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A Verification and Validation Framework to Increase the Accuracy and Credibility Wastewater Pipeline Performance Prediction Models

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Abstract: Models and tools are an essential part of the advanced asset management process, which provides informed decision support for management of drinking water, wastewater, and stormwater infrastructure. Various models and tools for infrastructure asset management are described in the literature. However, most of the proposed models fail to document the understanding of the system they are modeling or the reliability when applied to the real world practice. The models in literature were created with limited datasets, and there is a significant lack of methods and tools to verify and validate these models. This lack of the reliability documentation is hindering the implementation of these models in practice. This paper presents the framework developed for the PIPEiD National Database and Modeling Platform for the validation and verification of the models and tools for water infrastructure asset management. Practical applications of evaluating the existing models and tools with the proposed framework has been piloted. Field, experimental data has been collected from 30 participating utilities. This collected data has been applied in the proposed framework to document the accuracy of various models and tools for real world applications.
Keywords : PIPEiD, Wastewater

I. Introduction

Infrastructure asset management is a crucial process in addressing the problem of rapidly deteriorating infrastructure and deciding where and when resources are need to be spent. Water utility managers nationwide need to implement advanced infrastructure asset management strategies to tackle ever challenging tasks. Efficient asset management brings many benefits for utilities. These benefits are, but not limited to the desired outcomes listed below :

- Prolonged remaining asset life through efficient O&M program
- Desired level of service for consumers with a focus on system sustainability
- Minimized cost through sound operational and financial planning
- Long-term budgets with a focus on activities critical to sustained performance
- Improved responses to emergencies
- Improved security and safety of assets.

Researchers have proposed numerous models in order to help predict the condition/performance and failure of water pipelines. However, most of the proposed models fail to document accurate prediction of current or future performance. Verification and validation (Ve&Va) processes are well defined and documented on other domains of modeling to increase the accuracy of the models. Ve&Va is recognized as the primary method for improving the accuracy of computer models (Oberkampf et al. 2003). Specifically, Ve&Va ensures that the model and its implementation are correct. Striving to provide a substantial Ve&Va process can acquire significant accuracy of the model. In this paper, a framework for Ve&Va for drinking water prediction models to increase accuracy is proposed. The application of the proposed framework is then demonstrated by evaluating the accuracy of a current water pipeline performance prediction model.

This paper presents the framework developed for the PIPEiD National Database and Modeling Platform for the validation and verification of the models and tools for water infrastructure asset management. Practical applications of evaluating the existing models and tools with the proposed framework has been piloted. Field, experimental data have been collected from 30 participating utilities. These collected data have been applied in the proposed framework to document the accuracy of various models and tools for real world applications.

II. Proposed Verification and Validation Framework

Verification and validation (Ve&Va) are the processes by which evidence is generated, and credibility is thereby established, that computer models have adequate accuracy and level of detail for their intended use. The concept of systematic Ve&Va is not a new one. The software development community has long recognized the need for a quality assurance program for scientific and engineering software. Hamilton (1991), and Obenkampf et al. 2003 provides the bibliography for the approaches followed for the Ve&Va processes by various disciplines.

The Institute of Electrical and Electronic Engineers (IEEE), along with other organizations, has adopted guidelines and standards for software quality assurance (SQA) appropriate for developers (IEEE 1991). SQA guidelines, while necessary, are not sufficient to cover the nuances of computational physics and engineering or the vast array of problems to which end-users apply the codes (ASME 2006). The SQA guidelines generally do not focus on the details of computational physics and engineering directly, therefor are not suitable for scientific and engineering model Ve&Va (Obenkampf et al. 2003).

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Application-specific Ve&Va has been the focus of attention for several groups in scientific and engineering communities since the mid-1990s. The Department of Defense's Defense Modeling and Simulation Office (DMSO) produced Ve&Va guidelines suitable for large-scale simulations (U.S. Department of Defence 2003). For the area of computational fluid dynamics (CFD), the American Institute of Aeronautics and Astronautics (AIAA) produced the first Ve&Va guidelines for detailed, first-principle analyses (Obenkampf et al. 2003). American Society of Mechanical Engineers (ASME) has adopted these guidelines and Performance Test Codes committee (ASME PTC 60) was designated in 2001.

There are no application-specific Ve&Va guidelines in literature or practice which can be applied for performance prediction models in domain of civil engineering. To fill this gap, application-specific Ve&Va procedures were developed for performance prediction models. The definitions for the newly developed Ve&Va procedures are consistent with those published by the ASME PTC 60 committee which relies on the Defense Modeling and Simulation Office of the Department of Defense and by the American Institute of Aeronautics and Astronautics (AIAA) in their 1998 Guide for the Verification and Validation of Computational Fluid Dynamics. Figure1 summarizes the previous Ve&Va guidelines followed to create the Ve&Va procedures for this research.

