Identifying Potential Pipe Failures: Toronto Case Study

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The issue of aging water infrastructure is a widely acknowledged concern in Canada. Moreover, with C\$72 billion tied up in water and wastewater infrastructure in Ontario alone, it is a significant problem that is intensifying with time.

In this context, pipebreak failures are a key source of contaminant incursion into the drinking water supply system. Water, once it has entered the distribution system, is beyond the last point of treatment (with the exception of the incidence of chlorine booster stations), so if there is a loss of chlorine residual, any biological contaminant(s) may cause health impacts for the consumer. Those responsible for providing water to consumers have significant concerns with any failures in the water distribution network.

Since portions of Canada's water distribution networks may be reaching the end of their useful life, the need exists for a reliable method to identify the pipes most susceptible to failure, as part of proactive decision-making leading to planning for repair, replacement, and rehabilitation for municipalities (e.g. Cullinane et al, 1987; Lei and Saegrov, 1998; Male et al, 1990; Shamsi, 2006). In this context, the chapter describes a model formulation based on assessment of statistics of pipe breakage to provide dimensions of the decision-making procedure in terms of probabilities of future pipe breakage. Application of the model is demonstrated herein through analyses of the pipe break database from the Greater Toronto Area

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(GTA). While general in structure, the model is developed specifically from incidents of failure, as recorded, to then provide the probabilities of future breakage over alternative timeframes.

Underground pipes have carried drinking water in the GTA for human needs for more than a century. The distribution network components are primarily out of sight, but failures do occur. For example, approximately 32% and 36% of pipes in the Scarborough and Etobicoke databases, respectively, have broken at least once. Dimensions of failure from pipe/valve/connection include loss of water from the distribution systems, and may include ingress of contaminated water into the distribution systems. For example, 13% of municipal piped water is lost in distribution system leaks and this value is as high as 30% in some communities (Environment Canada, 2004). The consequences of failure may be extremely serious and include contamination of drinking water (e.g. LeChevallier et al., 2003), creation of traffic hazards, and business and social disruption, and imposition of significant repair costs. Therefore, it is highly desirable for water infrastructure engineers and managers to have numerous capabilities to monitor, to assess the condition of, and to predict the failure potential for, water distribution pipes.

Gaining an understanding of the condition of the water distribution system, and the potential for failure of elements of the system, is complicated by the wide array of underground water pipes in use today. Pipe materials used include concrete, asbestos cement, cast iron, ductile iron, steel and PVC, each with their own properties and characteristics that influence longevity of service of the individual pipes. Additionally, two pipes of the same material will perform differently according to such features including their respective diameters, quality of water flowing through them, soil type, operational conditions, traffic patterns, and installation and construction practices.

Improved understanding of the issues associated with pipe breakage requires knowledge and data related to the processes that lead to pipe corrosion and deterioration, climatic effects on pipe networks, and the development of scientific and innovative approaches for monitoring and maintenance, such as cathodic protection of pipes and in-situ lining for repair. Factors affecting pipe integrity include pipe material, soil characteristics, climatic conditions, operational pressures, age, diameter, and construction and maintenance practices. With improved characterization of the role of these processes in quantifying pipe breakage potential, researchers and water infrastructure engineers can develop improved multi-dimensional techniques to aid informed decision-making processes from a

risk management perspective. Many studies have been undertaken to date to examine factors affecting pipe integrity (e.g. Goulter et al., 1993; Rajani and Kleiner, 2001; Kleiner and Rajani, 2001).

The research described herein utilizes the data from the GTA to quantify statistics related to causative variables influencing pipe breakage potential, from which failure probabilities within alternative time horizons for the future can be predicted. The results of these analyses are then applied to develop pipe breakage probabilities under alternative scenarios in the GTA for pre-planning and co-ordinating pipe replacement with other infrastructure repair projects (e.g. road widening, repaving) that have been scheduled.

