THE EFFECT OF SOIL PROPERTIES ON ACOUSTIC WAVE PROPAGATION IN BURIED IRON WATER PIPES

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1. INTRODUCTION

An initial investigation, reported in last years proceedings by Long et al [1], was conducted to identify the dominant modes that propagate in buried iron water mains. In general, for propagation distances over 10 to 20m little evidence was found of the fundamental modes, which are labeled as L(0,1) and F(1,1) in Fig. 1. Displacements for both these modes occur predominantly in the pipe wall so scattering at pipe joints and fittings is likely to dramatically reduce the transmitted wave amplitude. Sound was found to propagate over significant distances as the mode labeled as alpha in Fig. 1, which at low frequencies is characterized by predominately axial water borne displacements. The established method of locating leaks by acoustic signal analysis [2] assumes that leak noise propagates non-dispersively at a velocity related to the low frequency asymptote of the alpha mode shown as the dashed line in Fig. 1. Leak location errors will occur particularly when testing larger bore pipes for which the alpha mode is more dispersive over the frequency range of interest. Thus we are interested in predicting the extent of alpha mode dispersion to make recommendations that might improve the accuracy of the established technique.

2. PARAMETERS THAT AFFECT ALPHA MODE DISPERSION

Predictions of the wave propagation characteristics in buried iron water mains have been made by simplifying the problem to one of an idealized cylindrical tri-layer system. Predictions were obtained using the Disperse software [3] that gives dispersion curves and mode shapes for flat or curved cylindrical systems that comprise an arbitrary number of layers. The parameters that significantly govern the profile of predicted alpha mode dispersion curves were found to be bore size, pipe wall thickness, pipe material and the properties of the medium that surrounds the pipe. To illustrate the effect, Fig 2 indicates the range in the alpha mode phase velocity dispersion that occurs when only the surrounding material is varied and the other three parameters are held constant. For a given pipe, reliable dispersion curve predictions require the values of the governing parameters to be known. Pipe materials and geometry are governed by standards and if details are not available from records then they could be determined on site using established NDT techniques. Soil acoustic properties in the region of buried pipes may vary considerably from site to site and their evaluation is not so straightforward.

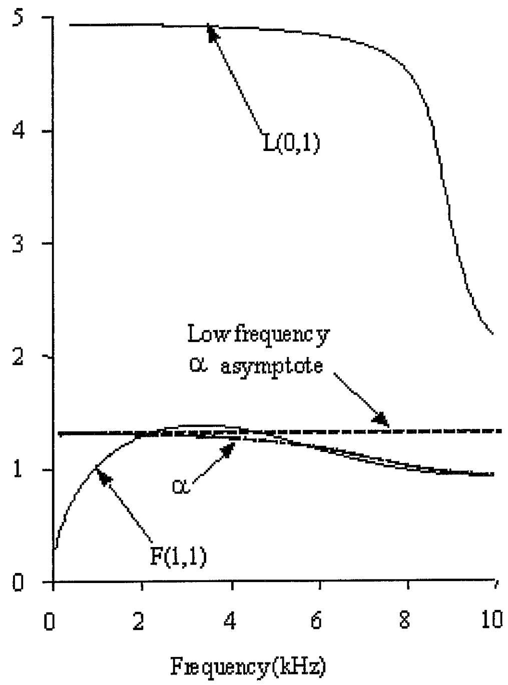

Figure 1. Phase velocity dispersion curves for a water filled 6 inch bore ductile iron pipe surrounded by a vacuum.

