The Relevance of Water Pipe Deterioration Prediction Models: A review

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Abstract: The water distribution networks deliver water of appropriate quality and quantity to consumers. The frequency of deterioration is increasing due to several factors leading to financial loses, decrease in hydraulic capacity and reduction in quality of service. The increase in the damage rate of water systems has imposed pressure on the engineers to predict the replacement of vulnerable pipes with minor economic loss to the government. The most significant issue faced by water companies and municipality is the leakage of water pipelines. The level of water loss in the distribution network is increasing worldwide. Hence, the need for an appropriate maintenance and replacement strategy is noteworthy. In order to predict the life cycle of the pipeline, suitable models are required to initially analyze the performance of each network. There are plenty of deterioration models available. An appropriate model will aid in developing an effective decision-making system to identify the risk prone segments and the best renewal method. This paper aims to review the various factors contributing to deterioration of water pipelines and the various models existing to analyze the deterioration rate. Finally, the paper summarizes the need for the accurate deterioration prediction model. The review concludes at the end that despite all the advancement in the area of deterioration prediction models, there is still huge scope with the availability of more data from the respective departments.

Index Terms: Artificial Neural Network, Deterministic, Deterioration, Prediction, Probabilistic, Statistical, Water distribution network

1 INTRODUCTION

An effective water distribution network should deliver water of proper quality under required pressure and right amount to consumers. Thus, the structural condition of the network is important for the continuity and quality of the water distribution services provided by the water distribution infrastructures (Andreas et al., 2015). Pipe bursts are the most prominent damage in the water distribution system. The major reason for this type of failure is the inadequacy of the pipeline to resist the internal force from the water pressure (Skipworth et al., 2002). Leakage of pipelines is not just an economical issue, but also has environmental impacts which results in sustainability and safety hazards. Other challenges faced by distribution network includes old pipelines, increased number of breakage and failure of pipelines, high costs for the maintenance and replacement of pipes. The severe outcomes of deterioration of pipelines are water service disruption and flooding. Also, the leakage of water pipelines reduces the water quality by facilitating the ingress of infectious germs at the point of damage (Berardi et al., 2008). One or more component of a water distribution system is undergoing deterioration. Thus, deterioration pattern of pipelines can be classified into structural and functional deterioration. The structural deterioration is associated with the inability of the structure of the pipe to overcome the different types of stresses embedded on it. Whereas, functional deterioration as the name suggests, is related to the functional parameters such as hydraulic capacity and water quality (Andreas et al., 2015). Several factors lead to leakage of pipes specifically improper connection of pipes, internal and external corrosion, heavy load coming on the load for instance traffic load, ground movement, temperature variations, damage due to excavation and so on (Puust et al., 2010).

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The objective of this paper is to review different factors affecting the deterioration of the pipelines and various models to analyze the deterioration rate of the systems. This paper thus gives a brief idea about the importance of a deterioration prediction model for the preservation of the water resource. Thus, it is hoped that this study will be a source of inspiration for the new researchers to extend their research into this field. The paper is structured as follows. After this introduction, the major factors contributing to water main deterioration is discussed in the section 2. This is followed by a review of various water pipeline deterioration models in section 3. In section 4, the importance of prediction model in the current scenario is mentioned and this review is summed up in the section 5 followed by the references.