22.1 Methodology

22.1.1 Mathematical Model Formulation

Consider the probability of pipebreaks, $P(\cdot)$, as:

$$P(N / k < T < k + 10, A) = \frac{\# \text{ of pipebreaks}}{\text{Total \# of pipes } (A)}$$

where:

- T = time of the break,
- K = number of years and hence bounding T by decades,
- N = the number of pipebreaks ($N = 1, 2, \dots$), and
- A = category of pipe type.

$$P\left(\frac{\sum_k^{k+10} N}{A}\right) = \frac{\# \text{ of pipebreaks } (A) \text{ for a given 10 year period}}{\text{total \# of pipes } (A)} \quad (22.1)$$

where k = a year chosen for the lower boundary of the decade being analysed (e.g. 1960, 1970)

Specifically, the pipebreak database is used to compile statistics indicating the pipebreak frequency within specific timeframes (decades) and for pipes within a particular category. Therefore, for example, $N = 1, 2, \dots$ the no. of breaks, and A = pipe material (i.e. asbestos cement (AC), cast iron (CI),

ductile iron (DI), polyvinyl chloride (PVC), etc.), and k = start year for period of analysis (as decades).

From the available database, the statistics of breakage failures can be derived, by categorizing the assembled data. The simple model that is structured in Equation 22.1 above, involves a series of assumptions, including:

1. the length of pipe doesn't change the probability of an individual pipe breaking;
2. the diameter of the pipe doesn't influence the probability of a pipe breaking;
3. only pipes placed after 1960 are considered so that pipe wall thickness variations can be ignored; and
4. the soil type does not influence breakage potential.

Given pipe material, the age of pipe is the determining factor explaining the statistics of pipe breakage. This establishes a very basic pipe break probability model with pipe age, prior break frequency, pipe type and soil conditions as explanatory factors for probability of future breakage frequency. By establishing this base level, analyses can be improved through the relaxation of other assumptions stated above, to establish a more robust model and examine the influence of different factors on pipe break probabilities.

22.1.2 Database

Statistical analyses for this research were undertaken on inventory and pipe break databases provided by the Water Infrastructure Management group with the City of Toronto. The inventory database consists of address, year placed in ground, pipe material, pipe length, pipe diameter and soil type. The pipe break database was categorized to select only those pipes which were placed since 1960, thus restricting the pipebreak analyses to timeframes over which there was relative constancy in pipewall thickness. The dates for first and second breaks were extracted from this categorized database. Age at the time of break was calculated by subtracting the year placed in the ground from the year in which the pipe broke for Scarborough and Etobicoke. Probabilities were calculated by relaxing the above assumptions, using frequency data for pipe material, pipe diameter, soil type, and age of pipe. The data were analysed for both first break and second break, and a combination of ages at time of first and second break. Probabilities were standardized by calculating probabilities as a ratio of the

number in a category that broke, divided by the total number in that category from the inventory database.

22.2 Results and Discussions

The following results demonstrate the probabilities of pipes breaking in response to different factors, and a combination of all factors for both first and second breaks. The results are listed separately for Scarborough and Etobicoke to enable a comparison of results. The pipe inventory for each region is quite similar and by utilizing both in the analysis, it strengthens the value of the statistical relationships discussed in the chapter.

The Scarborough database consists of 3161 pipes in the inventory. Of these, 2696 pipes (85%) were laid in silt/clay and 465 (15%) in sand/gravel. The Etobicoke database consists of 2162 pipes in the inventory. Of these, 1635 pipes (76%) were laid in silt/clay and 527 (24%) in sand/gravel. Ductile iron pipes account for 49% of the inventory in Scarborough and 52% in Etobicoke. Cast iron pipes are the next most prevalent, with 22% in Scarborough and 24% in Etobicoke. Further, approximately 40% of pipes in both municipalities are 150 mm diameter. Almost 40% of pipes in Scarborough and 60% of pipes in Etobicoke were built in the decade 1960-69; Scarborough had another 38% built in the decade 1970-79. (See Tables 22.1. and 22.2 for more detail.). It should be noted that less than 1% of pipes in Etobicoke and up to 26% in Scarborough have cathodic protection.

Table 22.1 Selected general characteristics of pipes in the Scarborough database.

Pipe material	Diameter	Sand/Gravel	Silt/Clay
AC	150	18	55
	200	10	30
	300	22	65
CI	150	65	415
	200	37	144
	300	13	124
DI	150	83	571
	200	55	545
	300	52	340
PVC	150	32	91
	200	26	75
	300	26	89

Table 22.2 Selected general characteristics of pipes in the Etobicoke database.

