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PCCP Profiling and Tube Wave Analysis of WRE Signal

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Abstract: Acoustic wave propagation due to the breakage or slippage of reinforced wire in water-filled prestressed concrete cylinder pipe (PCCP) attracts interest in non-destructive pipe testing. Current practice of acoustic emission (AE) detection and wire-break related events (WRE) recognition is based on field data analysis. This work deals with the theoretical investigation of WRE signal from generation to propagation through water-filled PCCP. The mathematical model is developed based on Navier's equation of motion. Newton's law of motion in equilibrium is used to consider the fluid-structure interaction during the propagation. To understand the characteristics of WRE signal and the impact of path on the signal, the dispersion behavior of wave propagation is analyzed by the tube wave analysis for various pipe profiles. COMSOL Multiphysics software is used to simulate this model and the results are compared with the theoretical solutions.

Keywords: PCCP Profile, Pipe stiffness, Acoustic emission, WRE signal, Tube waves.

1. Introduction

The PCCP has been widely used for the large-scale transmission of water or wastewater for more than half a century. These pipelines have generally been very reliable. However, there have been occasional failures caused by corrosion and breakage of the high-strength pre-stressed wires that reinforce these pipes. This causes sudden release of elastic energy stored in the prestressed wire in the form of acoustic waves [1-4] which is called WRE signal. The release of acoustic energy would continue as the defect extends and as plastic strains occur in the presence of the defect. If enough wires fail, the structural capacity of the PCCP is compromised and the pipe is in danger of a catastrophic rupture. Therefore, conducting condition assessment has become essential to ensure the continued safe operations.

Many methods were developed for the detection of WRE signal and to locate the corroded areas [5-16]. Acoustic Emission Testing (AET) is one of the main technologies used in related industry for non-destructive pipe detection. AET is a continuous condition monitoring system that establishes the level of active distress in individual PCCP pipes by measuring the frequency and number of wire related events that occur over a specified range in a defined period of time. These events are captured using hydrophones or accelerometers.

Current practise of AET detection and WRE signal recognition is based on field data analysis. There is no systematic theoretical analysis from WRE signal generation to propagation. Therefore, theoretical investigation of acoustic wave propagation of WRE signal in water-filled PCCP is the main interest of our work.

The vibration signal generated by AE of WRE in PCCP is related to deterioration passes through a number of media, such as pipes, water and surrounding media, before the signal is picked up by the sensors. This wave propagation is the convolution of the WRE signal and the impulse response of the pipe. The impulse response of the pipe varies depending upon water flow, diameter, thickness and stiffness of the pipe and surrounding media, etc. Therefore, to solve this problem we have to consider different physics and their interaction during the propagation. Analytical solution of this model is very complicated and difficult. We use COMSOL Multiphysics to simulate this model. The simulation results are then compared with the theoretical results.

In this paper, we develop a mathematical model to observe this WRE signal propagation through water-filled PCCP. The physical mechanism of an AE signal generation from wire deterioration within PCCP is investigated. We also investigate the impacts of the path on the spectral profiles of the vibrating WRE signal in different locations throughout the PCCP.

This paper is organized as follows. The mathematical formulation of the model is given in Section 2. The boundary conditions that are used during the simulation are given in Section 3. The problem description is presented in

Section 4. The use of COMSOL software to simulate the model and the results are given in Section 5. Finally in Section 6, concluding remarks and future extension of this work are presented.

2. Mathematical Formulation

The WRE signal generated by a wire break or slippage would propagate through the pipe structure and the water in the pipe. The PCCP structure mainly consists of concrete and steel component which are highly attenuative compared to the water inside the pipe. Therefore, for typical AE levels, the WRE signal that transmitted to the water column can be detected for several hundreds of feet, on contrary, in the pipe structure it can travel only 100 feet [17]. However, for the sake of computational brevity, the analysis will be done assuming that the WRE signal starts to propagate from fluid-pipe interface surface through fluid column only, which then interacts with the pipe wall.

