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On the Effects of Soil-Pipe Interface Conditions on the Fluid-Dominated Axisymmetric Wave in Buried Plastic Water Pipes

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Abstract: *This paper describes a theoretical investigation into the way in which the coupling conditions between a buried plastic water pipe and the surrounding soil affects the propagation characteristics of the fluid dominated wave in the pipe. Of particular interest, is whether the axial coupling between the pipe and the soil is an important factor for a typical Brazilian water pipe system. For typical soil in São Paulo city, it is found that the shear modulus of the soil has a profound effect on the wave motion in the pipe, and this is mainly through radial rather than axial coupling between the pipe and the soil.*

Keywords: *Leak detection, Water distribution, Buried plastic pipes.*

1. INTRODUCTION

In recent years, water scarcity has become a topic of great concern due to a steadily increasing demand for clean drinking water and decrease in water supplies resulting in potential social, environmental and economic effects. It has been calculated that in many water distribution networks, loss can frequently exceed 30% of the input volume and, in some cases it reaches much higher levels, from 40% to 50% because of leaks or pipe breaks resulting from holes, deterioration and damage (Brennan et al., 2017; Kanakoudis and Muhammetoglu, 2014).

If a leak occurs, the noise it generates will propagate along the pipe in the form of an acoustic wave, which is the axisymmetric (n=0) fluid-borne wave (s=1). The physical behaviour of this wave has been studied extensively because of its role in the detection of leaks in buried fluid-filled water distribution pipes (Muggleton et al., 2002). Pinnington and Briscoe (1994) proposed an analytical model to study the fluid-borne wave propagation as well as the energy distribution in buried plastic pipes in-air (in vacuo) by considering boundary conditions for thin-walled shells. More recently, some work has been devoted to the investigation of pipelines submerged in water, and also surrounded by soil (Muggleton et al., 2002; Muggleton and Brennan et al., 2004). Muggleton et al. (2002) developed a theoretical model, which is an extension of the model proposed by Pinnington and Briscoe (1994), to predict both wave speed and attenuation of a buried fluid-filled pipe. The authors investigated the effects of the surrounding medium by considering a plastic pipe surrounded by an infinite elastic medium which can sustain both compressional and shear waves. They focussed on the determination of the wavenumbers of the coupled system, as the real part of the wavenumber provides information about the wave speed and the imaginary part is related to the propagation loss. For the fluid-borne s=1 wave, it was shown that the presence of the pipe wall is responsible for reducing the wave speed compared to that for a rigid-wall pipe. Additionally, the surrounding medium can reduce it even more due to mass loading of the pipe. Two years later, this model was experimentally validated by Muggleton et al. (2004). In this work, the soil was treated as a fluid supporting two different waves, each of which exerted normal dynamic pressure on the pipe wall. Although the shear coupling of the pipe to the surrounding soil was not properly accounted for, the theoretical results and measurements for wave speed showed good agreement at low frequencies. At higher frequencies, however, the results matched the in-air case better than the buried pipe predictions due to possible uncertainties in the soil properties or even effects of the ground surface (which was not considered in the theoretical modelling).

In summary, the work discussed hitherto did not model the soil effectively, as it was treated as a fluid supporting elastic waves in the soil. These properties were considered in subsequent work by Muggleton and Yan (2013). However, they described an incomplete model in which the soil connected to the pipe in the radial direction, but was not connected in the axial direction. In effect, there was a lubricated contact between the pipe and the surrounding soil. The authors then derived analytical expressions for the s=1 wave. Later, Gao et al. (2016) proposed a more complete model in which the pipe connected to the soil both radially and axially. They carried out their investigation by an analytical method in which the effect of the soil loading on the pipe response is characterized by the soil loading matrix. An extended version of this model was later discussed by Gao et al. (2017) who investigated the loading effects of the surrounding elastic medium. In this paper the aim is to investigate the effects of neglecting the axial coupling between the pipe and the soil, specifically for a Brazilian water pipe system. As in previous work, the paper focusses on the effects of the soil on wave speed and wave attenuation of the fluid dominated wave.