Pipe material	Diameter	Sand/Gravel	Silt/Clay
AC	150	0	0
	200	1	1
	300	2	5
CI	150	59	196
	200	26	87
	300	42	93
DI	150	114	316
	200	45	136
	300	99	214
PVC	150	14	59
	200	20	76
	300	30	53

Applying the basic model, it can be seen from Tables 22.3 to 22.6, that the older the pipe, the greater the probability of failure. Cast iron pipes are more likely to fail than asbestos concrete, ductile iron or PVC for the first time in both regions. According to Doyle et al. (2003), cast iron pipes are more likely to fail than other material types mainly because they are highly susceptible to external corrosion. As an example, the results in Table 22.3 indicate that, for a CI pipe, in Scarborough, there is a 0.20 probability that a pipe, which has not broken previously, will break in the next 10 y. Consider now the question of road development: if a pipe which will be covered by the development of a new road is already 20 y old, then there is a probability of 0.50 that the pipe will break in the next 10 y. For a ductile iron pipe, this probability is only 0.25. From a planning perspective, it might be worthwhile replacing the cast iron pipe at the same time as the road development, rather than having to dig up portions of the road to repair the pipe in a few years time. Using the same example for pipes in Etobicoke (Table 22.5), there is a probability of 0.24 that a pipe, which has not broken previously, will break in the next 10 y. The probability that a pipe, which is already 20 y old, will break in the next 10 y is 0.59. If the CI pipe has already broken once in the first 5 y and is 20 y old, the probability of it breaking in the next 10 y is 0.11 for Scarborough (Table 22.4) and 0.13 for Etobicoke (Table 22.6). If the pipe broke in the first 10 y, the probability increases to 0.20 of breakage occurring in the next 5 y (Table 22.4) for Scarborough and 0.28 for Etobicoke (Table 22.6).

Table 22.3 Probability of first pipe break by pipe material and decade after placement, Scarborough

Pipe Material	Probability of first break in the next:			
	10 y	20 y	30 y	40 y
AC	0.05	0.10	0.15	0.18
CI	0.20	0.38	0.50	0.59
DI	0.06	0.20	0.25	0.26
PVC	0.01	0.01	0.01	0.01

Table 22.4 Probability of second pipe break by pipe material and decade after placement, Scarborough.

Pipe Material	Given first break in first 5 y, probability of second break in the next:				
	5 y	10 y	15 y	25 y	25 y+
CI	0.04	0.07	0.10	0.11	0.13
DI	0.02	0.03	0.04	0.04	0.04
	Given first break in first 10 y, probability of second break in the next:				
		5 y	10 y	15 y	20 y+
CI		0.10	0.17	0.20	0.26
DI		0.12	0.16	0.17	0.18
	Given first break in first 15 y, probability of second break in the next:				
			5 y	10 y	15 +
CI			0.15	0.23	0.33
DI			0.20	0.24	0.26

Table 22.5 Probability of first pipe break by pipe material and decade after placement, Etobicoke

Pipe Material	Probability of first break in the next:			
	10 y	20 y	30 y	40 y
AC	0.06	0.22	0.28	0.33
CI	0.24	0.42	0.59	0.67
DI	0.08	0.18	0.28	0.32
PVC	0.03	0.04	0.06	0.06

Table 22.6 Probability of second pipe break by pipe material and decade after placement, Etobicoke

Pipe Material	Given first break in first 5 y, probability of second break in the next:			
	5 y	10 y	15 y	20 y+
CI	0.05	0.08	0.11	0.13
DI	0.03	0.06	0.08	0.09
	Given first break in first 10 y, probability of 2nd break in the next:			
		5 y	10 y	15 y+
CI		0.10	0.18	0.28
DI		0.10	0.18	0.24
	Given first break in first 15 y, probability of 2nd break in the next:			
			5 y	10 y+
CI			0.14	0.33
DI			0.14	0.27

The basic model does not rely upon all the factors involved in pipe breaks. Relaxing some of the assumptions provides a more robust examination of pipe breaks for planning purposes. Tables 22.7 to 22.10 demonstrate the probabilities of failure given pipe material, pipe diameter and soil type. Probabilities are greatest for the first failure in smaller diameter pipes (Tables 22.7 and 22.8). They are also larger for CI pipes in these smaller diameters. Soil conditions of silt/clay, as opposed to sand/gravel, increase the risk of pipe breakage, particularly at smaller diameters. It is to be noted that these data have been normalized to account for other factors, such as the larger number of cast iron pipes laid in the ground over asbestos concrete, ductile iron and PVC. The results are further constrained to pipes laid after 1960, so CI pipes in the analysis are not older than other pipe material types.

