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Structural performance of buried prestressed concrete cylinder pipes with harnessed joints interaction using numerical modeling

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ABSTRACT

Broken prestressing wire wraps are the main cause of failure in buried prestressed concrete cylinder pipes (PCCP), which form the backbone of water and wastewater infrastructure networks in North America. Advanced numerical modeling using non-linear finite elements is used to model the effect of the number and location of broken wire wraps on the structural performance of Class 125-14, 96-in. PCCP. The modeling technique used is unique in that it considers full interaction between adjacent pipes with harnessed joints, as well as combined internal and external loading with full soil–pipe interaction. Performance indicators in the various components of PCCP are monitored as internal pressure is increased. A sensitivity analysis is presented for how manipulating the severity of the damage affects the failure pressure of the pipe. The results show that the internal fluid pressure required to cause failure can be as much as 34% lower when the damage is at the barrel of the pipe, and that the internal pressure that causes yielding of the wire wraps decreases by 66% as the damage worsens from 5 to 100 wire breaks.

1. Introduction

Prestressed concrete cylinder pipe (PCCP) originally appeared in 1942 as Lined Cylinder Pipe (LCP). After a decade, Embedded Cylinder Pipe (ECP) was developed as another type of PCCP with concrete encasement of the steel cylinder on both sides and prestressing wire wrapped around the outer concrete core. The design and manufacturing standards of PCCP in the United States are now published by the American Water Works Association (AWWA) in the AWWA C301 *Standard Specifications for Reinforced Concrete Water Pipe – Steel Cylinder Type, Prestressed* (AWWA C301-52), with the latest revision released in 2007 (AWWA C304-2007). While PCCP is widely used nowadays in underground water and wastewater transmission networks, the understanding of its behavior under combined internal and external loading is still being gradually developed.

PCCP consists of a concrete core, a steel cylinder, high tensile prestressing wires, and an outer mortar coating layer. The concrete core is the load-bearing component with the steel cylinder acting as a water barrier between inner and outer core concrete layers. Prestressing wires produce a uniform circumferential compressive pressure in the concrete core that balances tensile stresses developed in the pipe from internal fluid pressure. The mortar coating protects the prestressing wires from physical damage and external corrosion. Rupture of prestressing wires around the concrete core is common in PCCP and can be the result of damage due to corrosion, hydrogen embrittlement, overloading, or manufacturing defects. As a result of this loss of circumferential compressive load around the pipe, tensile stresses will develop that can lead to possible cracking of the concrete core and cause leak or damage in the pipe.

While the structural condition of underground water and wastewater mains can be assessed using ultrasonic tomography methods (Abi Shdid and Hajali, 2014; Yang et al., 2010), satellite detection of ground movement (Arsénio et al., 2014); direct inspections by remotely-controlled closed circuit television (CCTV), and more recently sewer scanner and evaluation technology (SSET) cameras, remains to be the most accurate and widely used method to detect damage in buried infrastructure elements such as PCCP. Such inspections need to be conducted on a regular and systematic basis in order to monitor deterioration rates and perform on-time replacement of pipes prior to their failure. However, the large size, underground nature, and operating conditions of these facilities make it prohibitively expensive to do so in a manner that mitigates the serious effects of their failure. Owners have therefore resorted to the use of risk curves that are developed based on numerical values assigned by inspectors that place any pipe in one of five internal condition grades (ICG) according to a subjective assessment of

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covariates such as pipe age, material, and extent of damage. Such risk models are then used to predict failure pressures and remaining life of pipe elements. A more accurate and efficient approach—than using subjective ICG—to producing failure data for developing such risk curves is the use of accurate numerical modeling such as the FEM method described by Jung et al. (2014) that models full interaction between buried pipes and the overburden soil.

2. Background

The behavior of PCCP under combined internal and external loading has been under investigation since the middle of the twentieth century, and studies of PCCP failures have led to the development of the design standards (AWWA Research Foundation, 2007). Despite standardizing the design and manufacturing of PCCP, the inclusive understanding of the structural behavior and performance of damaged PCCP is still in its infancy.

Advances in the field of numerical modeling techniques and finite element analysis have led to considerable benefits to many engineering industries (Mahendran, 2007; Ovesy et al., 2015) and not only allows the introduction of innovative and efficient products, but also the development of accurate design methods. Xiong et al. (2010) used a nonlinear FEM to study the correlation between the degree of prestressing stresses during manufacturing of PCCP and their associated resultant stresses in the outer concrete core and prestressing wires. The study also compared the resultant stress obtained with another FEM model that replaces the effects of tensile stresses in prestressing wires with an equivalent radial pressure around the pipe. The results obtained from the equivalent radial pressure model were within a 10% deviation of the proposed model (Xiong et al., 2010).