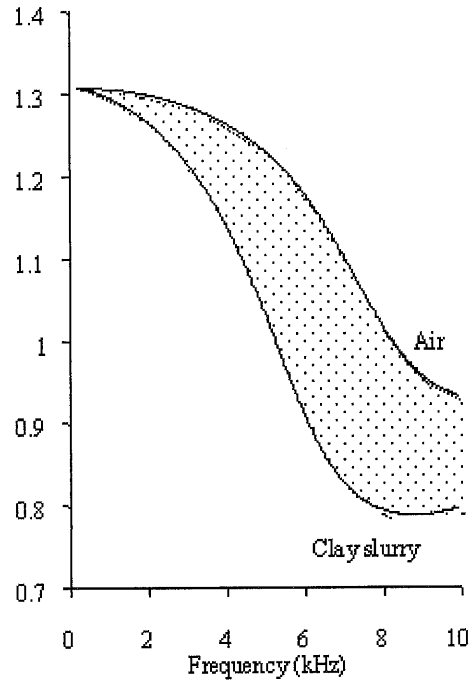

Figure 2. Range of phase velocity dispersion that occurs for a 6 inch bore, 7mm wall thickness, ductile iron pipe surrounded by material with impedance between air to a clay slurry.

3. PREDICTED SOIL PROPERTIES

The simplest analysis of a sandy soil would be to consider it as a homogeneous composite of quartz and pore fluid. The bulk longitudinal wave velocity C_L could then be found by the Reuss average of the phases [4]

$$C_L = (k/\rho)^{1/2} = \left[(n_f \rho_f + n_q \rho_q) \left(\frac{n_f}{k_f} + \frac{n_q}{k_q} \right) \right]^{-1/2} \tag{1}$$

where k is the bulk modulus, ρ the density, n the fractional content and the subscripts f and q denote fluid and quartz respectively. For a water saturated, medium grain size sand, where typically n_f = 40%, the predicted longitudinal velocity would be about 1660m/s. By contrast, dry medium sand would have a velocity of about 16m/s. Such extremes of velocity are reported in literature when measuring velocities of sea floor sediments by Bowles [5] and for beach sands by Bachrach et al [6]. For wet sand, any presence of air will reduce the velocity considerably since the effective density remains similar to saturated sand while the compressibility is dominated by the air. For soil that is under pressure as a result of being a depth z below the surface, a more consistent manner to predict wave propagation in granular media is to consider the incremental distortions that occur at the points of inter granular contact. Bachrach et al [6] conducted an investigation into how velocity varies as a function of depth z for dry sand and concluded that longitudinal velocity is proportional to $z^{1/6}$ which agrees with the Hertz-Mindlin [7] model for a random pack of identical spheres. Bowles [5] examined published shear velocity depth profiles for saturated sediments and showed that most published data expressed velocity as a power function of depth where the value for the power varied from 0.25 to

0.45. Typically a coarse grain sediment could be described by $C_S=62.52z^{0.354}$ and a finer grain by $C_S=42.71z^{0.307}$. This is consistent with Buckingham [8] who gives the relationship between velocity and depth for saturated sediments as $z^{1/6}$ and $z^{1/3}$ for longitudinal and shear velocities respectively.

4. EVALUATING IN SITU ACOUSTIC PROPERTIES OF SOILS BY THE GUIDED WAVE ATTENUATION METHOD

Most literature deals with the evaluation of acoustic properties of soils at large depths whereas water pipes are buried only approximately 1m from the surface for which conventional acoustic measurement techniques prove problematic [4]. We are developing a suitable technique that is based on a method described by Vogt et al [9] and [10]. A schematic of the experimental apparatus is shown in Fig. 3. A steel bar has a piezo electric element bonded at one end aligned so as to predominantly excite the L(0,1) mode when excited with a broad band pulse. The bar is inserted into soil over a length L resulting in the signals reflected from the far end being somewhat attenuated due to the propagating mode leaking energy into the soil. The amount of leakage is dependent on the soil acoustic properties. The mode attenuation characteristics as a function of frequency are obtained by dividing the FFT of the reflected signal for soil by that for air. Dispersion curves are fitted to the mode attenuation data from which the longitudinal and shear velocities of the soil are inferred. Fig 4 shows some typical experimental data for a bar surrounded by water and a clay slurry. The level of attenuation at low frequencies fixes the shear velocity for the surrounding medium whereas the longitudinal velocity is found from the slope of the data at higher frequencies. Fig 5 shows the inferred longitudinal velocities and Fig. 6 the shear velocities for wet sand as a function of simulated depth (achieved by applying a load W to the surface of the sand as shown in Fig. 3). The power law for the curves fitted to the data agree well with the predictions given by [8] and [9] that longitudinal velocity varies as the 1/6 power of depth and shear by the 1/3 power. This good agreement suggests that the bar acoustically couples to the soil and is sensitive to the bulk properties.