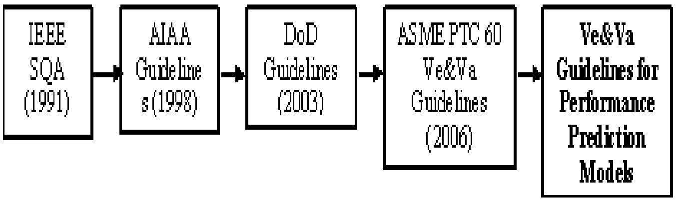

Figure 1. Ve&Va Guideline Development Background

III. Application Case Study

The model evaluated and verified within this paper is a fuzzy logic based model developed to evaluate the effects specific parameters have on wastewater pipes in determining their overall performance (Uslu and Sinha 2017). The model rates wastewater pipe performance in eight modules, including integrity, external corrosion, internal corrosion, surface wear, blockage, in/exfiltration, root intrusion, and capacity modules. The following figure summarize the methodology followed for the Ve&Va framework.

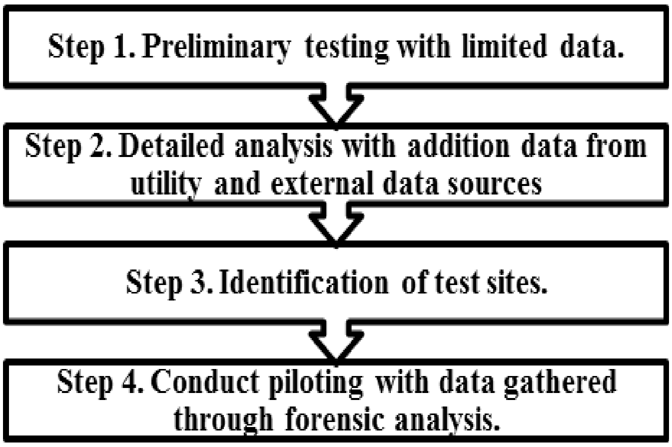

Figure 2. Site Selection Process through Testing

Preliminary Analysis

Performance index verification was conducted with the face testing method. Data collected from the participating utilities was run with the performance index. The network level results were evaluated for the selection of specific pipe segments to be further evaluated. For networks with a defect index value (PACP, SCREAM, etc.) the segments which gives the highest difference when compared with these defect indices will be selected. For networks with no defect indices, segments with the highest ratings will be further evaluated. Figure 3 and figure 3 summarizes the face verification process.

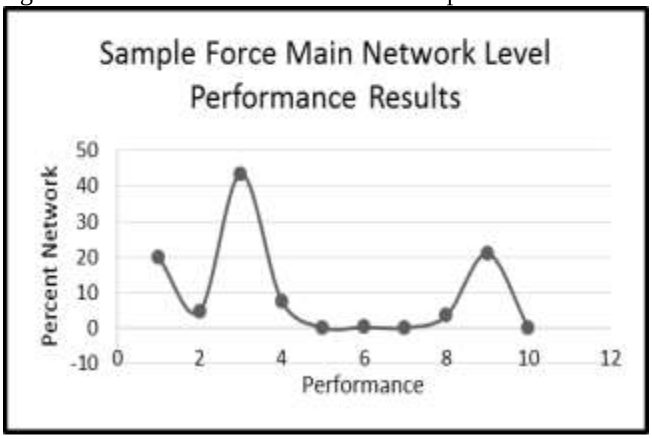

Figure 3. Preliminary Analysis Example

Detailed Testing

The validation of the performance indices were conducted with comparing the index results with available forensic studies conducted by the participating utilities.

A participating utility from the USEPA region #3 was conducting blockage performance analysis with sewer flow meters. There were a total of 2534 reading collected from their system indicating; 132 pipe blockages, 238 pipes in poor flow, 603 has fair flow, and 1561 has good flow. Figure 4 summarizes the geographical distribution of the sewer flow monitoring study.