2 FACTORS CONTRIBUTING TO THE WATER MAIN DETERIORATION

There are immense number of factors resulting in the damage of pipelines. The level of influence of each factor depends upon the location in which the pipes are installed and the operational conditions to which the pipes are subjected. The effect of each factor is dependent on the physical parameters of the pipe as well as the characteristics of the location of the pipe. The contribution made by each factor is an important matter while developing a model (Liu and Kleiner, 2013). The factors can be classified into Static, Dynamic, Physical, Environmental and Operational. Static factors are dependent on time. Examples of static factors includes length, diameter, type of soil, pipe material and so on. Dynamic factors changes with time. The dynamic factors which promotes pipe deterioration rate includes age, cumulative number of breaks, corrosivity of soil, pressure exerted by the water in the pipe and so on (Ismail and Shamy, 2009). There are several physical factors that lead to failure of pipelines. Pipe material is one of the factor since pipes made from different material fail in different ways. The composition of the pipes also determines its performance in terms of its load carrying capacity and corrosion resistance and also the water quality (Berardi et al., 2008). The most commonly used for water distribution are made of cast iron, concrete, cement, ductile iron and polyvinyl. The properties of each material determine the resistance to deterioration of pipelines. Deterioration due to corrosion is high on thin walled pipes and hence thickness of the wall of pipe is an important physical factor. Thus, thick-walled pipes have longer service life and also thick-walled pipes are more temperature resistant than thin-walled pipes. The strength of thin walled pipes are very less when compared to thick walled pipes making it more prone to breakage. According to Aydogdu and Firat (2015), age, length and diameter of pipe are prominent factors causing failure and deterioration. The deterioration rate becomes more prominent in older pipes mainly because they have been exposed to stress and pressure for a long time. The larger the pipe diameter bigger will be the area for water flow resulting in less pressure on the water pipe surface than the small diameter ones. Thus, larger diameter pipes are more successful than small diameter ones. Wang et al. (2009) also supports this observation. Presence of lining and coating is important because corrosion is not much affected on lined or coated pipes (Kutylowska and Hotlos, 2014). Poor installation practices and manufacturing defects of the pipes also contribute to failure of pipes. Early signs of damage are the outcome of poor installation practices adopted and the manufacturing defects. The type of joints in the pipe is also an influencing factor (Folkman, 2018). In the study of pipeline deterioration prediction models done by Clair and Sinha (2012), the physical factors are the most widely used in developing all the models. Some of the environmental factors causing failure includes corrosiveness of the soil in which the pipe is installed (Ismail and Shamy, 2009), properties of groundwater, freezing index, rain deficit and seismic activity (Kleiner et al., 2010). Infiltration or exfiltration, presence of trees, soil or backfill type and traffic or surface loadings also comes under this category (Ana and Bauwens, 2010). Other soil phenomenon like expansion and contraction impose stress on buried pipes. Traffic loading is a significant factor since the increase in the traffic volume increases the external pressure on the pipelines. This may cause cyclic fatigue failures and bursting especially in small diameter pipes (Aydogdu and First, 2015). Pipes which are located on slopes need to be monitored closely. These pipes are more susceptible to surface exposure and thus to weathering resulting in the breakage or leakage of pipelines. Operational factors which causes deterioration are internal water pressure, quality of water, velocity of flow and so on. The impact of hydraulic pressure on failure rate of pipelines was studied by Shirzad et al. (2014). Rajeev et al. (2014) discussed the effect of pressure of water in pipelines. The water pressure results in stress in the pipes. Kabir et al. (2015), considered hydraulic capacity, quality of water and structural integrity to predict the failure rate of the water mains. Quality of water is mainly determined by the aggressiveness of the water. Aggressiveness promotes corrosion. According to Ana and Bauwens (2010), operational factors includes sediment level, sewage characteristics, and maintenance and repair strategies in addition to the above-mentioned ones. Thus, all the factors resulting in deterioration of pipes can be grouped under physical, environmental and operational factors as given in table 1. The physical factors are the most important and with higher rate of occurrence. Physical factors include higher number of factors. The major factors are only tabulated here. Less important ones are eliminated for simplification. The researchers must use the other factors also which are not mentioned in this list while preparing the model, by giving less weightage (Clair and Sinha, 2012). Higher weightage should be given to factors mentioned in the table 1. Each factor is labelled from F1 to F15. The deterioration factors along with their explanation is provided in the table. Table 2 is an extension of the table 1. Table 2 shows the importance of each factor by noting down how frequently each factor is mentioned in the references. This gives the researchers an idea to decide the weightage while preparing the model. Labels of deterioration factors with their corresponding reference are given in Table 2. Each references are marked as alphabets and the journals which each alphabet represent are given at the end of table. The data from the table implies the importance of each factor.

***Table 1**. Summary of factors causing deterioration of water pipelines based on literature review*

Label	*Deterioration factors*	*Explanation*
I	*Physical Factors*	
F1	*Pipe material*	*Different material fails in different ways. Some materials are more vulnerable to corrosion.*
F2	*Thickness of pipe wall*	*Strength and corrosion resistance are higher in thick-walled pipes.*
F3	*Age of pipe*	*Deterioration rate in pipes usually increases with time*
F4	*Length of pipe*	*Due to difficulty in repair and replacement, long pipes are not monitored frequently. Thus, this affects the quality of water flowing through the pipe.*
F5	*Diameter of pipe*	*Small diameter pipes are more vulnerable to deterioration than large diameter pipes.*
F6	*Presence of lining and coating*	*Lining and coatings make the pipe more corrosion resistant and also increases the strength of the pipe.*
F7	*Poor installation practices and Manufacturing defects*	*Poor installation practice can damage the pipe at an early stage. Manufacturing defects cause the deterioration factors to easily attack the pipelines reducing the structural integrity.*
II	*Environmental Factors*	
F8	*Corrosiveness of the soil*	*Corrosive soil will increase deterioration rate of the pipe from the outside*
F9	*Properties of groundwater*	*Aggressive water and content of the groundwater contributes to the corrosion of pipes*
F10	*Freezing Index*	*Frost can increase the physical loading and stress on the pipe*
F11	*Rain deficit*	*Rain deficit contributes to deterioration rate*
F12	*Seismic activity*	*Seismic activity increases the stress in the pipelines due to vibrations and movements*
III	*Operational Factors*	
F13	*Hydraulic pressure*	*Hydraulic pressure increases the internal stress on the pipe*
F14	*Quality of water*	*Content of water flowing through the pipe may and aggressive water may induce corrosion in the pipeline*
F15	*Velocity of water*	*In unlined dead ended pipelines the rate of corrosion will be high*

