Review of rehabilitation strategies for water distribution pipes

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ABSTRACT

Effective rehabilitation strategies for water pipes play a very important role in both sustaining the reliability of water distribution systems and reducing costs. Pipe breakage prediction models provide a platform for effective rehabilitation strategies. The strength of the rehabilitation strategies is just an extension to those predictive models. There are different techniques and methods for modeling pipe breakage based on identifying breakage patterns using statistical or data-driven (mining) techniques. This review addresses those techniques from the perspective of rehabilitation strategy applications. Therefore, the rehabilitation strategies presented in the literature were reviewed according to three criteria: the level of pipe breakage prediction (pipe-group level or individual-pipe level), the phase, according to the bathtub curve, in which the predictive model is applicable and the performance of the system after rehabilitation. The use of artificial neural networks (ANNs) was found superior over statistical techniques for predicting pipe failure rates and consequently in rehabilitation strategies. However, ANNs are relatively less concerned with identifying specific relations between the variables involved. A proposal for the future research of environmentally integrated, optimal, dynamic and proactive rehabilitation and operation strategies is highlighted at the end of the article.

Key words | deterioration, pipe breaks, rehabilitation strategy, reliability, water distribution systems

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INTRODUCTION

Water distribution systems, as any other reparable mechanical system, are prone to fail in some random way during their lifetime. They may fail once installed and operated, during mid-life or when they age. Early failure is usually due to manufacturing, installation or design defects (infant mortality phase); the rate of failure decreases very rapidly once a system passes this critical period. It then starts its normal period of life (mid-life phase); this phase is characterized by a low and constant rate of failure (random failure). Failures of this phase are likely due to stresses exceeding the system's strength. As the system ages, the failure rate increases due to fatigue or material depletion (wear-out phase). This typical lifetime of most reparable systems is graphically displayed by a bathtub curve, as shown in Figure 1. It is worth noting that, although the bathtub curve depicts the failure rate of an entire system, each of the individual components (e.g., pipes) of this system may fail separately in different periods (infant mortality, normal life and wear-out phase).

The mechanical reliability of a water distribution system is determined according to the rate of occurrence of failure (ROCOF) during a given period of the system's lifetime. Quantification of the ROCOF (how often the system fails) is a step forward not only for measuring mechanical reliability but also for determining rehabilitation strategies. Statistical techniques, as a quantification tool, play two roles in both analyzing the failures of systems and determining the lifetime of a system, as indicated by whether failures are decreasing, constant or increasing over time. They can also be used to predict the rate of failure based on failure patterns. Here, it is important to point out the comprehensive review of statistical models for the structural deterioration of water mains by Kleiner & Rajani (2001). However, the current article differs from previous reviews

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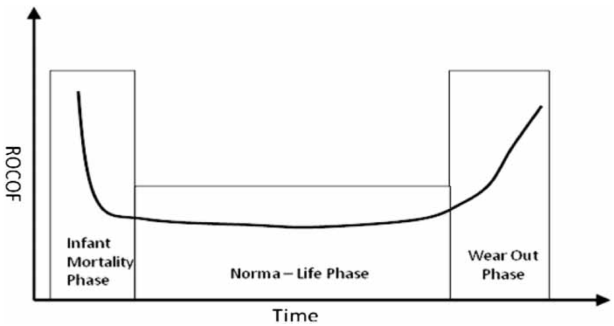

Figure 1 | The bathtub curve for reparable systems.

by addressing statistical methods not only as predictive modeling techniques but also from the perspective of rehabilitation strategy applications. In addition, we present more recent techniques that have constituted significant advancements in the field.

Rehabilitation strategies imply how often a unit will have to be replaced or repaired. Rehabilitation strategies include minimal repair and complete replacement (renewal). In a system with minimal repair, the failed system is restored to a condition that is statistically identical to its condition just prior to failure ('bad-as-old'). A renovated or replaced pipe can be treated as a new pipe, and the system is refreshed to a 'good-as-new' state. Therefore, operators of water distribution networks need scientific insight into piping failures so that they can make intelligent 'repair-or-replace' (rehabilitation strategy) decisions to keep the system reliable. This review describes how the different models and techniques used in water pipe breakage prediction can be used for rehabilitation decisions. In this article, the models are divided into covariate and multi-covariate models. From this point of view, the rehabilitation strategy of the system is reviewed and evaluated according to the applicability limitations of each model and technique.

