considerable interest. In general, in buried water pipes, acoustic energy propagates at relatively low frequencies [11]. 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 $s=1$, 2 waves [12–16]. The focus of the present paper is the $s=0$, torsional wave. Whilst, in the field, it has not been confirmed beyond reasonable doubt, it would seem logical to assume that, when a spiral fracture occurs in a pipe, torsional waves are excited and thence propagate along the pipe. Moreover, if it were possible to detect these waves from the ground surface, possibilities for the remote detection and monitoring of the fracture events open up.

Torsional waves in pipes have received considerable attention in the literature at ultrasonic frequencies to support commercial testing systems that have been in use in industry for a number of years. They are exploited for the detection and characterisation of cracks and other (small) pipe defects in both unburied and buried pipe, for example [17–24]. At these high frequencies, the fundamental torsional wave in a buried pipe is non-dispersive, propagating at the same speed as that in an *in-vacuo* pipe. Ultrasonic torsional waves have been used to measure the near-surface shear wave velocities of saturated soils [25], but no work has been done relating the soil response to that within the pipe wall. Little is available in the literature for the low-frequency regime, beyond the *in vacuo*, textbook solution. Kudlička [26] presented the dispersion characteristics of thick-walled pipes *in vacuo* and, moreover, investigated anisotropy. Parnes et al. [27,28] considered torsional waves in a clad rod and examined the conditions under which waves could propagate in the rod. Initially, the rod was treated effectively as a shell, but in the later work variation over the rod cross-section was included. However, he framed the analysis in terms of wavespeed, rather than wavenumber, and then made no allowance for the possibility of complex (as opposed to purely real) solutions. This severely restricts the conditions for which wave propagation can occur. Moreover, the response within the cladding was not investigated in detail. Thurston [29] investigated a similar problem, formulated it in terms of wavenumber and allowed for the possibility of attenuating waves, but did not present analytical expressions for the solutions. To the authors' knowledge no other work has, to date, been presented on the low-frequency behaviour of buried pipes and the concomitant response within the soil, in particular, in terms of an analytical solution. In this paper, the