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Continuation ratio model for the performance behavior of wastewater collection networks

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ABSTRACT

Canada's aged wastewater infrastructure is failing. New financial and environmental regulatory requirements demand municipalities to estimate operating and capital expenditures for running the systems into the future, and to develop plans for financial sustainability while protecting public health and the environment. Presently, wastewater pipelines' deterioration is not well understood and realistic deterioration models need to be developed.

This paper presents a new ordinal regression model for the deterioration of wastewater pipelines based on *continuation ratio* logits. The model is presented using the *generalized linear* model formulation, and takes into account the ordinal nature of the dependent variable and the interaction effects between explanatory variables. The model provides estimates of conditional probabilities for a pipeline to advance beyond a particular internal condition grade – to worse condition – depending on pipe *material* and *age*. The model development and validation procedure is demonstrated using high quality condition assessment data for reinforced concrete (RC) and vitrified clay (VC) pipes from the City of Niagara Falls wastewater collection system.

The new model is found to represent the RC and VC pipes' degradation behavior for in-service pipes up to 110 years of age at the City of Niagara Falls wastewater collection system. RC pipes' deterioration is found to be *age* dependent while VC pipes' deterioration is not *age* dependent. The VC pipe finding is contrary to other deterioration model studies that indicate that the type of pipe *material* is not significant and that the deterioration of VC pipes is *age* dependent. The analysis shows, for example, that the predicted conditional probability for RC pipes to advance beyond internal condition grade 3 is estimated to be 60% at 40 years of age and it increases to 90% at 80 years. Similarly, there is a 60% chance of advancing beyond grade 4 to collapsed/collapse imminent condition at 80 years of age for RC pipes. VC pipes are found to have an indefinite service life if installed without structural damage. However, VC pipes exhibited relatively higher conditional probabilities than RC pipes for advancing to worse internal condition grades for pipes up to 65 years of age. Poor installation practices that resulted in pipe defects, such as open/displaced joints and defective connections are deemed to be the factors that resulted in VC pipe deterioration.

The findings from the continuation ratio model can be used for risk-based policy development for maintenance management of wastewater collection systems. The proposed model can help in devising appropriate intervention plans and optimum network maintenance management strategies based on pipelines' age, material type, and internal condition grades. These predictions are critical if realistic wastewater networks' future maintenance and operation budgets are to be developed over the life of asset and to meet new regulatory reporting requirements. Further research is required to validate the proposed model in other networks and to determine if the method can be used to model the deterioration of pipe materials other than RC and VC.

1. Introduction

A large percentage of Canada's buried municipal water and wastewater piping networks have exceeded or are approaching their design life of 50–75 years. Therefore, this aging and deteriorating infrastructure needs to be renewed or replaced. Estimates of Canada's municipal infrastructure deficit vary from a $44 billion total municipal infrastructure shortfall (TD Economics, 2002) to over $125 billion (Mirza, 2007). The *municipal infrastructure deficit* is an estimate of the total additional investment needed to repair and prevent deterioration in existing, municipally owned infrastructure assets. Mirza (2007) reports that the infrastructure funding gap for existing water and wastewater is $31 billion and

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to meet new needs an additional $56.6 billion is required. The size and scope of the infrastructure problems facing municipalities and local governments is enormous as the decay of Canada's infrastructure creates severe domino effects – higher cost of maintenance, operation, rehabilitation, and repair; inefficiency and increased vulnerability; and increased threats to public safety and the environment. Mirza (2007) states that "without maintenance or with deferred maintenance, the municipal infrastructure deficit could be close to $2 trillion by 2065, and that with regular maintenance and good scientific management, the escalating infrastructure deterioration and the resulting infrastructure deficit is controlled within manageable levels."

In 2006, the Canadian Institute of Chartered Accountants Public Sector Accounting Board (PSAB) issued statement PS3150 which requires all Canadian municipalities and utilities, starting in January 2009, to report their tangible capital assets along with their depreciation on financial statements (OMBI, 2007). One of the PSAB requirements is the estimation of operating and capital expenditures for running the systems into the future. In the United States, the Governmental Accounting Standards Board (GASB) Statement 34, and in Australia, the Australian Accounting Research Foundation Standard 27 specifies similar accounting practices (see FHWA, 2000; Howard, 2001). To meet these specified accounting practices, knowledge on how the assets behave and deteriorate over time is imperative.

