Analysis of Pipe Breaks in Urban Water Distribution Network

Mofid Gorji-Bandpy and Majid Shateri

Abstract— *The goal of this paper is to present a descriptive analysis of the water pipe breakage data to predict the evolution of the annual number of pipe breaks and the application of the modeling strategy to the cities. To make a general diagnosis, one must collect and analyses data on the characteristics of water pipes and on their breakage histories. Since many city water authorities have only a few breakage histories, a modeling strategy, inspired by Survival analysis and using the annual number of water pipe breaks as an indicator of the structural state of a network, was applied to three cities in Mazandaran province, north of Iran, characterized by their brief recorded pipe break histories. The results show that the annual pipe breaks increase, but the rate of increasing of the annual pipe breaks can be reduced by replacement of the old pipes.*

Keywords— **Pipe break, Weibull distribution, Survival function, Deterioration.**

1. INTRODUCTION

Nowadays, managing the city water infrastructure systems often means managing critical situations, when unhappy consumers report water leaking in the streets due to a water pipe break and flooding of their houses due to a sewer overflow or even the collapse of the street pavement due to foundation washout.

Tools are needed to assess the present and future structural state of water pipes from readily obtainable data. A mathematical model can help water authorities in the diagnosis and planning of repair, rehabilitation, and replacement of water pipes. To model the overall structural state of water pipes, it is necessary to choose an indicator of their structural state. The average annual number of pipe breaks on a water pipe networks is the most commonly used indication. The number of pipe breaks is the most readily available data correlated to the structural state.

In this paper, a pipe breaks is defined as a failure resulting in water leaking to the surface, thus necessitating an immediate intervention on the network. Of course, water leaking from a failed pipe may reach the surface days after the initial break or it might not even reach the surface if, for example, sewer infiltration is possible in the vicinity. The main difficulty in developing mathematical models for this type of problem is the lack of data on both the water pipe network and the pipe breakage history. For a thorough analysis of pipe breakage, information must be known on the physical and environmental characteristics that have an impact on pipe failure. Most city water authorities have little information on their water pipes, such as pipe diameter, pipe material, and date of installation, but few have been maintaining thorough records of pipe breaks for longer than a decade.

A survey of water authorities in the province of Mazandaran in the north of Iran has helped us to identify a few cities that maintain pipe break records. We present here the results obtained in three cities, Behshahr, Sari and Ramsar. Of these three cities Sari has the longest pipe break history available in a usable format.

The main purpose of this paper is to apply an operational pipe break model to estimate present and future structural states of water pipe networks, and verify the performance in the above three mentioned urban waters networks. The modeling strategy is designed to require minimal data and take into account the fact that the number of previous break is a key factor. The model is designed to answer a global but important practical question: What is the replacement effort a city has to make in order to limit the number of annual pipe breaks over a given period? The development of a model dealing with the average annual number of pipe breaks is the first step in the diagnosis of the overall structural state of a network. By incorporating all of the data in a database for model development, one can obtain specific information on all pipe segments. It is necessary to identify the factors that are important in the degradation of water pipes and at the development of methods to help urban water managers in assessing the structural state of their water networks. Using elaborate sets of data, when coupled with an economic assessment model, will ultimately serve as a powerful decision making tool for water managers [1-4].

Research efforts on water pipe degradation generally fall in the following categories; physical analysis, descriptive analysis, and predictive analysis.

Physical analysis consists of evaluating of the scope and severity of corrosion on the internal and external pipe walls, and the estimation of resulting stresses from the loads applied to the water pipe [5-10]. Descriptive analysis consists of calculating descriptive statistics to provide insight on breakage patterns and trends. This kind of analysis can only be performed in the cities that have comprehensive databases on the characteristics of the pipe and on the pipe breaks. Due to the lack of data

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in the urban water breakage, there are very few case studies in Iran. This type of analysis is limited by the challenges faced for constructing databases and as a matter of fact, building such databases has been a concern for many researchers [11-13].

Predictive analysis is done by modeling past pipe breakage behavior in order to project it in the future. Different types of modeling strategies have been developed to evaluate the structural state of water pipe networks [14-16].