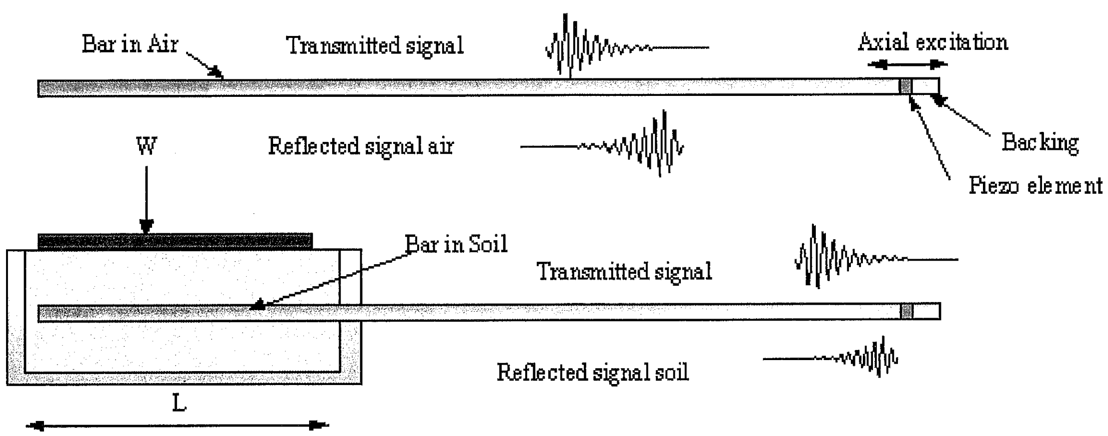

Figure 3. Schematic of guided wave attenuation method for evaluation of acoustic soil properties.

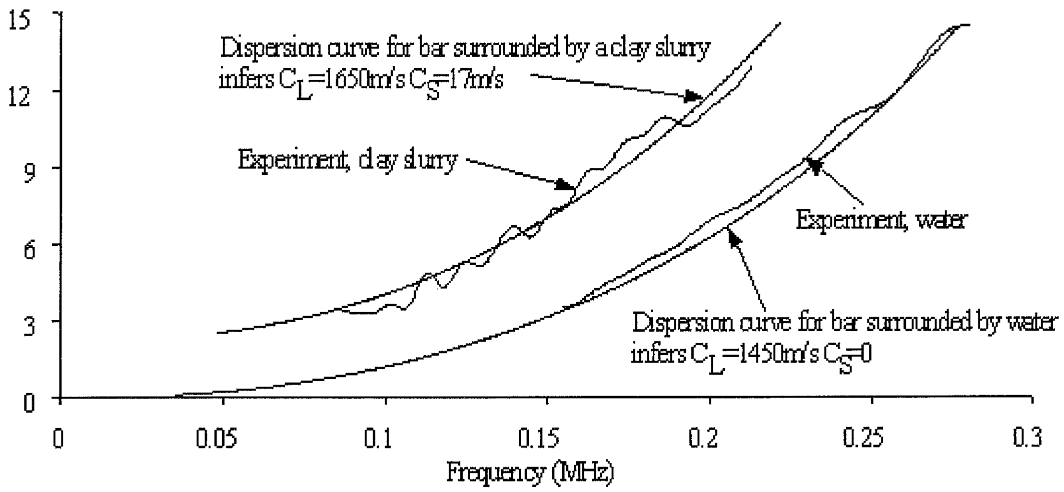

Figure 4. Example of the method of inferring material properties by fitting dispersion curves to L(0,1) mode attenuation data.