PIPE BREAKAGE PREDICTION MODELS

Pipe breakage predictive models can be classified into two types: covariate and multi-covariate models. The former considers the problem of incomplete data (right censoring), which is solved by aggregating pipes into homogeneous groups. When sufficient data of the breakage influential covariates are available, pipe grouping becomes less important; then, probabilistic multivariate models can be considered for breakage pattern modeling. Therefore, rehabilitation strategies based on both kinds of models differ at the level of rehabilitation. Some models are concerned with the pipe-group level while others are concerned with the individual-pipe level. In addition, each model is applicable to a certain phase of the bathtub curve. Thus, the performance of the system after rehabilitation using models is completely different. Some models bring the system to a 'bad-as-old' state, whereas other models bring the system to a 'good-as-new' state.

Covariate models

Covariate models consider the problem of incomplete data (right censoring), which is solved by aggregating pipes into homogeneous groups. Consequently, the results are intended for the pipe-group level. This, in fact, is a weakness of these models. The covariate models used in pipe breakage prediction modeling are linear and exponential regression models.

Regression-based models

All methods presented for predicting pipe breakage using regression analysis have certain drawbacks, such as a limited number of influential breakage factors considered, the classification of pipes into homogenous groups according to the influential factors considered, the implicit assumption of breaks being uniformly distributed along all of the water pipes, ignoring any probability of different event sequences (no random or stochastic variations), and assumptions regarding the condition of the system. Therefore, these models are not suitable for a prioritization of pipe rehabilitation because the results are obtained for pipe-group levels. Therefore, no rehabilitation strategy for individual pipes can be achieved. However, researchers have used pipe-group-based models for the assessment of individual pipe failure probability by assuming the same behavior for similar pipes. In addition, these models are mainly concerned with the mid-life period of the system.

This kind of analysis was first used in pipe breakage modeling by Shamir & Howard (1979). They used exponential regression analysis to quantify the effects of pipe age on breaking rate. They also determined the optimal time of replacement while minimizing the cost. In addition to the age, Walski & Pelliccia (1982) added the pipe casting and diameter and distinguished between the first break and subsequent breaks in the model of Shamir & Howard (1979). Clark *et al*. (1982) used a two-phase model: multivariate linear regression to predict the time to the first break and multivariate exponential regression to predict the number of subsequent breaks. For the linear regression, they used the diameter, absolute pressure, length and material of the pipe in addition to the industrial and residential development overlaying the pipes, as independent variables. In the exponential regression, they used the pipe's age, surface area and length of pipe in low and moderately corrosivity soil and the pipe's surface area in highly corrosive soil. These models were able to predict the first break and subsequent breaks for groups of pipes (based on age or material).

Time-linear regression modeling has been used in modeling water pipe breakage. For example, Kettler & Goulter (1985) used pipe age as an independent variable (predictor) to predict pipe breakage; they found a linear increase in pipe breakage with time. McMullen (1982) considered corrosion as the main factor of pipe failure; he constructed a linear relationship to predict the age of a pipe at first break. The data used in this model as well as the assumptions have been met with practically based criticism. Jacobs & Karney (1994) used pipe length and age as independent predictors to determine the probability of a day with no breaks using a linear relationship. They adopted a clustering concept and applied their modeling to three homogeneous age-based groups of cast iron pipes. They applied the modeling to independent breaks only (breaks that occur more than 90 days after and/or more than 20 m from a previous break) and to all of the recorded breaks as well. The application to independent breaks showed a higher correlation from which they concluded that independent breaks are uniformly distributed along pipes.