Current Canadian government guidelines (e.g., Ontario Ministry of the Environment, 2007; NAMS, 2002) indicate the service life for various civil infrastructure assets. For wastewater pipelines, the service life ranges from 40 to 75 years with limited or no asset deterioration knowledge (Ontario Ministry of the Environment, 2007; NAMS, 2002). The absence of asset deterioration knowledge necessitates Canadian municipalities to make unsubstantiated assumptions about the timing and volume of capital expenditures so they can comply with PSAB and other government and regulatory requirements. These unsubstantiated assumptions will most likely result in an under- or over-estimation of assets' future operational and capital needs. To develop realistic future life-cycle asset operation and maintenance financial needs, it is imperative that asset deterioration behavior is understood and realistic deterioration models are used for future predictions.

This paper provides an overview of wastewater pipelines' condition assessment methodology and protocols. It also discusses ordinal regression models and their applications in civil engineering. An ordinal regression model, based on *continuation ratios* is developed and described along with its assumptions and estimation procedure for predicting wastewater infrastructure deterioration. The new deterioration model is demonstrated using the City of Niagara Falls wastewater collection pipelines' condition assessment data. The procedures for verification of assumptions, determination of parameter estimates, validation, and model interpretation are presented. The paper concludes with a discussion on the results and deterioration model limitations.

2. Literature review

2.1. Condition assessment of wastewater pipelines

Remotely controlled Closed Circuit Television (CCTV) and more recently Side Scanning Evaluation Technology (SSET) cameras also known as Sewer Scanner and Evaluation Technology (SSET™) are used for visual inspections of the interior of wastewater pipelines (Chae et al., 2003; Iseley et al., 2001). Pipelines' inspections are completed by an operator remotely moving the camera down the pipe and coding all observed defects using a defect condition coding system. In North America, two wastewater pipeline defect condition classification systems are predominately used: (1) Manual of Sewer Condition Classification (MSCC) third edition defect coding system developed by Water Research Center (WRc) in the United Kingdom; and (2) Pipeline Assessment and Certification Program (PACP) developed by National Association of Sewer Service Companies (NASSCO) and WRc.

The Manual of Sewer Condition Classification, first published in 1980, became the national standard in the UK and many other parts of the world. In 1994 and 2004 WRc published the third and fourth editions of the MSCC, respectively. In 1994, the North American Association of Pipeline Inspectors (NAAPI) adopted WRc's MSCC third edition and developed a certification program for CCTV operators and reviewers. In 2002, NASSCO published PACP to meet the needs of wastewater pipelines' industry in the United States. The Sewerage Rehabilitation Manual (SRM), also published by WRc (see WRc, 2001), describes a wastewater pipelines renovation decision making process that is adopted in the United Kingdom and Canada. The first edition of the SRM was published in 1986 and the current fourth edition was published in 2001. The SRM determines the structural and operational performance of wastewater pipelines by assigning scores to MSCC defects based on their type and severity. The structural defect scores are transformed – based on pipeline's peak defect score – to structural Internal Condition Grade (ICG) of 1–5, with 1 being the best or acceptable and 5 being the worst or near collapsed state. The continued use of the SRM methodology, in United Kingdom and Canada, validates the methodology as a good approach for determining pipelines' current condition states. The general principles of the SRM also form the basis for the European Standard EN752–5 – Drain and Sewer Systems Outside Buildings: Part 5 Rehabilitation. This further validates the SRM approach. NASSCO's PACP manual contains a pipeline condition rating scheme that varies from 1 to 5. The PACP condition rating depends on average score (total defects score divided by the number of defects) rather than peak score as used by the WRc. Unlike WRc's SRM, the PACP manual has no detailed decision making process. Presently, limited published data exists to validate the PACP defect scores rating system in North America. According to Stantec (2009), usage of average scores instead of peak scores for condition rating is a limiting issue of the PACP methodology. PACP methodology, therefore, may not be able to accurately prioritize rehabilitation needs of wastewater collection systems (Stantec, 2009).

In 2004, the Ministry of Finance in Ontario, Canada, completed a survey to investigate municipal water and wastewater systems' asset management practices. This survey found that among the responding Ontario municipalities, 17% do not perform inspections for condition assessment, and of those who do perform inspections, 33% do not record the results of the inspections (PricewaterhouseCoopers, 2003). The survey also found that large municipalities (more than 50,000 populations) typically have better asset management practices and that asset management approaches range from "don't fix it if it is not broken" strategies to the use of computationally intensive and sophisticated software tools. This survey demonstrates the current state-of-art in asset management by municipalities in Canada and most likely in North America.

2.2. Wastewater pipelines deterioration models

State-of-the-art techniques for deterioration modeling of wastewater pipelines include: (1) expert judgment, (2) expected value methodology, (3) binary logistic regression, (4) ordinal probit regression, and (4) Markov chains. Kathula et al. (1999) proposed a Sanitary Sewer Management System (SSMS) based on experts' opinion. Wirahadikusumah et al. (1999) developed a Markov chains model for the deterioration of wastewater pipelines. The transition probabilities matrix for the Markov chains model is