2. AXISYMMETRIC FLUID-DOMINATED WAVENUMBER PREDICTION

At low frequencies, below the pipe ring frequency, the axisymmetric (n=0) fluid-dominated (s=1) wavenumber in a fluid-filled pipe surrounded by an elastic medium is given by the complete model (soil-pipe interface under compact contact) as

$$k = k_w \left(1 + \frac{K_{\text{water}}}{K_{\text{pipe}} + K_{\text{soil}}}\right)^{\frac{1}{2}} \tag{1}$$

where $k_w = \omega\left(\rho_w / B_w\right)^{\frac{1}{2}}$ is the free-field wavenumber of water, which is a function of the density ρ_w, bulk modulus B_w and the angular frequency ω. The term $K_{\text{water}} = 2B_w / a$ is the stiffness of the water and

$$K_{\text{pipe}} = \frac{K_{\text{pipe}}^{(\text{stiff})}}{(1-\nu_p^2)} + K_{\text{pipe}}^{(\text{inertia})} = \frac{E_p h}{a^2(1-\nu_p^2)} - \omega^2 \rho_p h \tag{2}$$

is the dynamic stiffness of the pipe-wall where a is the mean radius, h is the thickness, ρ_p, E_p and ν_p are the density, Young's modulus and Poisson's ratio of the pipe respectively. The term $K_{\text{pipe}}^{(\text{stiff})}$ denotes the stiffness component of pipe wall and $K_{\text{pipe}}^{(\text{inertia})}$ corresponds to the inertial component.

The term $K_{\text{soil}} = K_{\text{soil}}^{(a)} + K_{\text{soil}}^{(b)}$ corresponds to the dynamic stiffness of surrounding medium, where

$$K_{\text{soil}}^{(a)} = \frac{\mu_s}{a}\left[2 + \frac{k_{r1}^r a k_r^2 a^2 \left[\frac{H_0(k_{r1}^r a)}{H_0'(k_{r1}^r a)}\right]\left[\frac{H_0(k_{d1}^r a)}{H_0'(k_{d1}^r a)}\right]}{k_{r1}^r a k_{d1}^r a \left[\frac{H_0(k_{r1}^r a)}{H_0'(k_{r1}^r a)}\right] + k^2 a^2 \left[\frac{H_0(k_{d1}^r a)}{H_0'(k_{d1}^r a)}\right]}\right] \tag{3}$$

$$K_{\text{soil}}^{(b)} = \frac{E_p h}{a^2(1-\nu_p^2)}\left[-\frac{\nu_p^2}{\left(1+\frac{S_1}{k^2a^2}\right)} + j\frac{2\nu_p S_2}{ka\left(1+\frac{S_1}{k^2a^2}\right)} + \frac{S_2^2}{k^2a^2\left(1+\frac{S_1}{k^2a^2}\right)}\right] \tag{4}$$

in which

$$S_1 = -\mu_s \frac{(1-\nu_p^2)a}{E_p h}\left[\frac{k_{d1}^r a k_r^2 a^2}{k_{r1}^r a k_{d1}^r a \left[\frac{H_0(k_{r1}^r a)}{H_0'(k_{r1}^r a)}\right] + k^2 a^2 \left[\frac{H_0(k_{d1}^r a)}{H_0'(k_{d1}^r a)}\right]}\right] \tag{5}$$

and

$$S_2 = j\mu_s \frac{(1-\nu_p^2)a}{E_p h} ka \left[2 - \frac{k_r^2 a^2 \left[\frac{H_0(k_{d1}^r a)}{H_0'(k_{d1}^r a)}\right]}{k_{r1}^r a k_{d1}^r a \left[\frac{H_0(k_{r1}^r a)}{H_0'(k_{r1}^r a)}\right] + k^2 a^2 \left[\frac{H_0(k_{d1}^r a)}{H_0'(k_{d1}^r a)}\right]}\right] \tag{6}$$

where the surrounding medium radial wavenumbers, k_{d1}^r and k_{r1}^r, given by $k_{d1}^r = \sqrt{k_d^2 - k_1^2}$ and $k_{r1}^r = \sqrt{k_r^2 - k_1^2}$ where k_d and k_r are the compressional and shear wavenumbers in the surrounding medium, respectively, given by $k_d^2 = \omega^2 \rho_s / (\lambda_s + 2\mu_s)$ and $k_r^2 = \omega^2 \rho_s / \mu_s$, in which ρ_s is the density of the surrounding soil and

$\lambda_s = B_s - \frac{2}{3}G_s$, $\mu_s = G_s$ are the Lamé coefficients, which are a function of bulk modulus B_s and shear modulus G_s of the soil. The term H_0 is the Hankel function of zero order and second kind that describes the outgoing waves in the surrounding soil, and ' denotes the spatial derivative. The attenuation of the s=1 wave in terms of dB/m is given by (Brennan et al., 2017)

$$\text{Attenuation} = \frac{-20\,\text{Im}\{k_1\}}{\ln(10)} \tag{7}$$

For the incomplete model (soil-pipe interface under lubricated contact) the terms S_1 and S_2 are equal to zero. Moreover, for a fluid-filled pipe in-air there is no surrounding soil present in the model, so that $K_{\text{soil}} = 0$.