Navier's equation of motion is used to model this propagation. For a homogeneous isotropic elastic medium, the equation is [18]

$$\mu\nabla^2\mathbf{u}+(\lambda+\mu)\nabla(\nabla\cdot\mathbf{u})=\rho\frac{\partial^2\mathbf{u}}{\partial t^2}, \qquad (1)$$

where **u** is the displacement vector, μ and λ are the Lame constants and ρ is the density.

The vector **u** can be decomposed into scalar ϕ and vector ψ velocity potential which satisfy the following wave equations [19-20]

$$\nabla^2\phi-\frac{1}{v_L^2}\frac{\partial^2\phi}{\partial t^2}=0, \qquad (2)$$

$$\nabla^2\psi-\frac{1}{v_S^2}\frac{\partial^2\psi}{\partial t^2}=0, \qquad (3)$$

where v_L and v_S represents the longitudinal (*L*) and shear (*S*) wave velocities of the medium, respectively. The waves in the water can be characterized by the *L*-wave only [21], whereas, in the pipe structure both *L*- and *S*-wave must be solved entirely [19].

The AE source which generates these waves is the elastic energy that is released from the breakage or slippage of the prestressed wire. Considering this source [22] and using pressure-velocity relation in Eq.(2), the pressure wave in water can be written as

$$\frac{1}{\rho_W v_W^2}\frac{\partial^2 p}{\partial t^2}+\nabla\cdot\left(-\frac{1}{\rho_W}\nabla p\right)=g, \qquad (4)$$

where g is the source, ρ_W is the water density and v_W is the speed of WRE signal in the water.

The WRE signal which propagated through water column appears as acoustic wave pressure on the pipe wall of the water-pipe interface and generates consistent displacements and deformations [23]. Since the pipe structure is much stiffer than the fluid, therefore, it will interact without causing separation or voids, which means that the radial displacements and pressure at the fluid-structure interfaces must be compatible and in equilibrium. In equilibrium condition, the total work done in the pipe structure due to these displacements and deformations is equal to the work from external pressure forces. Newton's law of motion in equilibrium is used to model this fluid-structure interaction.

The acoustic pressure force that acts on the pipe structure can be written as [24]

$$\boldsymbol{F}_W=-\boldsymbol{n}_W p. \qquad (5)$$

To satisfy the Newton's second law of motion, the work inside the pipe structure is calculated using the normal acceleration of the pipe surface at the fluid domain boundary as

$$\boldsymbol{a}_P=-\boldsymbol{n}_P\cdot\nabla\mathbf{u}'. \qquad (6)$$

Here $\boldsymbol{n}_W$ and $\boldsymbol{n}_P$ represents the outward-pointing unit normal vector seen from inside the pipe and acoustic domain, respectively and ($'$) represents the time derivative of displacement vector in three principal directions.

2.1 Tube Waves

The plane wave propagation of WRE signal through water-filled PCCP is affected by the characteristic of pipe profile. This characteristic mainly depends on the thickness and elastic properties of the pipe materials and the surrounding medium. The elastic wave generated in the pipe structure depends on these characteristics, which then propagating into the fluid and decreases the velocity of acoustic wave of WRE signal. This reduced wave is known as 'Tube Wave'. The impact of the path on low-order mode WRE signal propagation can be illustrated by using this tube wave analysis.

Mathematically, tube wave is expressed as[25]

$$v_T = \left[\frac{1}{v_W^2} + \frac{\rho_W}{M_P} \right]^{-1/2}, \tag{7}$$

where,

$$M_P = E_P \left[2\left(1+\gamma_P\right) + \frac{D^2}{t\left(D+t\right)} \right]^{-1}, \tag{8}$$

and D is the diameter of the pipe, E_P, γ_P and t are the elastic (Young's) modulus, thickness and poisson's ratio of the pipe materials and surrounding medium, respectively.

3. Boundary Conditions

The boundary conditions that apply to simulate this model are as follows:

a. continuity of pressure,
b. continuity of acceleration, and
c. radiation condition.

The boundary condition, continuity of pressure is used to represent the acoustic pressure forces in the fluid to the pipe structure. The continuity of acceleration is used to apply the normal acceleration in the pipe surface to the fluid boundary.

