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On the effects of soil properties on leak noise propagation in plastic water distribution pipes

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ABSTRACT

In many countries, leaks are located in water distribution pipes by using the cross-correlation of pipe vibration measured either side of a suspected leak. However, in modern plastic pipes this can be problematic due to strong coupling between the water, the pipe and the soil, affecting the propagation of leak noise within the pipe. This paper concerns an analytical, numerical and experimental investigation into the way in which soil properties influence leak noise propagation in buried plastic water pipes. The analytical model allows a detailed investigation into the physical effects of the soil on leak noise (wave) propagation in the pipe, in particular on the wave-speed and wave attenuation. Results highlight that, in addition to the pipe hoop stiffness, the shear stiffness of the soil can have a significant effect on the wave-speed in the pipe. Experimental measurements were conducted at two different sites - one in the UK and the other in Brazil. In the UK system, both dilatational and shear waves in the soil propagate away from the pipe, resulting in large wave attenuation in the pipe. However, in the Brazilian system, only shear waves propagate resulting in smaller wave attenuation in the pipe.
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1. Introduction

Water leakage is a serious problem in many countries. It is estimated that 40–50% of drinking water is wasted through leakage in developing countries, and less than 10% in countries where the utilities are well-maintained, such as Japan [1,2]. To determine if a leak is present in a specific part of the network, pressure measurements together with flow measurements are often used [3]. Leak noise correlators can then be used to determine a more precise location of the leak [4]. Although correlators work well for metallic pipes, their performance with plastic pipes is more limited [5–7]. Two main factors affect correlator performance in this case. They are the relatively high rates of attenuation experienced by the leak noise propagating along the pipes and the variability in the speed (wave-speed) at which it propagates. The wave-speed can be heavily influenced by the pipe properties and the surrounding soil [8–13]. The maximum distance between the sensors on either side of the leak is limited by the attenuation of the leak noise. Further, the accuracy with which the leak can be located is related to

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the accuracy of the wave-speed estimate. In nearly all cases, the wave-speed is estimated from an empirical database determined from calculations made using assumed material properties and pipe geometry.

Motivated by differing measurements of pipe wave-speed and attenuation at two different sites, one in the UK and one in Brazil [14], the aim of this paper is to determine the way in which soil properties affect the characteristics of the pipe wave responsible for leak noise propagation. The investigation focuses on the factors that affect wave-speed and wave attenuation. It includes analytical modelling of wave propagation in a buried water pipe, development of a numerical model based on the finite element method whereby the water, the pipe and the surrounding soil comprise a fully coupled three-part system, and experimental measurements of pipe wave-speed and attenuation at two different sites, one of which is in the UK and the other is in Brazil. The analytical model is formulated in terms of the dynamic stiffness of the pipe and the soil, which facilitates physical insight into the effects of soil parameters on leak noise propagation.

The paper is organised as follows. Following this introduction, analytical and finite element models of a generic pipe system are described in Section 2. Following validation of the analytical model in Section 3, a detailed investigation into the physical effects of the soil on wave propagation in the pipe is then carried out in Section 4. It also describes a parametric study. Finally, some conclusions are drawn in Section 5.

2. Modelling of the pipe system

Two models of the pipe system are described in this section, namely an analytical model and a finite element model. The analytical model is developed to allow a detailed analysis to be conducted into the way in which the soil properties affect the propagation of leak noise (wave-speed and attenuation). However, because this model contains some simplifying assumptions, a finite element model is also developed. This model has fewer simplifying assumptions and so it can be used to help validate the analytical model. Moreover, it can be used to readily give a picture of the wave propagation in the system.

2.1. Analytical model

Several analytical models of a buried water pipe system have been developed in the literature, with differing levels of complexity, for example. [8,10,12], but the simplest one that contains the essential physics is believed to be the one in Ref. [10]. In this model, it is assumed that the pipe only connects dynamically with the soil in the radial direction, so there is no excitation of the soil in the axial direction of the pipe. Although this assumption is not strictly justified from a physical point of view, it does significantly simplify the model and facilitates physical interpretation of the effects of the soil on leak noise propagation in the pipe. In Ref. [12] it is shown that the inclusion of a no-slip condition between the pipe and the soil has only a marginal effect on the wave propagation properties in the frequency range considered in this paper (0–600 Hz). Moreover, in the numerical model described in the next section, no simplifying assumptions are made about the pipe-soil interface, and the results are found to be comparable with the analytical model for the cases studied. Thus, for the purposes of this paper, a slip condition between the pipe and the surrounding soil is assumed.

A schematic diagram of a buried plastic water pipe is shown in Fig. 1. It has a mean radius a and pipe-wall thickness h, with density ρ and complex Young's modulus $E^* = E(1+\mathrm{j}\eta_p)$ in which E is the storage modulus and η_p is the loss factor. The pipe contains water with bulk modulus B_{water}, and is buried in soil with density ρ_{soil}, and bulk modulus $B^*_{\mathrm{soil}} = B_{\mathrm{soil}}(1+\mathrm{j}\eta_d)$, where B_{soil} is the storage modulus and η_d is the compressional loss factor. The shear modulus is given by $G^* = G(1+\mathrm{j}\eta_s)$, where G is the storage modulus and η_s is the shear loss factor. The approximate complex wavenumber related to leak noise propagation is given in Ref. [10], which is written here in the following form to aid physical insight

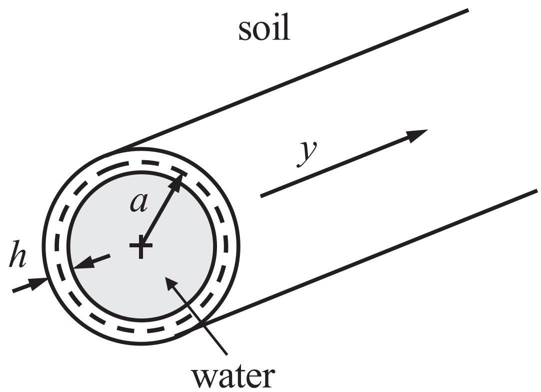

Fig. 1. Schematic diagram of the buried pipe showing the pipe geometry.

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