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Evaluation of ultrasonic inspection and imaging systems for concrete pipes

Shivprakash Iyer [a], Sunil K. Sinha [a,*], Michael K. Pedrick [b], Bernhard R. Tittmann [b]

[a] Department of Civil & Environmental Engineering, The Pennsylvania State, University, University Park, PA, 16802, USA
[b] Engineering Nano Characterization Center (ENCC), The Pennsylvania State, University, University Park, PA, 16802, USA

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ABSTRACT

Accurate pipeline condition assessment is vital to developing a cost effective and sustainable buried asset management system. Maintenance and rehabilitation of pipeline systems pose a major challenge for most municipalities in North America given their budgetary constraints, demand on providing quality service, and the need for preserving their pipeline infrastructure. This paper presents the proof-of-concept for an automated buried pipeline condition assessment system that can provide additional depth perception of defects in addition to surface assessments provided by current technologies. An ultrasound acoustics-based methodology is proposed to acquire depth perception and complement 2-D crack features available from the SSET camera for inspection of concrete pipes. Experimental results show that the ultrasound immersion scanning and C-Scan Imaging provides rich data for building a reliable defect detection system. The proposed automated inspection system can lead to overcoming many limitations of the current manual inspection practice (i.e. subjecting defect rating system) and can provide a more accurate assessment of buried pipe conditions.

1. Introduction

Beneath North America's roads lie 1.6 million miles of pipelines that bring purified water to homes and carry away waste water (sewage and storm water). Aging wastewater management systems discharge billions of gallons of untreated sewage into U.S. surface waters each year. Maintenance and rehabilitation of pipeline systems pose a major challenge for most municipalities in North America given their budgetary constraints, demand on providing quality service, and the need for preserving their pipeline infrastructure. Unsurprisingly, the American Society of Civil Engineers' 2009 Report Card for America's Infrastructure gave a *D*-grade to water/wastewater infrastructure. It has been estimated that upwards to 40% of the United States' underground infrastructure will have failed or will be on the brink of failure within 20 years, unless efforts are initiated to renew it [1,2]. This necessitates the need to monitor, detect and prevent any unforeseen failures in the working of these underground pipelines that are complex in nature. Accurate pipeline condition assessment is vital to developing a cost effective and efficient pipeline M&R program. At present, the assessed condition of buried pipes is based on the subjective visual inspection of Closed Circuit Television (CCTV) surveys [3]. CCTV surveys are conducted using a remotely controlled vehicle carrying television camera through a buried pipe. The data acquired from this process consist of videotape, photographs of specific defects, and a record produced by the technician. It is a well-known fact that the diagnosis of defects depends on experience, capability and concentration of the operator thus making the detection of defect error prone. Sewer Scanner and Evaluation Technology (SSET) is an innovative technology for obtaining unfolded images of the interior of buried pipes [4,39]. This is achieved by utilizing scanner and gyroscope technology, as shown in Fig. 1. In spite of buried imaging technologies making giant strides in recent years, the basic means of analysis remain unchanged: a qualified technician is still required to identify defects on a television monitor. Additionally, a defect that appears on the surface to be insignificant (less than 5 mm mouth opening) might actually exist throughout the thickness of the pipe. An operator would usually classify such a defect as a 'minor defect' and shift attention to those that may appear critical on the surface but do not extend into the depth of the pipe. This may prove to be catastrophic because of the defect being classified as 'minor' due to lack of enough information. It may well be the case that the so called 'minor' defect will lead to a pipe collapse much earlier than the other cracks that were classified to be critical based on surface analysis only. Hence, any crack (or defect) classification system that primarily depends on surface characteristics is incomplete and needs to be complemented with additional depth perception to provide for a reliable, accurate and effective buried pipeline asset management system. Therefore, this research study presents the proof-of-concept for an automated buried pipeline condition assessment system that can provide additional depth perception of defects in addition to surface assessments.

Ultrasonic assessment techniques for concrete can be developed and implemented only if the interaction between ultrasonic waves

* Corresponding author. Tel.: +1 540 231 942.
E-mail address: ssinha@vt.edu (S.K. Sinha).

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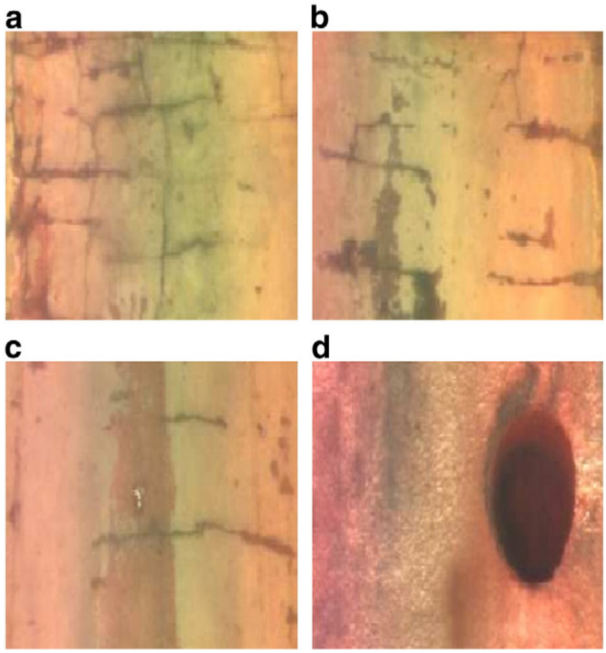