The radiation boundary condition is used on the outer perimeter of the model. For the outward travelling wave, this boundary condition provides minimal or no reflections from the model boundary.

4. Problem Description

Consider a uniform and smooth circular shape water-filled pipe surrounded by the soil medium. For simplicity assume that the pipe is made of high-strength concrete only. Damping and fluid-flow velocity are absent here. The base dimensions and properties of the medium are given in Figure 1 and Table-1, respectively.

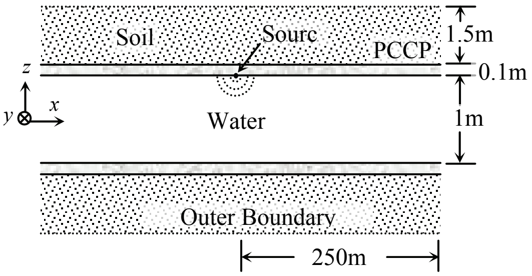


Figure 1: Model geometry with dimensions.

Table-1: Properties of the medium.

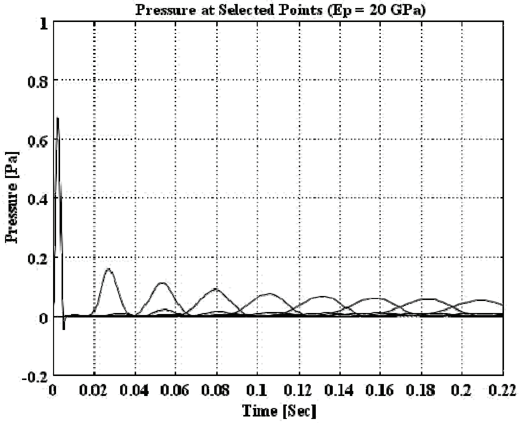
Properties	Water	Concrete	Soil
Density of medium (ρ), kg/m^3	997	2400	1270
Speed of acoustic wave (v), m/s	1500	--	463
Elastic(Young's) modulus (E), Pa	--	40^9	--
Poisson's ratio (γ)	--	0.33	--

5. Simulation Results Using COMSOL

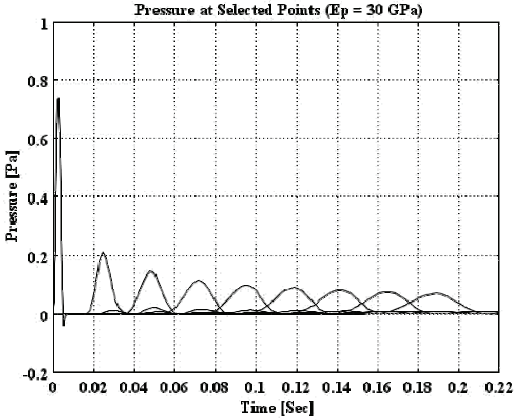
The finite element based software COMSOL Multiphysics is used to simulate the WRE signal propagation through PCCP. The transient analysis of mathematical model outlined above is applied in two scenarios, water-filled pipe in air medium and in soil medium. The 'solid, stress-strain' and 'pressure acoustic' modes of COMSOL's acoustics module are used for this purpose [24]. The acoustic pressure in the water domain at the surface of the structure is considered as a boundary load on the solid pipe structure to ensure the continuity of pressure. The harmonic stresses and strains inside the solid structure are calculated using the normal acceleration of the solid surface at the acoustic domain to ensure the continuity in acceleration. Outer boundaries of the model are truncated by using radiation boundary condition with the cylindrical and plane wave propagation.

During the simulation, we use different dimensions and stiffness of the layered medium. This exemplifies the effect of pipe profiling on tube mode propagation of WRE signal through water-filled PCCP. All simulations are done for the 200Hz excitation frequency as this frequency is below the first cut-off frequency of the pipe used here [26]. The constant volume velocity source [27] with 1e-2 m^3/s flow strength is used to optimize the result. The time response of the system is taken at selected points in the pipe (at 0m, 50m, 100m, 150m, 200m from source).