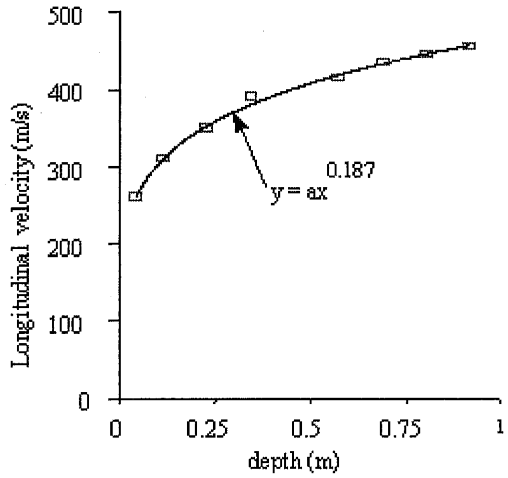

Figure 5. Evaluated longitudinal velocity of wet sand as a function of depth.
□ Experimental points, — best fit curve.

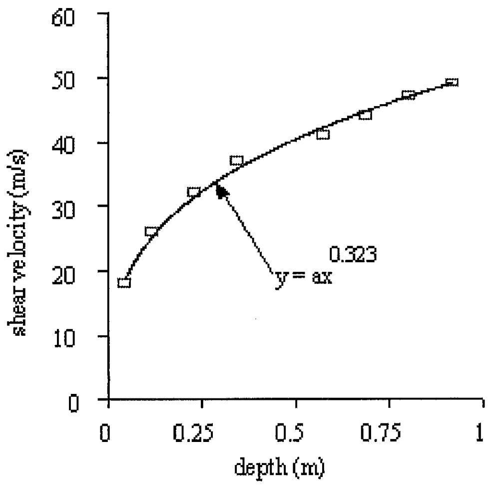

Figure 6. Evaluated shear velocity of wet sand as a function of depth.
□ Experimental points, — best fit curve.

5. MEASURED SOIL PROPERTIES

The guided wave attenuation method has been used to evaluate the acoustic properties of soils that surround buried water mains at two sites in the of south England at Guildford and Greenwich and one in the north close to Alnwick. The mode attenuation data obtained for tests conducted on each soil type shown in Fig. 7 suggests different soil characteristics. The Greenwich clay had a sticky consistency, the Guilford clay could be torn apart easily while the Alnwick soil was drier than the other two and crumbled under pressure. Dispersion curves are shown fitted to the attenuation data to infer shear and longitudinal velocities. For depths of around 1m the different soils tested exhibit similar shear velocities but have quite varied longitudinal velocities. This can be attributed to the variation in fractional air content in the soil.