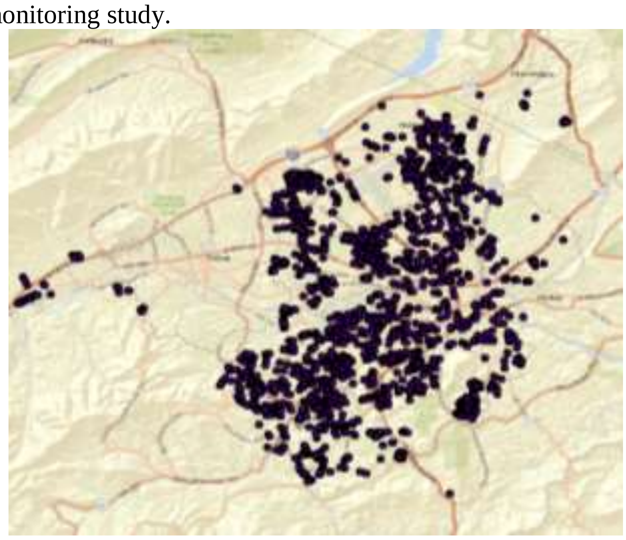

Figure 4. Sewer Flow Monitoring Study from Participating Utility

The performance index was run for the same segments and the results for the forensic study and the performance index was compared. For the normalization purposes, index results were combines ranges as shown in the table 1 under column "Index

Result Range". As summarized in the table 1, the accuracies are ranging between 69.70 % and 48.92% depending on the range evaluated.

Table1. Blockage Forensic Study Results Comparison

No	Number in Performance State	Index Result Range	Number in Performance State	Performance Index Accuracy
Blockage	132	10 to 9	92	69.70%
Poor	238	8 to 6	131	55.04%
Fair	603	4 to 5	295	48.92%
Good	1561	1 to 3	1043	66.82%

Forensic Studies

Detailed forensic studies were conducted by selecting specific sites of interest through perpetual data analysis and gathering more pertinent information through the process summarized in figure 5-15. This process was followed to identify 6 sites at a participating utility varying in age, location, material, environmental, and operating conditions.

After three perpetual runs, 21 parameters were collected from various sources. These parameters were used to run the index and determine regions of interest for the forensic tests and piloting. Table 2 summarizes the parameters used for site selection. Table 3 summarizes the 5 specific sites to run the forensic analysis and pilot the performance index.

Table 2. Collected Parameters for Site Selection.

No	Parameter	Data Source	No	Parameter	Data Source
1	PipeID	GIS	12	Cathodic Protection	GIS
2	Line Number	GIS	13	Soil Corrosivity	USGS Database
3	Pipe Material	GIS	14	Pipe Break Rate	Failure Data
4	Pipe Diameter	GIS	15	Pipe Break <5 Years	Failure Data
5	Pipe Age	GIS	16	Operating Pressure	Sahara Inspections
6	Line Number	GIS	17	Flow Velocity	Sahara Inspections
7	Pipe Joint Type	GIS	18	Treatment Plant	GIS
8	Pipe Slope	GIS	19	Number of Gas Pockets	Sahara Inspections
9	Node Length	GIS	20	Length of Gas Pockets	Sahara Inspections
10	Pipe Lining	GIS	21	Remaining factor of Safety	BEM Inspections
11	Failure Type	Failure Data			

Table 3. Selected Piloting Sites and Characteristics

Site Number	Pipe Material	Pipe Vintage	Pipe Diameter (Inches)
1	Asbestos Cement	1968	14
2	Asbestos Cement	1968	16
3	Asbestos Cement	1968	20
4	Ductile Iron	2002	30
5	Cast Iron	1949	1949

Forensic Tests for Piloting Sites

Numerous forensic tests are conducted at the piloting sites in order to compare the results with the performance index. Figure 4 summarized the forensic tests conducted at the piloting sites.

Figure 4. Forensic Tests for the Piloting Sites

Piloting Results

Site #1

First selected site was a 48-year-old, 14" diameter asbestos cement pipe. The phenolphthalein testing indicated 62% of the wall thickness was remaining. The results of the forensic analysis are summarized in table 4. The results of the wall thickness tests and the performance index results using the data collected with the forensic analysis agree.

Table 4. Site #1 Forensic Test Results

Parameter	Value	Parameter	Value
Pipe Material	AC	Ground Cover	Yard
Pipe Diameter	14 inches	H_2S	30 ppm
Pipe Age	48 years	Tidal Influences	Yes
Pipe Depth	5 ft	FOG	No
Pipe Location	Right of Way	Cathodic Protection	No
Pipe Shape	Circular	Thrust Restraint	No
Soil Type	Sandy Clay	Height of Bedding	0
Soil Moisture	Low	Soil Resistivity	17881 ohm/cm
Stray Currents	No	Wastewater pH	7.5
Ground Water Table	Below Pipe	Soil pH	6.9

Site #2

Second selected site was a 48-year-old, 16" diameter asbestos cement pipe. The phenolphthalein testing indicated 50% of the

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wall thickness was remaining. The results of the forensic analysis are summarized in table 5. The results of the wall thickness tests and the performance index results using the data collected with the forensic analysis agree.