Table 2. *List of factors with their corresponding references*

Label	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15
A	●		●	●	●										
B			●	●	●										
C						●		●		●		●			
D	●	●	●		●		●	●					●		
E	●		●							●	●				
F													●	●	●
G								●	●	●					
H	●	●	●	●	●			●		●	●	●	●	●	●
I	●	●	●	●	●										
J	●	●	●	●	●										
K			●	●	●				●			●			
L:			●	●	●										

A:	Berardi et al. (2008)	G:	Ismail and Shamy (2009)
B:	Aydogdu and Firat (2015)	H:	Kabir et al. (2015)
C:	Kutylowska and Hotlos (2014)	I:	Wang et al. (2009)
D:	Folkman, 2018	J:	Clair and Sinha (2012)
E:	Kleiner, 2010	K:	Ana and Bauwens, (2010)
F:	Shirzad et al. (2014)	L:	Kakoudakis et al. (2016)

3 WATER MAIN DETERIORATION MODELS

The aftereffects of pipeline failures are huge at the economic social and environmental level. Numerous models have been developed in the past and still researchers are developing water pipe deterioration models for analyzing the failure rate of pipelines to aid in the Decision Support System for optimal asset management of the water distribution network (Kutylowska and Hotlos, 2014). The basic requirement for the development of any model is sufficient data. Thus, the initial step of the model development is data collection. The major difficulty faced by the researchers to develop accurate data analysis techniques are the unavailability of the proper data. The government should implement certain initiatives for the water companies and municipalities to maintain and preserve the data related to the water systems. This will enhance the amount of data collection level of the researchers to develop more efficient decision support systems (Puust et al., 2010). The deterioration models are either physically based approaches or statical methods. The models can be classified into four sections which are Statistical models, Probabilistic models, Deterministic models and Artificial Intelligence models. Statistical models are commonly used to homogeneous groups of pipes. This category of models can predict the useful life, time of failure or replacement required based on the data collected. The models are developed based on regression. A model was developed based on Evolutionary Polynomial Regression (EPR) for predicting the number of breaks in each homogeneous group and failure rate of individual pipe (Berardi et al., 2008). To predict the annual break rate of individual pipe made of different materials, Wang et al. (2009) developed five multiple regression models. Osman and Bainbridge (2011) compares two statistical models rate-of-failure (ROF) models and transition-state (TS) models. ROF model concentrates in predicting the breakage rate of pipes while the other model predicts the time between successive failures. The probability or relative frequency of an event occuring is analyzed by probabilistic models (Jouni and Palmer, 2001). According to Clair and Sinha (2012), probabilistic models can predict pipe condition, widely used in infrastructure management involving repair, rehabilitation and replacement and development of these models require extensive data. Kabir et al. (2015) developed a probabilistic modal using Bayesian Belief Network Model to evaluate the frequency of failure of metallic pipelines. The modal can rank the water mains and identify the pipelines requiring repair, rehabilitation and replacement. Deterministic models are simple, but it is not effective compared to other methods (Large et al., 2014). The deterministic models can be classified into time-exponential models and time- linear models. These models generate better results for homogeneous water pipelines provided grouping of the pipelines is done perfectly (Kleiner and Rajani, 2001). Davis et al. (2009) proposed a deterministic model based on Linear Elastic Fracture Mechanics theory and Elastic Plastic Fracture Mechanics theory for the lifetime prediction of pipelines made up of polyvinylchloride and polyethylene materials. Another category of models are mathematical models which are developed based on Artificial Neural Networks (ANN) and Fuzzy logic. Large et al. (2014) developed a model based on ANN techniques for identifying pattern of pipe failure in New York City. Achim et al., (2007), developed a Neural Network model for analyzing the rate of breakage of pipelines. The work was done with the support of Australian Research Council and they validated the model. Geem et al. (2007) developed ANN model and applied to real-world case in South Korea.