There are three main types of models namely:

1) Aggregate models, which are exponential or linear models of the number of breaks versus the age of pipes [17].
2) Regression models, which considers factors that influence the degradation of pipe [18,19], and;
3) Probabilistic models, of which survival analysis is the most widely used approach.

Survival analysis has been used successfully to predict pipe breakage behavior by many researchers in the past two decades, and most frequently used in the biomedical fields, to water pipe failure problems [20,21]. This kind of analysis is a statistical technique that deals with time to failure data, and incorporate the fact that, while some pipes breaks, other do not, and this information has a strong impact on the analysis.

Many researchers have shown that the breakage pattern strongly depends on the number of previous breaks that pipes have experienced [22]. As a matter of fact, the number of previous breaks is often reported as the most important factor for predicting future breaks. Survival analysis is particularly useful in this field when pipe break records have been maintained for a good portion of the water pipe network history. This kind of analysis cannot, however, be used in this study because the recorded pipe histories in our case studies are not long enough to provide adequate information on the pipe breakage behavior. To our knowledge, we have found a few studies that addressed the problem of brief recorded pipe breakage history [23,24]. A methodology is used in the present study to estimate parameter values of the water pipe breaks model. The method on a statistical basis is the relative performance of a Weibull distribution compared to an exponential distribution for a given break order.

2. GENERAL CHARATERISTICS OF THREE CITIES

Table 1 presented some general characteristics for the three cities. Water pipe loosely follows street patterns in the cities, so pipe segments are usually defined from one street corner to the next. The average length of a pipe segment is highly variable and depends mainly on the discretization of the water pipe network adopted by the city.

In terms of break history, Sari has the longest recorded pipe break history and the highest ratio of pipe breaks per 100 km, while Behshahr has the lowest recorded pipe break history. Based on the reported ratios of pipe breaks per 100 km and the perception of water managers on the global state of their water pipe networks, ratios of 40 breaks per 100 km and up are considered high and indicate a network in poor condition.

Table 1. Some characteristics of Three Cities

Characteristics		**Cities**		
		Behshahr	Sari	Ramsar
Approximate population		73696	205146	34038
Pipe network length (km)		185.82	485.06	139.4
Ratio of pipe length (m) per habitant		2.52	2.36	4.10
Percentage of water losses	2000	38.8%	40.7%	34.1%
	2001	23.6%	32.3%	29.3%
Year of installation of first pipes		1956	1952	1954
Number of years of recorded pipe breaks		5	7	6
Number of pipe breaks per 100 km in 2002		393	424	292

Table 2. Percent of breakage in different years

Name of cities	**Year**	**Percentage of breakage**	
		Network	**Branch**
Behshahr	2000	36	64
	2001	19	81
	2002	36	64
Sari	2000	23	77
	2001	22	78
	2002	24	76
Ramsar	2000	36	64
	2001	39	61
	2002	31	69

Networks with ratios between 20 and 39 are considered in acceptable condition, while the ratios less than 20 indicate that the network is in good condition [25]. Overall, this represents well the perception of the three water manager's interviewed in this study. Table2 presents the percentage of breakage in the year 2000, 2001 and 2002. We can see that the percentages of breakage in branch are higher than in network. In terms of the tendency in the annual number of pipe breaks for the duration of the recorded history, there is a strong increase in the annual number of pipe breaks with time in all three urban water cities. These will be presented along with the modeling results.

Because of degradation of networks we have an increase in annual number of pipe breaks with time in all cities. Information gathered on all pipe segments are as follows:

1) Pipe diameter	4) Year of installation
2) Pipe length	5) Type of soil; and
3) Pipe type of material	6) Land use above the pipe

3. DESCRIPTIVE STATISTICS

Basic descriptive statistics are presented to give insight on the impact of different risk factors on the structural deterioration of water pipes. Statistics on pipe diameter, installation period, and pipe material are presented herein. These are calculated based on the total pipe length in 2001, and with only the pipe breaks that could be associated with a single pipe segment. Statistics on breakage rates are estimated by taking the ratio of the number of breaks on pipes in a given category and the total pipe length in that category in 2001. This gives an indication of the breakage behavior in a given category.