Table 5. Site #2 Forensic Test Results

Parameter	Value	Parameter	Value
Pipe Material	AC	Ground Cover	Yard
Pipe Diameter	20 inches	H2S	15 ppm
Pipe Age	48 years	Tidal Influences	No
Pipe Depth	3 ft	FOG	No
Pipe Location	ROW	Cathodic Protection	No
Pipe Shape	Circular	Thrust Restraint	No
Soil Type	Sandy Clay	Height of Bedding	0
Soil Moisture	Low	Soil Resistivity	15, 076 ohm/cm
Stray Currents	No	Wastewater pH	7.5
Ground Water Table	Below Pipe	Soil pH	6.9

Site #3

Third selected site was a 48-year-old, 20" diameter asbestos cement pipe. The phenolphthalein testing indicated 61% of the wall thickness was remaining. The results of the forensic analysis are summarized in table 6. The results of the wall thickness tests and the performance index results using the data collected with the forensic analysis agree. Figure 10 summarizes this agreement between the ground truth and the index results.

Table 6. Site #3 Forensic Test Results

Parameter	Value	Parameter	Value
Pipe Material	AC	Ground Cover	Yard
Pipe Diameter	20 inches	H2S	15 ppm
Pipe Age	48 years	Tidal Influences	No
Pipe Depth	3 ft	FOG	No
Pipe Location	ROW	Cathodic Protection	No
Pipe Shape	Circular	Thrust Restraint	No
Soil Type	Sandy Clay	Height of Bedding	0
Soil Moisture	Low	Soil Resistivity	15, 076 ohm/cm
Stray Currents	No	Wastewater pH	7.5
Ground Water Table	Below Pipe	Soil pH	6.9

Site #4

Fourth selected site was a 14-year-old, 30" diameter ductile iron pipe. Ultrasound tests were conducted to determine the remaining wall thickness. The results of the ultrasound tests are summarized in figure 11. The results of the forensic analysis are summarized in table 7. The results of the wall thickness tests and the performance index results using the data collected with the forensic analysis agree.

Table 7. Site #5 Forensic Test Results

Parameter	Value	Parameter	Value
Pipe Material	DI	Ground Cover	Ditch
Pipe Diameter	30 inches	H2S	10 ppm
Pipe Age	14 years	Tidal Influences	No
Pipe Depth	15 ft	FOG	No
Pipe Location	ROW (Railroad)	Cathodic Protection	No
Pipe Shape	Circular	Thrust Restraint	No
Soil Type	Sandy Clay	Height of Bedding	0
Soil Moisture	Low	Soil Resistivity	66,751 ohm/cm
Stray Currents	No	Wastewater pH	7.5
Ground Water Table	With Pipe	Soil pH	7.1

Site #5

Fifth selected site was a 67-year-old, 18" diameter ductile iron pipe. This specific segment was failed a year prior to analysis and was replaced. The results of the forensic analysis are summarized in table 8.

Table 8 Site #5 Forensic Test Results

Parameter	Value	Parameter	Value
Pipe Material	RC	Ground Cover	Ditch
Pipe Diameter	36 inches	H2S	30 ppm
Pipe Age	50 years	Tidal Influences	No
Pipe Depth	15 ft	FOG	No
Pipe Location	Highway	Cathodic Protection	No
Pipe Shape	Circular	Thrust Restraint	No
Soil Type	Sand	Height of Bedding	0
Soil Moisture	Very Low	Soil Resistivity	43,253 ohm/cm
Stray Currents	No	Wastewater pH	7.5
Ground Water Table	Below Pipe	Soil pH	7.1

IV. Conclusions and Recommendations

The prediction and decision making models are a strong tool in an asset managers arsenal to conduct an efficient advanced asset management program. There are many models used in the condition evaluation and prediction, risk analysis, and renewal prioritization of drinking water and wastewater pipelines. However, most of these models have not been used by the utilities because of confidence problems. This paper proposed a framework and discussed the practical applications that can be used to verify and validate these models that are used for pipeline infrastructure asset management. By following the proposed framework to verify and validate the models that utilities are using, the accuracy and the confidence on the models can be greatly improved. Thus, the asset management programs for water utilities would benefit greatly by utilizing the decision support models that are proven to be correct and accurate by using this framework. This framework is precise enough to prove the correctness and accuracy of many different types of models created for decision support for asset management of drinking water pipelines. Also, it is flexible enough to be compatible with different nature and mathematical methods used for these models.

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