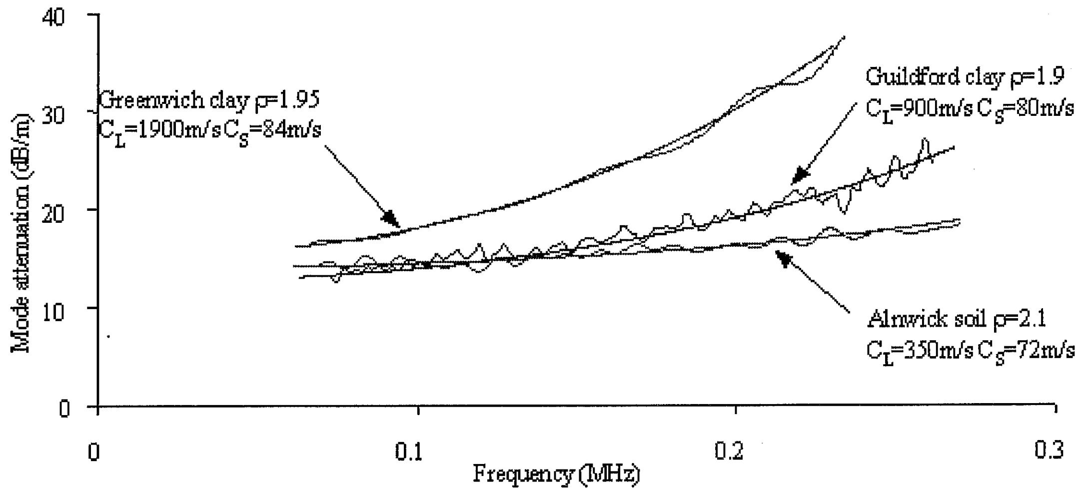

Figure 7. Evaluated acoustic properties for soils that surround buried water pipes – experimental results and fitted dispersion curves.

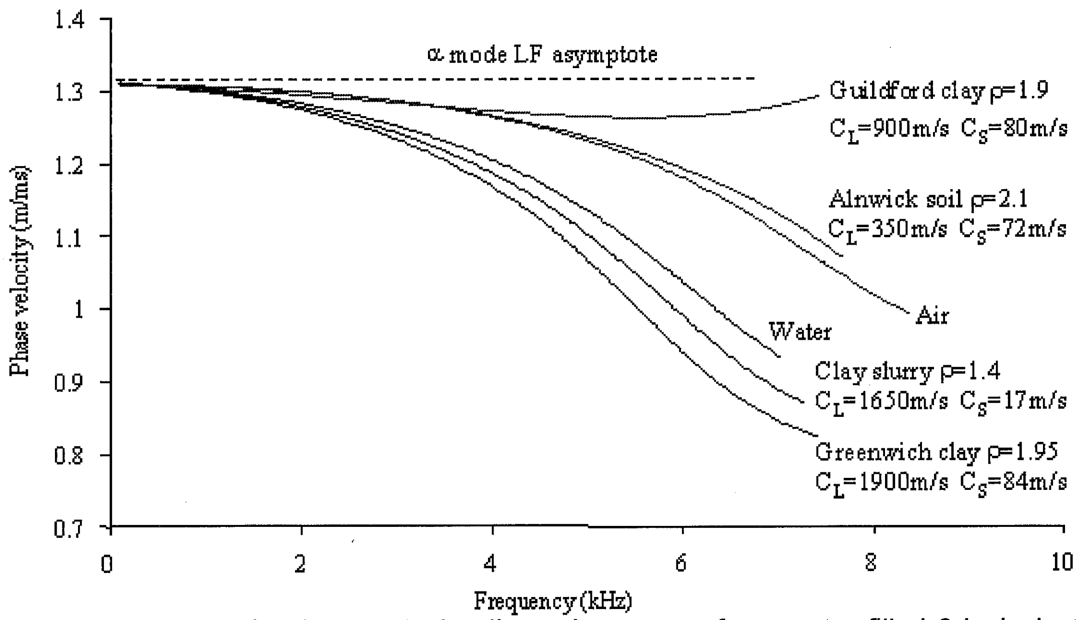

Figure 8. Alpha mode phase velocity dispersion curves for a water filled 6 inch ductile iron pipe surrounded by various outer media.

6. PREDICTED EFFECT OF MEASURED SOIL PROPERTIES ON ALPHA MODE DISPERSION

The measured soil properties have been used to predict dispersion curves for a range of possible buried water mains. Typical alpha mode phase velocity dispersion curves for a 6-inch bore pipe surrounded by various outer media are shown in Fig. 8. The horizontal dashed line represents the low frequency asymptote of the alpha mode assumed to be the velocity that sound propagates along water mains by the established leak location technique. It is evident that for a given pipe the alpha mode phase velocity dispersion characteristics are strongly affected by the impedance of the medium that surrounds the pipe.