4 NEED FOR WATER MAIN DETERIORATION PREDICTION MODELS

Tourism, industry and agriculture sectors are the backbone of an economy. All these sectors are water dependent. The water demand of these sectors is huge and it is the responsibility of the government and municipality to make the necessary provisions to meet this need (Shirzad et al., 2014). Government has implemented various initiatives to preserve the water resource. Thus, economic growth of an economy is directly proportional to the efficient management of water resource. The data from the various municipalities reveals that most of the water distribution system was laid more than 100 years ago and are at the verge of deterioration. It is evident that with time the functionality of these systems will be reduced, and replacement will become necessary (Ismail and Shamy, 2009). The cost of replacement of deteriorated pipelines will be huge and if they are left without replacement, the economic, social and environmental consequences will be massive as discussed earlier. Thus, a water pipeline deterioration prediction model is necessary to aid the utility managers to develop decision support system in order to carry out required repair procedures at appropriate time. Timely management of pipelines will extend the replacement time of the pipelines thereby reducing the economic loss and increasing the lifetime of the pipelines (Osman and Bainbridge, 2011). The inspection of water distribution system includes the pipe condition assessment in which the present condition, structural health, impact on water quality and hydraulic capacity are determined (Liu and Kleiner, 2013). The presence of any factors that negatively affects the structural health of pipeline, water quality or even hydraulic capacity may result in deterioration of water pipeline. The number of bursts occurred in a pipeline in a particular period of time is a strong factor to analyze the present condition of the pipeline. Even when the number of bursts is low, the pipes need proper repair or replacement based on the surrounding conditions. As mentioned earlier, the financial support needed for the replacement of water mains is very high (Jouni and Palmer, 2001). This also implies the importance of having a proper deterioration prediction model. The major effect of deterioration is the leakage of pipelines. The leakage is the process in which the water is lost due to various reasons at an uncontrollable rate. Thus, the primary objective of the prediction model should be to monitor the leakage rate and if the leakage rate is severe, necessary repair options should be adopted immediately. The development of deterioration prediction model is a complex task. As mentioned in section 2, each factor should be given a weightage according to its importance. The importance/contribution of each factor is still debated since at various location the deterioration factors prominent will be different according to the environmental and operational conditions (Clair and Sinha, 2012). According to Andreas et al. (2013), in order to develop an effective decision-making system, accurate predictions of expected number of failures of the distribution network pipes are imperative. The deterioration prediction models will help in determining the maintenance and replacement period for individual pipes. In addition, these models will help in determining the possible number of failures in the entire system. Thus, the benefits of an accurate prediction model includes:

i. Determination of inspection time of pipelines
ii. Helps the utility managers to plan the repair procedure
iii. Extends the replacement time
iv. Extends the lifetime of the pipelines
v. Reduces the cost associated with the maintenance
vi. Increase the safety and efficiency of the pipelines.

All the benefits mentioned above implies the relevance of a deterioration prediction model. It is obvious from the literature review that there are plenty of factors contributing to the deterioration of water pipelines. With the data available in the table 1 and table 2, researchers can generate highly efficient prediction models. Water is becoming a scarce resource in most of the countries and hence it is crucial to analyze the factors causing water pipeline failure and to develop the most successful model to plan the proper repair, rehabilitation and replacement strategy (Kleiner and Rajani, 2001).

5 CONCLUSION

The number of pipelines getting deteriorated is increasing tremendously worldwide. The factors responsible for the deterioration are enormous. The prominent deterioration factors will be different in pipes located at different locations and it also depends upon the operational conditions to which each pipe are subjected. As per the previous studies conducted by the researchers, the most important factors causing deterioration are physical factors including pipe material, pipe age, length and diameter of pipes and the presence of protective coating on the pipe. The repair and replacement of pipelines are now becoming a major matter of concern since the pipes which are not inspected and managed properly will result in huge loss at the economic, social and environmental levels. The researchers have started developing models to analyze the deterioration rate of pipelines at an early age. The models already developed are mainly categorized into statistical, probabilistic, deterministic and artificial intelligence models. Statistical models are found to provide a cost-effective analysis compared to physically based approaches. The benefits of an accurate prediction model are many. Global warming and water scarcity also reflect the need to develop a prediction model for analyzing the deterioration rate of the pipelines. The benefits associated with the development of deterioration prediction model for water pipelines also gives light to scope of extending this idea to oil and gas pipelines also. In the future, the researchers can coordinate all the factors affecting water and oil and gas pipelines and make efforts to create a comprehensive model which can be applied globally to all types of pipelines.

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