3. NUMERICAL SIMULATION FOR A BRAZILIAN PIPE SYSTEM

A numerical simulation is performed for the frequency range 0 - 600 Hz, well below the ring frequency of the plastic pipe system, with properties of Young's modulus $E = 2$ GN/m² and density $\rho_p = 900$ kg/m³. The pipe has a mean radius of $a = 35.8$ mm, a thickness of $h = 3.4$ mm, and the bulk modulus of the water inside the pipe is $B_w = 2.25$ GN/m². The bulk modulus of soil is $B_s = 4.5$ GN/m² and the density of soil is $\rho_s = 2000$ kg/m³, which is thought to be representative of the soil found in São Paulo. More details can be found in Brennan et al. (2017). The results are obtained by solving Eqs. (1) - (7) and are shown in Fig. 1. The figures on the left side of Fig. 1 correspond to a shear modulus of the soil of $G_s = 2.41\times10^8$ N/m^2. The figures on the right-hand side of Fig. 1 correspond to a shear modulus of the soil of $G_s = 2.41\times10^7$ N/m^2 , i.e., ten times less, and are shown to illustrate the importance of the shear modulus of the soil.

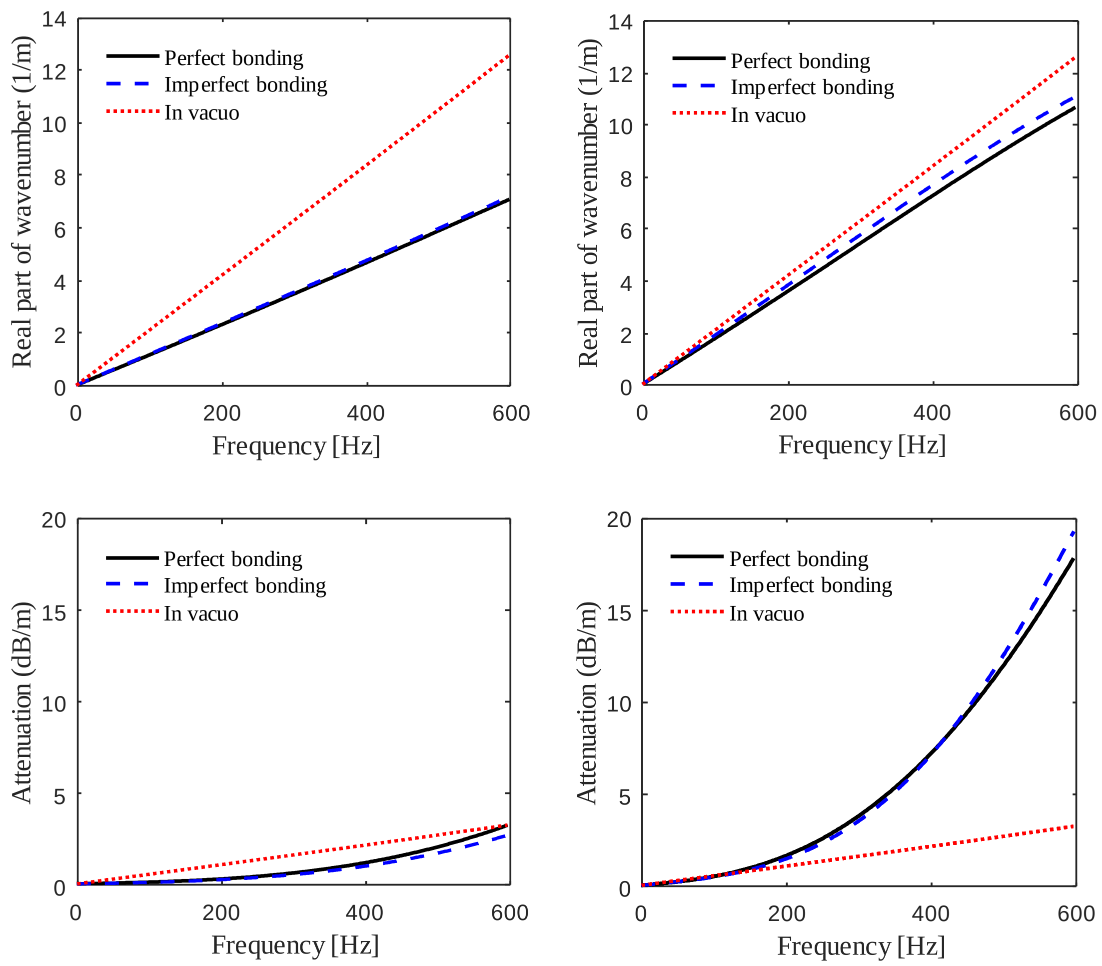

Figure 1. Predicted wavenumbers and attenuation for two different values of shear modulus G_s=2.41×10^8 N/m² (on the left side) and G_s=2.41×10^7 N/m² (on the right side).

It can be seen in Fig 1. that for a shear modulus of the soil as $G_s = 2.41\times10^8$ N/m^2, the complete model (perfect bonding) which assumes the frictional stress at the pipe-soil interface under a compact contact, presents similar behaviour predicting wavenumber and attenuation compared to the incomplete model (imperfect bonding), where the coupling condition is under a lubricated contact. If the shear modulus is ten times less, the estimated curves are slightly different, as can be seen in the figures on the right. The soil with a high shear stiffness has the effect of reducing the real part of the wavenumber (and hence increasing the wavespeed) compared to the in-vacuo case. The attenuation in the in-vacuo case is due entirely to