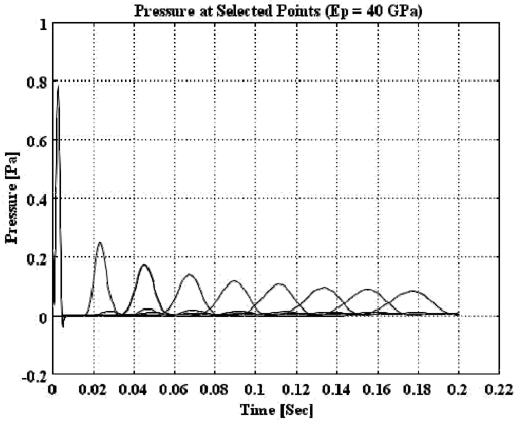
In Figures 2 and 3, the pipe is considered in air-medium with base dimensions and properties (as given in Fig.1 and Tab.1). The elastic properties (E_P) of the pipe are varies in Figure 2, as 20GPa, 30GPa, 40GPa with densities (ρ_P) as 2200 kg/m^3, 2300 kg/m^3, 2400 kg/m^3, respectively, to verify the effect of pipe materials on WRE signal. In Figure 3, pipe thickness (t_p) varies as 0.15m and 0.2m by keeping all other parameters constant to observe the effect of pipe thickness on wave propagation.



(a) E_P = 20GPa (calculated v_T = 0.98 km/s).

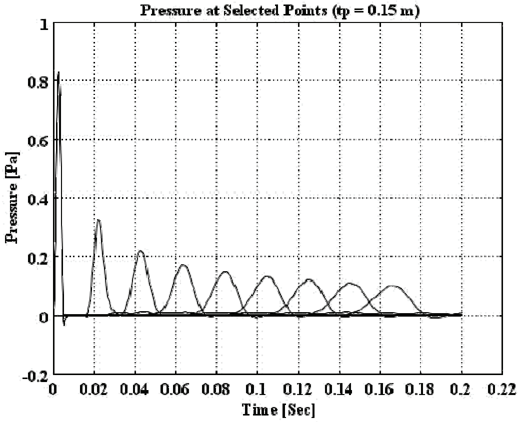


(b) E_P = 30GPa (calculated v_T = 1.09 km/s).

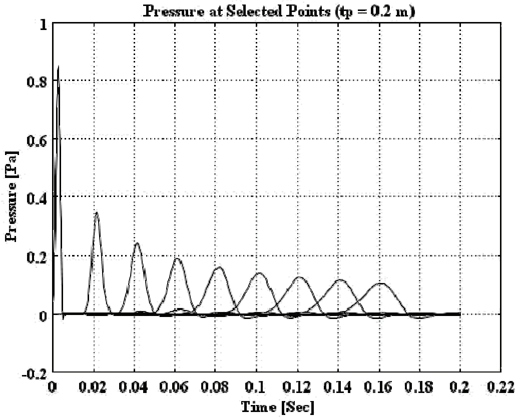


(c) E_P = 40GPa (calculated v_T = 1.16 km/s).

Figure 2: Tube wave response at different E_P.



(a) t_p = 0.15m (calculated v_T = 1.24 km/s).

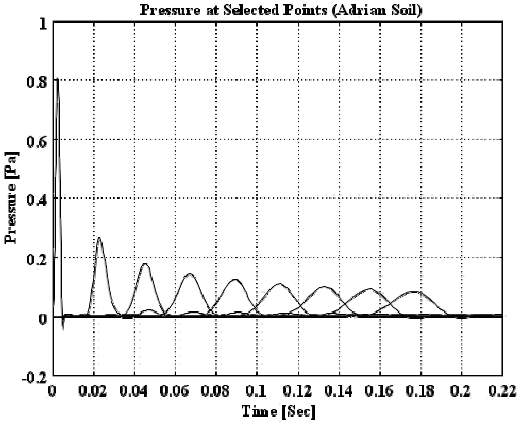


(b) t_p = 0.2m (calculated v_T = 1.28 km/s).