Fig.1 presents the length of pipes versus different pipe materials for three cities. The asbestos pipes are widely used in these cities, while steel pipes are used in one city and much less than asbestos pipes.

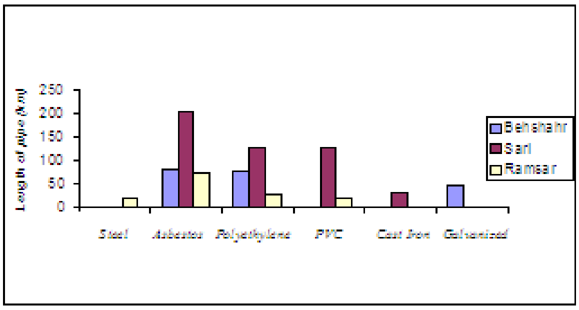

Fig.1. Pipe length versus different materials for three municipalities in 2001

Fig.2 presents the breakage percentage in both network (NT) and branch (EN). Breakage percentages are higher for branches.

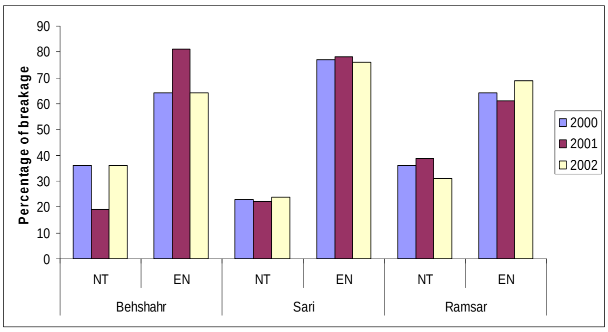

Fig.2 . Percentage of pipe breakage for three cities in three successive years

Fig.3 presents the number of pipe breaks versus different pipe diameters for just asbestos pipes. The most number of pipe breaks is related to smaller diameters. It is because of their thinner pipe walls and smaller moment of inertia [8,10].

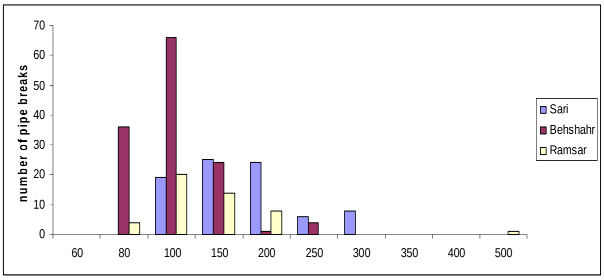

Fig.3 . Number of pipe breaks versus different pipe diameters for just asbestos pipes

Sari can be considered as having the "oldest" water pipe network, which has been developing the least rapidly in recent years, where as Behshahr can be considered as having the "youngest" water pipe network, which has been developing the most rapidly in recent years.

Fig.4 presents the breakage rates of pipes in 1996 to 2002. There is an increase in breakage rate for the above mentioned cities, which is the expected behavior for a deterioration process.

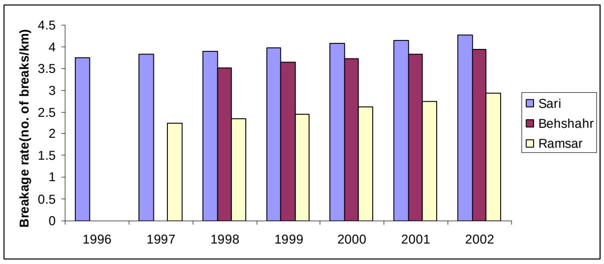

Fig.4 . The breakage rates of pipes in 7 successive years

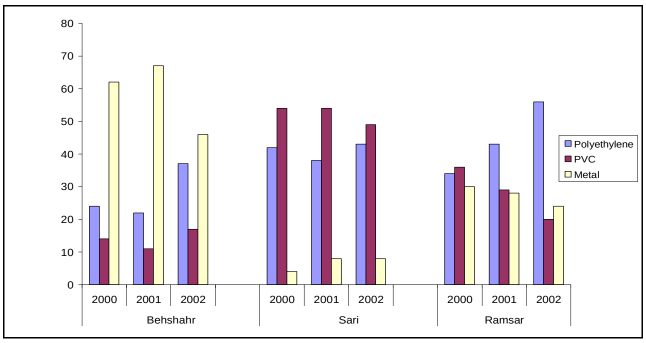

Fig.5 . Percentage of pipe breaks for the three types of materials in 2000, 2001 and 2002

Fig.5 presents the percentage of pipe breaks for the three types of materials in 2000, 2001 and 2002. It is obvious that polyethylene and PVC has the most percentage of pipe breaks in Ramsar and Sari while metal and polyethylene has the most percentage of pipe breaks in Behshahr.