losses within the pipe wall. When the pipe is surrounded by soil, the attenuation is due to both material losses and radiation losses. However, when the pipe is surrounded by a soil with a large shear stiffness, the attenuation is less than in the in-vacuo case. This is because the real part of the wavenumber is decreased (which means that the wave speed is increased), and this increases the wavelength for a given frequency and hence reduces the attenuation at this frequency. In the case when the shear stiffness of the soil is smaller, then the real part of the wave number is not affected so much (and hence the wavespeed and the wavelength are not affected), however energy propagates away from the pipe in the form of a shear wave increasing the damping affect and hence attenuation compared to the in-vacuo case. In the case of high shear stiffness, it can be seen that the effects of neglecting the axial coupling between the pipe and the soil are very small, and are relatively small when the shear stiffness is small.

Figure 2 shows the predicted wavespeeds. When a pipe is buried in the Brazilian soil in which the bulk and shear modulus are relatively high, the soil adds stiffness, and this increases the wavespeed considerably as can be seen in Fig. 2. The effects of reducing the shear stiffness but maintaining the bulk stiffness has the effect of reducing the wave speed as shown in Fig. 2. It can be seen that the wave speed only changes marginally with frequency. In Figure 3, the real and imaginary part of dynamic stiffness of the soil terms normalized by the static hoop stiffness of the pipe $\hat{K}^{(a)}_{\text{soil}} = K^{(a)}_{\text{soil}} / \left(\frac{Eh}{a^2}\right)$ and $\hat{K}^{(b)}_{\text{soil}} = K^{(b)}_{\text{soil}} / \left(\frac{Eh}{a^2}\right)$ are shown.

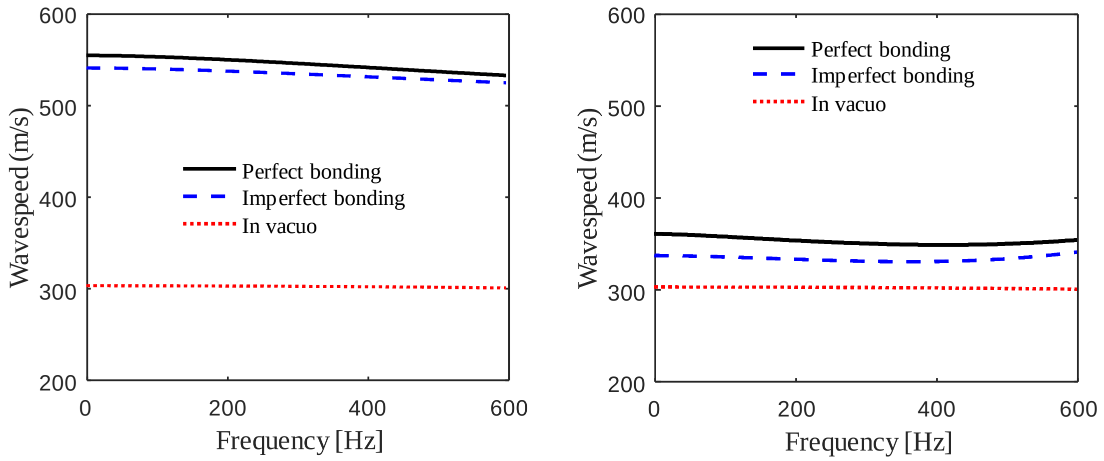

Figure 2. Predicted wavespeeds for two different values of shear modulus G_s =2.41×10^8 N/m² (on the left side) and G_s =2.41×10^7 N/m² (on the right side).