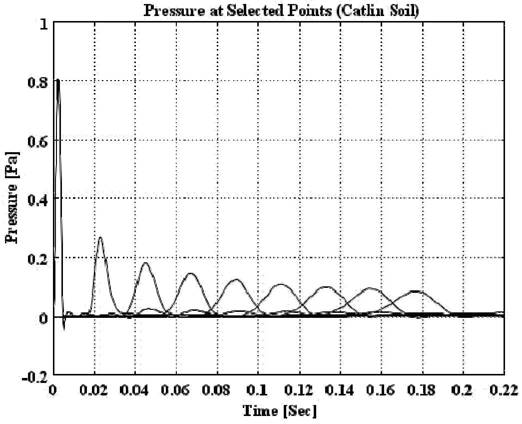
Figure 3: Tube wave response at different t_p.

From the figures above, it is seen that the propagation speed is reduced to a lower speed due to the tube wave effect [26], compared to the speed of the acoustic wave in water (approx. 1.5km/s). The calculated theoretical v_T which is given below in each graph, is matched with the simulation results. It also seen that the increasing of the pipe elasticity and thickness, increases the stiffness of the pipe, and leaser its influence on wave speed and strength.

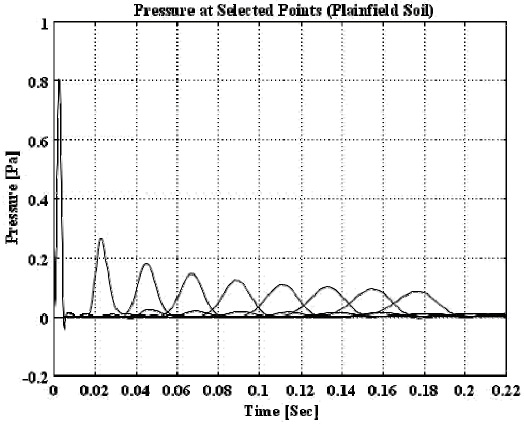
In Figure 4, consider the water-filled pipe is surrounded by different kinds of soil medium. In this work, we are mainly interested to know in what extent soil properties affect the WRE signal propagation. Therefore, we chose three kinds of soil sample, Adrian, Catlin and Plainfield soil [28] to cover the wide range of soil elastic properties (Table-2). All other parameters (as in Fig.1 and Tab.1) are kept as constants.



(a) Adrian soil (calculated v_T = 1.169 km/s).



(b) Catlin soil (calculated v_T = 1.170 km/s).



(c) Plainfield soil (calculated v_T = 1.172 km/s).

Figure 4: Tube wave response at different soil.

Table-2: Properties of the soil sample [29].

Soil Series (Code)	**Density**, kg/m^3	**Propagation Speed**, m/s
Adrian (ADA)	920	373
Catlin (CAB)	1270	463
Plainfield (PLA)	1510	634

In the graphs above, we found that the simulation results have a good agreement with the calculated theoretical v_T. However, if we compare these results with the result of same pipe in air medium (Fig.2c), we can see that, v_T values are the nearly same in all cases. It is possible, because the stiffness of the PCCP is much higher than the soil medium. Therefore, it is seen that the tube wave propagation of PCCP does not get affected by the surrounding soil formation.

6. Conclusions

It is observed that the speed of acoustic waves traveling in the fluid surrounded by the finite stiffness pipe profile is lower than the actual speed of waves in the unbounded fluid or fluid surrounded by infinite stiffness medium. The stiffness of the pipe increases with the increasing elastic properties of pipe materials and pipe thickness which increases the tube wave speed.

In contrast to the soil properties the pipe profile, which depends on the pipe materials and thickness that play an important role on the overall system stiffness. Therefore, in case of high stiffness pipe profile, there is no need for more attention in the estimation of accurate soil parameters. Moreover, from the results, it is observed that the high stiffness pipe can reduce signal energy penetration. This is important information for the sensor sensitivity when the WRE signal is measured far away from the source. In this paper we verified our simulation results with the theoretical calculated values. We can also verify these results with the experiment to validate our analysis.

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