Rauniyar (2013) conducted full-scale experimental tests and numerical modeling of ECP under three-edge bearing load. The study utilized three-dimensional nonlinear finite element analysis for the numerical modeling, and used composite material with complex stress phenomenon due to prestress and interaction between the various component layers of the ECP. The model accounted for the contribution of each component, the manufacturing process, and the simultaneous effects of shrinkage, creep and relaxation (Rauniyar, 2013). More advanced models have been used in recent studies to investigate the behavior of PCCP using an extended form of the finite element method (XFEM). Alavinasab et al. (2011a) used XFEM to study crack initiation, growth, and life prediction analysis of damage in Prestressed Concrete Noncylinder Pipe (NCP). Nonlinear FEM has been used not only in static analysis of PCCP, but also in the dynamic response of PCCP. Alavinasab et al. (2010, 2011b) used FEM to evaluate the natural frequencies and mode shapes for Structural Health Monitoring (SHM) of PCCP.

The structural performance of damaged PCCP is dependent on the number of broken prestressing wire wraps as well as on the location of such break regions along the length of the pipe. Alavinasab et al. (2013) studied the effect of the location of broken wire wraps on the strength of PCCP using advanced computational modeling. The study compared three different locations for the defect: at the spigot joint, at the bell joint, and in the barrel of the pipe. The study however consider no interaction between the bell end and spigot end of adjacent pipes, which leads to overly conservative results that assume complete disjointedness of adjacent pipes. The results found that strength reduction for a PCCP with low to medium number of wire wrap breaks at a joint was about 20%. The paper argued that cracking in the pipe will occur much sooner when the defects occurred at the joint rather than in the barrel of the pipe. Alavinasab and Hajali (2014) studied the effects of broken wire wraps at the joint in the safe operation of an adjacent pipe.

Kang and Davidson (2013) used finite element analysis to study the effect of concrete lining on the structural performance of buried concrete-lined steel pipes. The approach utilized detailed soil modeling and presented a design method for the concrete lining of pipes (Kang and Davidson, 2013). Allouche et al. (2014) examined the performance of liners for the rehabilitation of cured-in-place pipes (CIPP). The study evaluated the usefulness of various types of testing for tracking the deterioration of CIPP liners in-service and concluded that they are more cost effective than replacement of damaged concrete pipes (Allouche et al., 2014).

Artificial Neural Networks (ANN) were used by Amaitik and Amaitik (2008) to develop a PCCP wire breaks prediction model. The ANN was trained on real-world acoustic monitoring data. The ANN takes the monitoring period, pipe age, soil resistivity, design pressure, design soil density, design soil cover, type of pre-stressing wire wrap, wire diameter, and wire pitch as inputs; and predicts the number of wire breaks (Amaitik and Amaitik, 2008). ANNs were also used successfully to predict the compressive strength of concrete and its degradation under corrosion attack in buried concrete wastewater collection pipes (Hewayde et al., 2007). Another approach was developed by Kleiner et al. (2004) to model the deterioration of buried PCCP using a fuzzy rule-based, non-homogeneous Markov process. The model yielded possibility of failure at every point along the life of the pipe. However, adequate and sufficient data to validate the model were not provided (Kleiner et al., 2004).

Other studies have attempted to use probabilistic models for investigating the trends of structural deterioration of concrete pipes. Younis and Knight (2010) used a new ordinal regression model for the deterioration of reinforced concrete wastewater pipelines based on cumulative logits. The model was presented using the Generalized Linear model formulation and incorporated the interaction effect between the explanatory variables (Younis and Knight, 2010). However all such models do is predict the probability of a buried concrete pipe falling in one of the five ICGs, as compared to the others that give a numerical value for the ICG of a pipe. They hence fall short of accurately modeling the failure based on an exact measurement of deterioration variables such as broken wires.

3. Problem statement and contribution

3.1. PCCP joints

The rigid nature of PCCP makes the joint a very important component of the pipeline. The function of a pipe system generally determines the performance requirements of the joints, but in general, joints make construction a lot easier. Joints are also designed so that when pipe sections are laid together they will make a continuous line of pipe with an interior free from irregularities. Joints are normally designed to provide soil-tightness, water-tightness, the ability to accommodate lateral and longitudinal movement, and the strength to handle shear that induces vertical deformation.

Joints in PCCP consist of a spigot ring, a bell ring, a rubber gasket, a steel spigot ring, a steel bell ring, grout on the exterior of the joint between the two pipes, and a harness clamp. Spigot and bell steel rings are welded to the steel cylinder from the ends. Joints are designed to allow a pipe to deflect during installation and operation while maintaining a watertight seal. After the spigot steel ring is pushed home into the bell steel ring, the clamp halves of the harness are tightened using bolts for sealing of the joint. When joined, the bell and spigot ends compress the rubber gasket into a groove to form a high pressure seal. A schematic of the PCCP joint is shown in Fig. 1; such a joint provides high shear strength, excellent water tightness, and flexibility. A layer of mortar or cement paste is