Fig. 1. Typical images of buried pipe scanned by Sewer Scanner and Evaluation Technology (S SET) camera.

and the material through which it propagates is well understood. Concrete is a heterogeneous material made up of a weighted combination of aggregates, water, cement and admixtures. Many different concrete mix designs can be prepared with lightweight aggregates, several types of sand and gravel, different water to cement ratios, and admixtures. Concrete pipes are usually formed using zero-slump concrete or concrete with a very low water to cement ratio. It is known that the strength of wave energy (or power) propagating in concrete is influenced by several intrinsic material factors such as size of aggregate, degree of compaction, admixtures, porosity of concrete mix, etc. To provide proof-of-concept for inspecting concrete pipes, by conducting laboratory experiments on a representative block made from the same concrete mix used to form pipes, using the ultrasound immersion technique. The aim of this step is to evaluate the technique, determine an optimum frequency range, angle sensitivity, and liftoff. This paper focuses on investigating the use of ultrasound acoustics to acquire depth perception and complement 2-D crack features available from the SSET camera. The improvement in interpretation of surface scanned images by implementing new algorithms and techniques from image processing has already been accomplished by the authors [5–8]. The next paper will focus on the development of automated signal classification system for processing ultrasonic signals acquired from the system discussed in this paper [9]. The proposed automated inspection system can lead to overcoming many limitations of the current manual inspection practice (subjective defect coding) and can provide a more accurate assessment of buried pipe conditions. Section 2 gives a brief introduction to nondestructive testing (NDT) and concrete NDT in particular. Section 3 discusses the challenges and suitable approaches for pipe inspection. Section 4 introduces NDT techniques chosen for feasibility studies and discusses their limitations. It also describes the proposed inspection methodology and provides reasons for selection. Section 5 explains different ways of representing ultrasound inspection data. Sections 6 and 7 present the experimental program and results from the proposed inspection method. The motivation for developing an automated signal classification system is presented in Section 8.

2. Ultrasonic nondestructive testing (NDT)

Ultrasonic is the name given to the study and application of ultrasound, which is sound of a pitch too high to be detected by the human ear, i.e. of frequencies greater than about 18 kHz [10]. Ultrasonic waves have a wide variety of applications over an extended range of intensity, including cutting, cleaning and destruction of tissue at the upper extremity, and non-destructive testing (NDT) of structures at the lower end. Ultrasonic testing consists effectively of the propagation of low amplitude waves through a material to measure the time of travel and change in intensity for a given distance. In spite of the development of test techniques and equipment, the use of NDT for inspecting concrete poses many difficulties. Compared to metal and metal-based materials, NDT of concrete is a relatively immature discipline. The heterogeneous nature of concrete and unspecified code or standard of concrete NDT are two main areas where concrete inspection technology lags behind. Concrete is a multi-phase material consisting of a coarse aggregate comprising particles of more than 5 mm in diameter, a fine aggregate (i.e., sand), cement and admixtures. The coarse granular structure, such as the relative concentration of the constituent particles, degree of compaction, moisture content, and the nature of defects gives rise to a high degree of acoustic scattering leading to attenuation. For this reason, testing in concrete is usually limited to the kilohertz frequency range. Ultrasonic techniques that detect defects, measure the mechanical properties, or monitor the state of deterioration in concrete structures have been a topic of considerable interest to the civil infrastructure community [11,12,38,42]. The ultrasonic pulse velocity method uses compression waves to evaluate the conditions of materials like concrete [13]. The ultrasonic pulse velocity is by far the most widely accepted method for assessing the quality of concrete in structures [14]. Structural changes taking place in concrete during loading has also been monitored with the ultrasonic pulse velocity method. The use of ultrasonic velocity measurements for nondestructive evaluation of Portland cement concrete was proposed in the late 1940s [15]. Although Jones studied the behavior of concrete during loading, his work focused on the development of relationships between ultimate compressive strength and pulse velocity. Later researchers found that in addition to the time domain analysis used in earlier studies, the frequency domain can provide significant information [16,14]. Na et al. investigated the feasibility of detecting and quantifying delamination at the interface between steel bar and concrete using ultrasonic guided waves [17]. This technique could predict and quantify the degree of separation or delamination but was unable to localize the exact location of the separation between the transducer and receiver. Na et al. also conducted another study to compare the delamination between steel/concrete and glass fiber reinforced polymer/concrete interfaces using guided waves [18].

Research in detecting defects in concrete has mainly been focused on single surface breaking cracks [19]. Most efforts made use of time-of-flight (TOF) methods to determine the depth of simulated cracks (notches with well-defined tips) in concrete where the velocity of wave propagation in concrete is known and a characteristic wave pulse–crack interaction is realized [20–22]. However, the TOF method is not effective when realistic concrete cracks are tested. Song et al. proposed a self-compensating surface wave transmission coefficient measurement technique to measure surface-breaking cracks and notches in concrete [19]. But, the transmission coefficient is sensitive to changing crack depth and is reliable only in a certain range. Ramamoorthy et al. studied the determination of depth of surface-breaking cracks in concrete specimens using an ultrasound diffusion technique [23]. Their method demonstrated feasibility for notch defects for which the two surfaces were not in contact. Results for realistic cracks with surfaces in contact were not discussed. Jung et al. investigated the feasibility of detecting defects in concrete beams