Table 3. Causes of breakage in percent

City	Year	Causes of breakage											
		Vertical Impact on pipe		Pipe Corrosion		Pipe material with poor quality		Different Institution*		High pressure		Unknown	
		EN	NT	EN	NT	EN	NT	EN	NT	EN	NT	EN	NT
Behshahr	2000	6.8	5.1	41	52	33.5	26	3.3	4	1.4	4.5	14	8.4
	2001	7	3.7	36	56	18	18.5	3	7.5	9	3	27	11.3
	2002	7.5	4.3	34	64	15.5	13	4.5	7.8	12	4	26.5	6.9
Sari	2000	37	36	7.5	5.4	30.5	26.6	13.	18	3	3.2	9	10.8
	2001	37	37	3	7.5	22.5	30.5	10.5	13	19	3	8	9
	2002	34	35	6	7	26	32	9	12	14	4	11	10
Ramsar	2000	6.7	7.5	21.4	23.5	11.5	4.3	17.5	19	39	41	3.9	4.7
	2001	7.4	10.5	22.5	22.5	12.4	3	16.5	21	38	40	3.2	3
	2002	6.3	11.3	21.2	21.5	14.9	2.9	17.3	20.4	37.5	41.2	2.8	2.7

* Careless drilling operations done by different institutions such as gas and oil, etc. companies

Table 3 represents the causes of breakage in three cities in the year 2000, 2001 and 2002.

4. MATHEMATICAL MODEL FOR WATER PIPE BREAKS

As mentioned previously, the goal of modeling is to predict adequately the annual number of pipe breaks in the future in order to apply more effective strategy to reduce the rate of breakage. The modeling strategy must take into account the installation of new pipes, the impact of pipe replacement, and the fact that the pipe segments exhibit a different pipe breakage behavior, depending on their break history.

The time step chosen for modeling is one year, which was commanded by the time scale of pipe degradation and the uncertainty on the date of occurrence of breaks compared to their date of recording. The occurrence of a first break will likely result in other breaks in the vicinity, and that breakage behavior strongly depends on break order. To distinguish between the different orders of breaks, one must identify the time to failure between the installation and the first break, between the first and second break, and so on. This is called data stratification in survival analysis [26]. Times to failure can be modeled by different distributions, depending on the breakage behavior associated with that break order. Since records of pipe breaks rarely exist for the entire history of the networks, the real order of pipe breaks is often unknown for all pipe segments laid before the year when pipe breaks started to be rigorously recorded. This makes the use of textbook survival analysis impractical. In this study the modeling strategy uses two distributions to model the different break orders:

1- Weibull distribution

2- Exponential distribution.

The first one is associated with the first break order (time to failure from installation to first break), while the second distribution is used to describe the behavior of subsequent breaks (time to failure from first to second break, second to third, and so forth). This model is referred to as the Weibull/exponential model.

The Weibull distribution is defined by two distinct parameters, β and $\frac{1}{\eta}$. The exponential distribution is a special case of the Weibull distribution when $\beta = 1$, with only one parameter, β_2. Then the three statistical functions can be used to represent a given distribution and can be defined as, the hazard function, the survival function and probability density function. The hazard function $\lambda(t)$ corresponds to the instantaneous probability of having a break between t and $t + \Delta t$ conditional to survival up to time t. The hazard function is defined, for the Weibull and exponential distribution, respectively, as [26];

$$\lambda(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} \tag{1}$$

$$\lambda(t) = \beta_2 \tag{2}$$

For the Weibull distribution, the shape of hazard function depends on parameter β and is monotonously increasing for β>1, decreasing for β<1, and independent of time when β=1 (exponential distribution).