Homogeneous Poisson process (HPP)

The Homogeneous Poisson process (HPP) is widely used for reparable systems and water distribution systems in particular because water distribution systems spend most of their lifetime operating in the long flat constant repair rate portion of the bathtub curve, which was introduced previously as the normal life or mid-life phase. The HPP is the only model that applies to that portion of the curve, so it is the most popular model for system reliability evaluation and reliability test planning. This model assumes that the mean times between failures are independent and identically distributed according to an exponential distribution, which implicitly means that the failure rate is considered to be constant. Accordingly, the HPP cannot be used to predict an early failure lifetime; other distributions or functions are used for that phase, such as hazard functions. In addition, the HPP cannot be used for individual pipes. Therefore, no optimal rehabilitation time can be determined using the HPP. Rehabilitation strategies based on this technique bring the system to the 'bad-as-old' state (minimal repair). Because the HPP cannot be used to predict early failures, researchers have used other functions for this purpose. For example, Andreou *et al*. (1987) and Marks *et al*. (1987) developed a proportional hazard (PH) model to include a two-stage pipe failure process. The early failure stage was characterized by fewer breaks and was represented by the PH model, whereas the later stages, with multiple and frequent breaks, were represented by a Poisson-type model. Meanwhile, Li & Haims (1992a, b) did not stop at the pipe breakage rate prediction stage; they followed Andreou *et al*. (1987) and formulated a two-stage decision-making model. In the first stage, a semi-Markovian model was applied to individual water mains to determine the optimal repair/replace decision at various deterioration states while maximizing the availability of the water main. The second stage uses a multilevel decomposition approach to optimally distribute the available funds among the distribution network components to maximize the overall system availability. Malandain *et al*. (1998) used a Poisson regression to fit the failure rate at the level of sets of pipes homogeneous in material, diameter and type of surrounding soil. Madanat *et al*. (1995), and later Wirahadikusumah *et al*. (2001), employed multiple regressions to model the deterioration of infrastructure facilities.

Non-homogeneous Poisson process (NHPP) – power law

This model allows the breakage rate to vary with time. The Non-homogeneous Poisson process (NHHP) can model both increasing and decreasing failure rates. Therefore, the NHHP is used to model a system when the target is a minimal repair process or a return to the 'bad-as old' state. The NHPP was used by Kleiner & Rajani (2010) to predict the breakage pattern of individual pipes considering three dynamic factors: the freezing index, the cumulative rain deficit and the snapshot rain deficit. However, the technique was not as successful in estimating the number of breaks per pipe ($R^2 = 0.43$) as in estimating the number of breaks per year of the entire group ($R^2 = 0.61$).

Davidson & Goulter (1994) proposed a probability distribution termed a recursive Poisson distribution as an improvement over the non-homogeneous Poisson probability distribution. They suggested that, because subsequent breaks in a cluster are not entirely random but rather are affected by previous breaks, the probability distribution of these breaks is really not of the Poisson type. The distribution they proposed, however, could not be derived analytically, and thus, their model was still not predictive because actual breaks had to occur for the recursive process to be applied. Goulter & Kazemi (1988) used the NHPP to predict the probability of subsequent breaks given that at least one failure had already occurred.

Weibull distribution

The Weibull distribution is a very flexible lifetime distribution model. The shape parameter allows the Weibull distribution to assume a wide variety of shapes that can be used to characterize failure distributions in all three periods of the bathtub curve. A basic Weibull distribution has two parameters: a shape parameter and a scale parameter. The scale parameter determines when, in time, a given portion of the population (e.g., the pipes) will fail. The shape parameter (beta) is the key feature of the Weibull distribution that enables it to be applied to any phase of the bathtub curve. A beta value of less than 1 models a failure rate that decreases with time, as in the infant mortality period. A beta value equal to 1 models a constant failure rate, as in the normal life period, and a beta value greater than 1 models an increasing failure rate, as during the wear-out phase. Therefore, a Weibull distribution can be used to model a system when the rehabilitation target is supposed to renew the whole system or return the system to a 'good-as-new' state. There are several ways to view this distribution, including probability plots, survival plots and failure rate (hazard function) versus time plots. For example, Brémond (1997) and Lei (1997) applied the PH model using the Weibull probability baseline hazard function for water main failure.