7. EXPERIMENTAL INVESTIGATION

Some experiments have been conducted on buried water mains at various sites in the UK to verify the alpha mode dispersion predictions. Fig. 9 shows a schematic of the chosen experimental technique. At each site three pits were dug so as to get localized access to the full circumference of the buried pipe over a length of about 1m. At one location a tapper device was mounted on the pipe to intermittently excite vibrations in the pipe wall. The propagating signal was received at another location by four accelerometers mounted equi spaced around the pipe circumference. The averaged signals at each accelerometer were summed together to improve signal to noise and help eliminate any unwanted anti symmetric vibrations. The phase velocity was then calculated in the manner given by Long et al [1] by obtaining the phase spectrum of the received signal relative to that of the tapper or the signal received at another location. For dispersion curve predictions, soil properties were evaluated using the mode attenuation technique, wall thickness was determined by the ultrasonic pulse echo technique and the pipe outer circumference was measured directly.

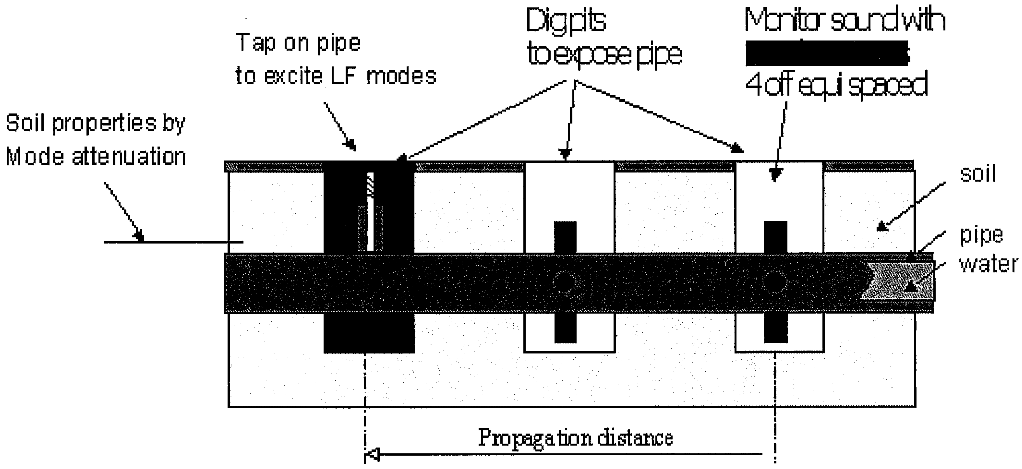

Figure 9. Experimental technique for evaluation of alpha mode phase velocity in buried water pipes

8. COMPARISON BETWEEN EXPERIMENTAL AND PREDICTED DISPERSION CURVES

Both Fig. 10 and Fig. 11 show a comparison between experimentally extracted and predicted alpha mode phase velocity dispersion curves for a 6-inch bore ductile iron pipe. The propagation distances were 30.3m at the Guilford site (Fig. 10) and 45.4m at the Alnwick site (Fig. 11). A comparison between experimentally extracted and predicted phase velocity dispersion curves for 10 and 14 inch bore cast iron pipes tested at the Greenwich site are shown in Fig. 12 and Fig. 13 respectively. Experimentally extracted phase velocity dispersion curves are shown over the frequency bandwidth that coincides with good coherence between the excitation and received signals. The experimental results indicate the dispersion characteristics that were predicted when modeling acoustic wave propagation in buried water mains as an idealized cylindrical tri-layer system.