Considering the Weibull/exponential model, the average number of breaks, $n(T_1,T_2)$ on a given pipe segment during the time interval (T_1,T_2) can be computed as follows [27]:

$$n(T_1,T_2)=[F(T_1)-F(T_2)]+\beta_2\{T_2[1-F(T_2)]-T_1[1-F(T_1)]-\int_{T_1}^{T_2} dtt.f(t)\} \quad (3)$$

where $F(T_i)$ the survival function is associated with the Weibull distribution at time T_i and $f(t)$ is the probability density function associated with the Weibull distribution and are as follows;

$$F(T_i)=e^{-(\frac{T_i}{\eta})^{\beta}} \quad (4)$$

$$f(t)=\frac{\beta}{\eta}(\frac{t}{\eta})^{\beta-1}e^{-(\frac{t}{\eta})^{\beta}} \quad (5)$$

The reference time=0 corresponds to the year of installation of the pipe. The development of Eq.3 can be found in Ref.27. It has been shown by Mailhot et al. [23] that complex models other than three simple modeling strategies do not necessarily yield more exact results. Exponential distribution was used to describe the time to failure between first and second, the second and third, etc. breaks and between breaks up to 20^{th} order [20] and a unique parameter value for cities where it is impossible to estimate different parameter values for different break orders with some degree of certainty. So, we used an average parameter value representative of the overall aging process associated with subsequent breaks. This modeling strategy cannot take into account the variability in the annual number of pipe breaks due to factors other than deterioration resulting from the natural aging of pipes. Severe winters, flooding, soil properties, water chemistry and traffic disturbances can cause higher breakage rates in a given year.

5. RESULTS AND DISCUSSION

The obtained calibration parameters are presented in Table 4 for the three cities. Pipe segments in Behshahr are at the highest risk for subsequent failures, as indicated by its value for β_2. After that Ramsar and then Sari have lower risk but not much.

As we can see the parameter β of Weibull distribution is larger than 1 for all groups of pipes. Survival functions associated with the Weibull distribution (time to failure from installation to first break) are shown in Fig.6 for Sari, Ramsar and Behshahr. The value of the survival function gives the proportion of pipes that have not failed at time t. Therefore, the higher the curve, the longer it takes for the first break to occur. At time=0 (year of installation) none of pipe segments have failed. As time increases the risk of first breaks increases because of degradation.

Table 4. Calibration Parameters for Weibull-Exponential distribution for Sari, Behshahr and Ramsar

Parameters	Sari	Behshahr	Ramsar
β	2.559	2.271	2.088
$\frac{1}{\eta}$	0.020	0.023	0.021
β_2	0.021	0.023	0.022

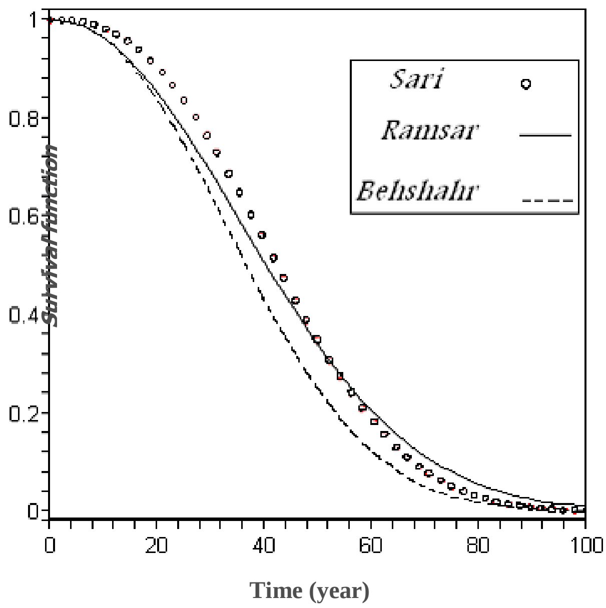

Fig.6 . Survival function associated with the first break for three cities

The following input data are required for each pipe segment to run the model; the pipe segment number, the year of installation, number of recorded breaks, year of first recorded break, year when recording began, and year of analysis.