Exponential distribution

The probability of elapsed time until a pipe failure can be found experimentally following the exponential probability distribution; the hazard plot of this distribution (ratio of failure to survival) is likely to be constant. Accordingly, using this distribution means that the failure rate of the system is assumed to be constant. Hence, this distribution is actually a special case of the Weibull distribution (beta = 1). This property makes this distribution very effective for systems in mid-life (normal life period). In other words, this distribution is not suitable when early failure or wear-out of the system is concerned. Therefore, this distribution is useful for verifying whether a system is meeting reliability requirements for the mean time between failures (MTBF). The MTBF is applicable in normal life periods, where the failure rate is almost constant. In pipe breakage modeling, when the failure rate is considered constant, the main time between failures is implicitly assumed to be exponentially distributed. Quimpo & Shamsi (1991) used an exponential distribution to describe the breakage rate for each pipe to estimate the reliability of a water supply network. However, this distribution alone is not suitable for the rehabilitation prioritization of large systems.

Nevertheless, exponential and Weibull distributions can be combined for stratification or for identifying the order of breaks, i.e. the time to failure between installation and the first break, between the first and second break, and so on, which is often unknown for pipe segments laid before pipe breaks began to be rigorously recorded. Gorji-Bandpy & Gorji-Bandpy (2007) introduced a modeling strategy that uses the Weibull distribution and an exponential distribution to solve this problem. The former was used to find the first break order (time to failure from installation to first break), while the second distribution was used to describe the behavior of subsequent breaks (time to failure from the first to second break, second to third, and so forth). Therefore, an optimal rehabilitation strategy can be achieved with a combination of exponential and Weibull distributions.

Lognormal distribution

Lognormal distribution is commonly used to model the lives of units whose failure modes are of a fatigue-stress nature. Because this includes most, if not all, mechanical systems, lognormal distributions have a widespread application. Consequently, the lognormal distribution is a good companion for the Weibull distribution when attempting to model these types of units. Lognormal distributions are used to model continuous random quantities when the distribution is believed to be skewed, such as lifetime variables (NIST 2010). The use of this distribution (as well as the Weibull) requires that at least two failures have occurred to estimate the two parameters (shape and scale parameters). However, if one parameter is assumed to be known (the shape parameter) then a model can be derived.

Park (2008) used a loglinear and power law process (Weibull process) to model failure rates and estimate the economically optimal replacement time of individual pipes in a water distribution system. They found that the former method showed better performance than the latter. Furthermore, the 'failure-time-based' method was shown to be superior to the 'failure-number-based' method for the water mains under study. However, because there was no consideration of any influential break factors (except for the number of failures) in the modeling, there are concerns about the applicability of this work. Later, Ekinci & Konak (2009) presented and compared applications of the log-linear ROCOF method and the power law process for modeling pipe failure rates.

Markov analysis models

Before addressing the multivariate models, it is worth noting another method used for pipe breakage prediction and development rehabilitation strategy, the Markov analysis (MA) method. The MA model provides a means of analyzing the reliability and availability of systems whose components exhibit strong dependencies. In other words, the MA can be applied when the events that may occur to the system depend on its history. The major drawback of Markov methods is that Markov diagrams for large systems are generally exceedingly large, complicated and difficult to construct. However, large systems that exhibit strong component dependencies in isolated and critical parts of the system may be analyzed using a combination of MA and simpler quantitative models. In pipe breakage modeling, Gustafson & Clancy (1999) modeled the breakage history of water mains as a semi-Markov process. The semi-Markov process implies that the time to the next break is completely independent of the times between previous breaks; it does not depend solely on the break order. Wirahadikusumah *et al*. (2001) developed a few Markov models for sewers using different techniques to calibrate the Markov transition probability; these were non-linear optimizations. Micevski *et al*. (2002) discussed the relevance of a multistage Markov model for modeling the deterioration of stormwater pipes. However, the model was based on pipe cohorts and was not intended to predict the future condition of a single pipe. Therefore, rehabilitation strategies based on this method would not be able to consider all of the variations that might occur in the system with time. This method assumes that a break will happen as long as the conditions that caused a previous break continue to exist.

Multivariate models

When sufficient data of influential covariates on breakage are available, pipe grouping becomes less important. In this case, probabilistic multivariate models can be considered for breakage pattern modeling and establishing rehabilitation strategies. Multivariate models can overcome and give more strength to the results. The multi-variate models that are used most extensively for applications to individual pipes are the PH model and the accelerated lifetime model.