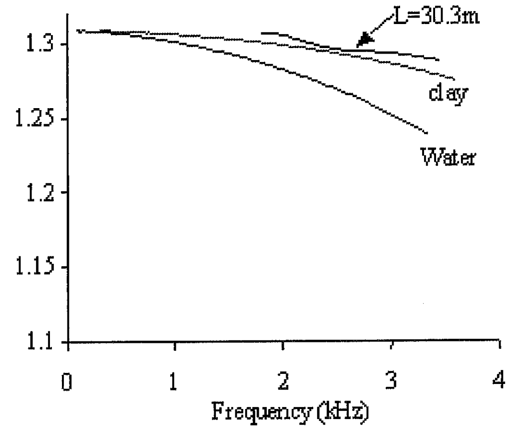

Figure 10. Experimental results for 6-inch ductile iron pipe in Guildford compared with predicted alpha mode phase velocity dispersion curves.

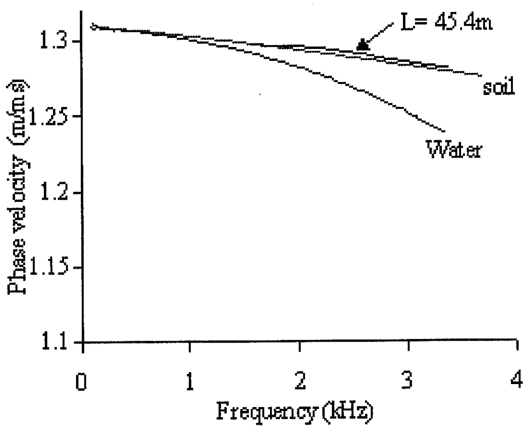

Figure 11. Experimental results for 6-inch ductile iron pipe in Alnwick compared with predicted alpha mode phase velocity dispersion curves.

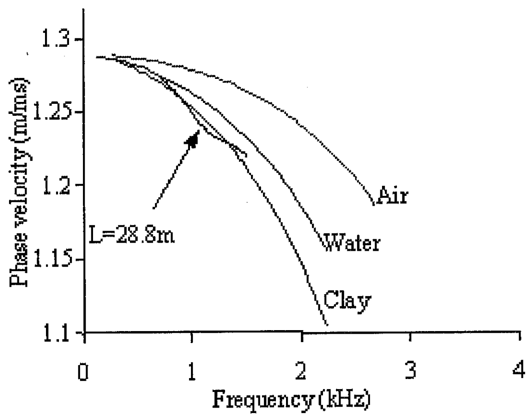

Figure 12. Experimental results for 10-inch cast iron pipe in Greenwich compared with predicted alpha mode phase velocity dispersion curves.

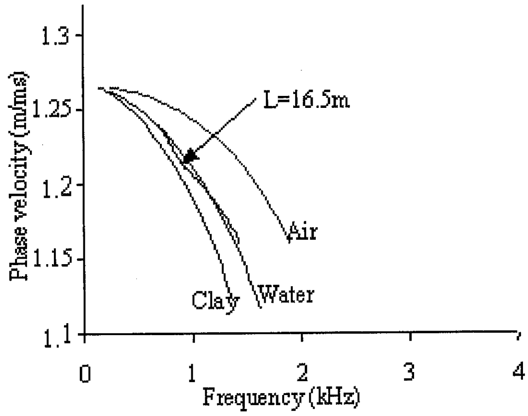

Figure 13. Experimental results for 14-inch cast iron pipe in Greenwich compared with predicted alpha mode phase velocity dispersion curves.

9. CONCLUSIONS

The established acoustic technique for locating leaks in buried water pipes assumes that leak noise propagates non dispersively. Experimental results indicate that sound propagates significant distances as a dispersive water borne mode. The discrepancy between the actual and assumed behavior can lead to leak location errors. The accuracy of leak location could therefore be improved if the wave propagation dispersion characteristics for a given water main were predicted and accounted for in the signal processing. Dispersion curve predictions require a knowledge of pipe geometry, pipe material properties and the acoustic properties of the soils that surround a pipe. A suitable technique is being developed to measure the in situ, near surface acoustic properties of unconsolidated materials which normally prove problematic to evaluate when using conventional methods.

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