Figs.7-9 present the observed average number of breaks and those estimated by the model in each city. In all cases, the sets of parameters obtained using the calibration strategy have permitted the adequate reproduction of the overall tendency of pipe breakage, especially considering that the pipe break histories used for calibration were quite brief. As have previously mentioned the risk of failure associated with the exponential distribution is independent of time. These values and β_2 are presented in Table 4.

6. CONCLUSION

In this paper a descriptive analysis of the water pipe breakage was presented to predict the evolution of the annual number of pipe breaks and the application of the modeling strategy to the cities. To make a general diagnosis, it is necessary to collect the data on the characteristics of water pipes and the breakage histories. A simple three parameter model, based on the estimation of the probability of break occurrence depending on the break order (first and subsequent breaks), for three cities that have recorded their break repairs for a relatively short period compared to the history of their networks, was successfully used to reproduce average tendencies and predict tends in the annual number of pipe breaks in those cities. In ten years, the cities of Behshahr, Sari and Ramsar would see their annual pipe breaks increase by 10.81 %, 6.9% and 47.4 %, respectively. But the rate of increasing annual pipe breaks can be reduced by replacement of old pipes.

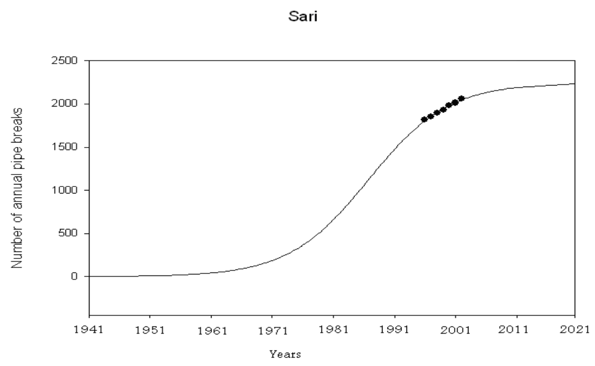

Fig.7 . Observed and simulated annual pipe breaks in Sari

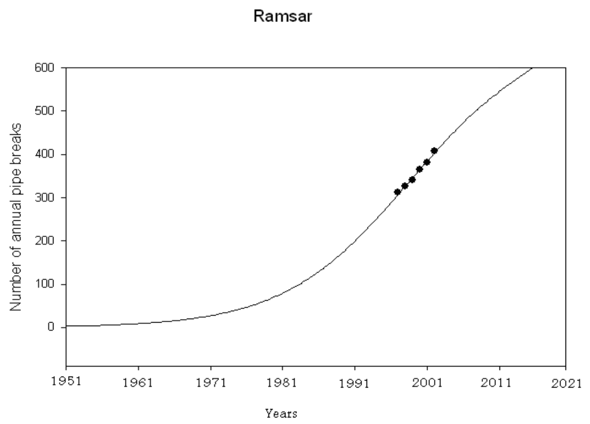

Fig.8. Observed and simulated annual pipe breaks in Ramsar

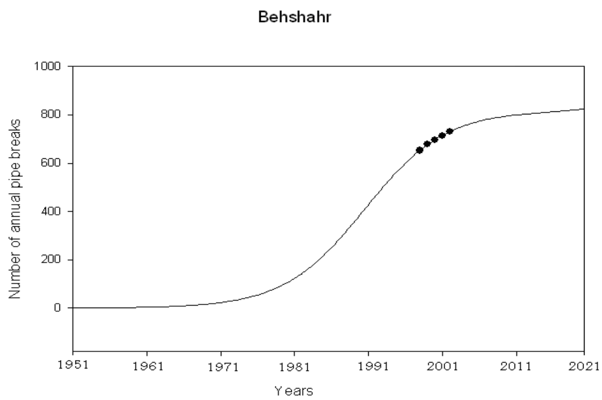

Fig.9. Observed and simulated annual pipe breaks in Behshahr

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NOMENCLATURE

β	Parameter of Weibull distribution
$\frac{1}{\eta}$	Parameter of Weibull or exponential distribution
$\lambda(t)$	Hazard function
$F(t)$	Survival function
$f(t)$	Probability density function
$n(T_1, T_2)$	Average number of pipe breaks on a given pipe segment during interval $[T_1, T_2]$.

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