The PH model

The PH model is a technique for estimating the effects of different covariates influencing the time to failure of a system. For example, a pipe break may occur under a combination of different accelerated stresses, such as temperature, traffic load, etc. It is clear then that such factors affect the failure rate of a pipe. In other words, the PH method is the best alternative when the following conditions are met: (a) the estimation of parameters rather than the shape of the hazard are needed; (b) the effect of increments or reductions of the covariate on the hazard rate must be examined; and (c) the importance of influential covariates on the time to break must be measured quantitatively. However, the effect of those covariates is assumed to be the same at all times. Therefore, the PH technique can be relied upon to establish proactive rehabilitation strategies. In addition, PH results can provide recommendations for design, extension and operation depending on the inputs involved in the model.

The PH model was used by Marks & Jeffrey (1985) to predict water main breaks. The influential covariates on pipe breakage were determined using multiple regression techniques. Andreou *et al*. (1987) used a PH model to predict failure at an early age and used a Poisson-type model for the later stages.

Accelerated lifetime model

PH models are not the only way to relate survival to covariates. The most important alternative to PHs is an accelerated life model (sometimes called an accelerated failure time model). Accelerated life models have been found to overcome the problem of the lack of failures. The concept behind these models is to make failures occur by testing at much higher stresses than the units would normally experience in their intended application. Models that relate high stress reliability to normal use reliability are called acceleration models (NIST 2010). As within PH models, in an accelerated life model, there is a different survivor function for each individual. The PH model is more like an acceleration model than a specific life distribution model, and its strength lies in its ability to model and test many inferences about survival without making any specific assumptions about the form of the life distribution model. In its original form, the PH model is non-parametric, i.e. no assumptions are made about the nature or shape of the underlying failure distribution. The Weibull and exponential models are actually special cases of the PH model. In the literature, Lei (1997) and Eisenbeis *et al*. (1999) applied the accelerated lifetime technique to model pipe breakage. Although this method can be used to develop a proactive rehabilitation strategy, it must be calibrated by testing the model with actual values to avoid any over or under estimation.

Data mining techniques

Despite the extensive use of statistical methods, some researchers have reported that statistical techniques cannot achieve absolute success in pipe breakage modeling or in developing rehabilitation strategies. Clark *et al*. (1982) reported that the complex nature of pipe breakage mechanisms and the highly variable rate of pipe breakage in existing pipe networks and water systems have led to the failure of many statistical studies and attempts to obtain predictive models for future breaks. Recently, Yamijala (2007) reported that the accuracy and usefulness of the various statistical models have not been systematically compared. Their opinions about statistical methods were based on the following:

1. They are very limited in the breakage pattern of a single pipe because there is often an insufficient number of breaks of a single pipe to conduct a credible analysis, and breaks at the level of individual pipes are needed for making inspection and maintenance decisions in any proactive rehabilitation strategy.
2. They have also created uncertainty about the effects of pipe aging on pipe breaks. For example, Walski & Pelliccia (1982), Clark *et al*. (1982) and Kettler & Goulter (1985) reported that age is not the only governing parameter of pipe breakage; however, the majority of statistical models developed consider pipe age as the most important variable describing the time dependence of pipe breakage with corresponding rehabilitation strategies based on this assumption.

Therefore, many attempts to develop methods and techniques to overcome these disadvantages have been introduced. The data mining (data-driven) method is one of those techniques. The use of data mining models (DMMs) such as artificial neural networks (ANNs) has been found to be a useful alternative in predicting pipe failure rates and consequently in rehabilitation strategies. If significant variables are known, while the exact relationships among them are unknown, ANNs are suitable for performing a function fitting with multiple parameters on the existing information and predicting possible relationships in the near future. The main advantage of this technique is that it is distribution-free, i.e. it does not require assumptions or knowledge about the statistical distribution of the data. The other important advantage is that DMMs can be applied the individual-pipe level. These are obvious advantages over most statistical methods requiring data modeling, which is difficult when there is no knowledge of the distribution functions (Benediktsson *et al.* 1990).

Statistically, use of DMMs can be considered to be a multivariate technique with an important advantage over the PH and accelerated lifetime models: the effects of the covariates can be handled as time variables. However, data mining is relatively less concerned with identifying specific relations between the variables involved. For example, uncovering the nature of the underlying functions or the specific types of interactive, multivariate dependencies between variables is not the main goal of data mining. Instead, the focus is on producing a solution that can generate useful predictions.