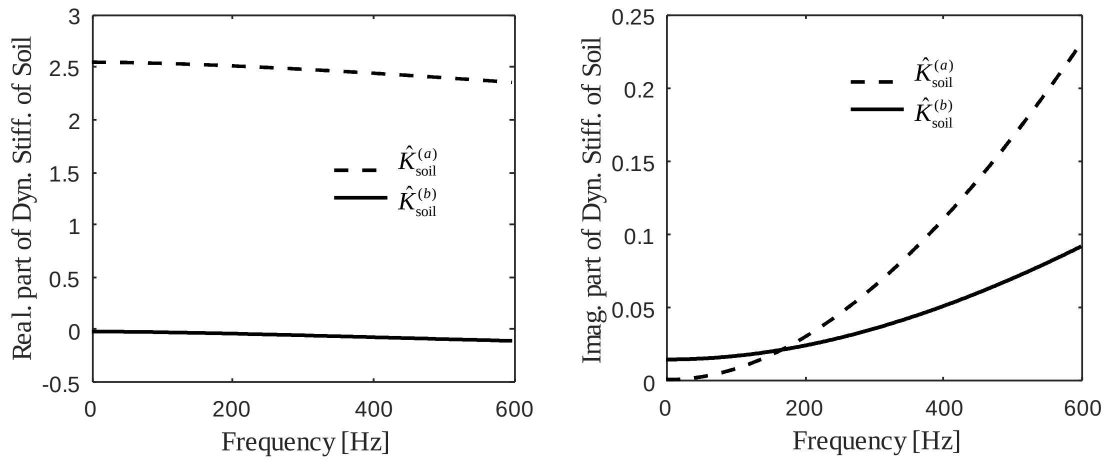

Figure 3. Normalized dynamic stiffness components $\hat{K}^{(a)}_{\text{soil}}$ and $\hat{K}^{(b)}_{\text{soil}}$, real part on the left side and imaginary part on the right side for G_s =2.41×10^8 N/m² .

It can be seen from Fig. 3 that the real part of the term $\hat{K}_{\text{soil}}^{(a)}$ is positive and only weakly dependent on frequency, indicating that this component of the soil dynamic stiffness adds as a stiffness on the pipe. As it is about 2.5 times the stiffness of the pipe wall, it has a profound effect on the wave speed, as shown in Fig. 2. The real part of the term $\hat{K}_{\text{soil}}^{(b)}$ is negative, and its modulus is much smaller than that of $\hat{K}_{\text{soil}}^{(a)}$. It therefore acts as a small mass loading effect on the pipe wall. The respective imaginary parts of dynamic stiffness of the soil are also showed in Fig. 3. It can be seen that below about 180 Hz, the imaginary part of $\hat{K}_{\text{soil}}^{(b)}$ is greater than the imaginary part $\hat{K}_{\text{soil}}^{(a)}$. Above this frequency, the situation changes so that $\hat{K}_{\text{soil}}^{(a)}$ is greater than $\hat{K}_{\text{soil}}^{(b)}$. Furthermore, it can be seen that both components are seen to be important in the propagation of energy from the pipe into the soil, and hence attenuation of leak noise propagation in the pipe.

4. CONCLUSIONS

This paper has presented a theoretical investigation into how the soil-pipe interface affects the propagation characteristics of the axisymmetric (n=0) fluid-dominated (s=1) wave. For a typical pipe and soil properties found in parts of Brazil, it has been found that coupling between the pipe and the soil in the radial direction has a much greater effect on the speed of leak noise propagation in the pipe, than coupling in the axial direction. In terms of the attenuation of leak noise in the pipe, it has been found that both radial and axial coupling between the pipe and the soil are important.

5. ACKNOWLEDGEMENTS

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7. AUTHORAL RESPONSIBILITY

“The authors are solely responsible for the content of this work”.