Applications of the DMM as a prediction tool to establish rehabilitation strategies have been presented by many researchers. For example, Sacluti (1999) used ANNs to predict pipe failure rate in a water distribution network in a Canadian city. Ahn *et al.* (2005) introduced a procedure based on ANNs to predict the pipe failure rate in a water distribution network in Seoul City, South Korea. Jafar & Shahrour (2007) presented a data analysis of the degradation rate of water mains using ANN. Tabesh *et al.* (2009) used ANNs and neuro-fuzzy systems to predict pipe failure rate and to attain an improved assessment of the reliability of the pipes. Christodoulou & Deligianni (2009) presented a neuro-fuzzy decision-support system for the performance of multi-factored risk-of-failure analysis and pipe asset management. Likewise, Christodoulou & Deligianni (2010) reported that the ability to integrate risk analysis and asset management decision support systems (DSSs) is among the most important components of sustainable management strategies for water distribution networks. Bubtiena *et al.* (2011) used ANNs to predict pipe breakage as a platform for proactive rehabilitation strategies.

FUTURE RESEARCH

The goal of any rehabilitation strategy is to sustain the reliability of a system and reduce costs. This should be achieved through environmentally integrated, optimal, dynamic and proactive rehabilitation and operation strategies. Despite this being an understandable concept in the reports reviewed in this field, this comprehensive strategy has not been covered well in the literature. Such a strategy provides status information about any element in the system and the optimal time of repair or replacement in the form of DSS. The DSS of the proactive rehabilitation strategy on predictive modeling of failure, whereas a prioritization strategy depends on the consequences of failure (risk cost related to failure). The risks involved should be clearly defined, including the most influential factor(s) of failures, from which the priorities of implementation can be ranked.

The main features of the proposed proactive integrated strategy are as follows.

1. It must be a proactive, initiative and preventive strategy rather than a reactive strategy. A proactive strategy must be capable of determining what kind of rehabilitation is required (replace or repair), localizing the element (pipe) in the system (network) and determining the proper time of action. A proactive strategy should be reinforced by a comprehensive and highly accurate predictive tool. Such a strategy would helps to maintain a sustainable system with high reliability.
2. It must be optimal; the strategy must be based on the risk criteria of implementation priority. The risk criteria should be based on environmental, social, economical and health consequences. The rehabilitation timing and the proper decision between repair and replacement should be optimized.
3. It should be environmentally integrated, taking into consideration the surrounding environment of the element (pipe) such as the weather, soil and water quality and including it in the predictive modeling. The reasons for failures and deterioration should be determined; analyses of the elements that have already failed (degrading modes) can help determine the criteria of design, operation, extension and upgrading.

4. It must be dynamic to support sustainability; this reliability requirement has not considered thus far. Using predictive modeling, the elements expected to fail within a certain time can be determined, as well as determining the element first to maintain according to prioritization strategy the previous elements required for maintenance, according to a prioritization strategy. In addition, the implementation time should be optimized, linked with using simulations and a hydraulic solver. A dynamic strategy should be capable of recognizing the effects of replacement or repair of any individual element on the other element(s), including the elements that decided to be repaired or replaced; based on this, the strategy can be upgraded. A dynamic strategy should also be capable of considering uncertainties, such as the aging of elements.
5. It must be able to determine the element(s) that are interdependent to overcome weaknesses in the measurement of mechanical reliability.

CONCLUSION

This article addressed statistical and data mining methods from the perspective of rehabilitation strategies and predictive modeling techniques. The models were divided into covariate and multivariate models. Accordingly, the rehabilitation strategies of the systems were reviewed and evaluated. The rehabilitation strategies presented in the literature were reviewed according to three criteria: the level of the break prediction (for the pipe-group level or individual-pipe level), the phase, according to the bathtub curve (infant, mid-life or wear-out phases), and the performance of the system after the rehabilitation. The use of ANNs was found to be a useful alternative for predicting pipe failure rates and consequently for rehabilitation strategies and could overcome some of the drawbacks of statistical methods. However, data mining is relatively less concerned with identifying specific relations between the variables involved. Proposal for the future research of environmentally integrated, optimal, dynamic and proactive rehabilitation and operation strategies was highlighted at the end of the article.

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