If a pipe has failed once, it is highly likely that it will fail again. Tables 22.9 and 22.10 summarize the probabilities for a second failure at various diameters, pipe materials and soil types. The calculations for these tables are based on the second break, regardless of how long after the first it occurred and what age the pipes were. Soil material is a less important factor in second breaks than first breaks for smaller diameter pipes and becomes more important for larger diameter pipes. Again, the difference in probabilities between cast iron and ductile iron pipe materials decreases for second breaks.

Table 22.7 Selected probabilities for first pipe failure by soil and material, Scarborough.

Pipe Diameter	150 mm		200 mm		250 mm		300 mm	
Soil Material	Sand/Gravel	Silt / Clay	Sand/Gravel	Silt / Clay	Sand/Gravel	Silt / Clay	Sand/Gravel	Silt / Clay
CI	0.62	0.73	0.54	0.61	--	0.00	0.23	0.37
DI	0.22	0.39	0.09	0.24	0.00	0.50	0.15	0.19
PVC	0.00	0.02	0.00	0.00	--	--	0.00	0.03

Table 22.8 Selected probabilities for first pipe failure by soil and material, Etobicoke.

Pipe Diam	150 mm		200 mm		250 mm		300 mm		350 mm	
Soil Mat	Sand/Gravel	Silt / Clay	Sand/Gravel	Silt / Clay	Sand/Gravel	Silt / Clay	Sand/Gravel	Silt / Clay	Sand/Gravel	Silt / Clay
CI	0.75	0.86	0.65	0.78	0.60	0.56	0.38	0.38	0.50	0.25
DI	0.38	0.46	0.40	0.36	0.10	0.40	0.16	0.21	0.67	0.24
PVC	0.00	0.02	0.05	0.04	--	0.00	0.17	0.09	--	--

Table 22.9 Selected probabilities for second pipe failure by soil and material, Scarborough

Pipe Diameter	150 mm		200 mm		250 mm		300 mm	
Soil Material	Sand/Gravel	Silt / Clay	Sand/Gravel	Silt / Clay	Sand/Gravel	Silt / Clay	Sand/Gravel	Silt / Clay
CI	0.75	0.74	0.80	0.73	--	--	0.67	0.67
DI	0.83	0.79	1.00	0.69	--	0.67	0.63	0.63

Table 22.10 Selected probabilities for second pipe failure by soil and material, Etobicoke

Pipe Diam	150 mm		200 mm		250 mm		300 mm		350 mm	
Soil Mat.	Sand/Gravel	Silt / Clay	Sand/Gravel	Silt / Clay	Sand/Gravel	Silt / Clay	Sand/Gravel	Silt / Clay	Sand/Gravel	Silt / Clay
CI	0.73	0.71	0.76	0.78	1.00	0.67	0.44	0.29	1.00	0.00
DI	0.65	0.74	0.67	0.73	1.00	0.62	0.50	0.39	0.75	0.35

* Extremely high probabilities are an artifact of low numbers of occurrence

The length of pipe is the distance between ‘tees’ for each pipe section. It does not appear to have a significant impact on the likelihood of failure, for either first or second pipe breaks (Tables 22.11 and 22.12). For the Scarborough dataset, 32% of all pipes broke once and 73% of these broke a second time. Similarly, in Etobicoke, 36% of pipes broke once and 64% of those broke a second time. Pipes less than 100 m in length are least likely to break the first time and pipes between 400-500 m in length are marginally more likely to break second time around (data for pipe lengths over 1000 m are inflated as a result of very low numbers).

Table 22.11 Probability that a pipe will experience a first and second break given the length of the pipe, Scarborough

Length of pipe	Probability of a 1st break	Probability of a 2nd break
0-100 m	0.19	0.70
101-200 m	0.39	0.73
201-300 m	0.44	0.73
301-400 m	0.46	0.68
401-500 m	0.39	0.88
501-1000 m	0.46	0.74
>1500 m	0.50	1.00

Table 22.12 Probability that a pipe will experience a first and second break given the length of the pipe, Etobicoke

Length of pipe	Probability of a 1st break	Probability of a 2nd break
0-100 m	0.20	0.48
101-200 m	0.46	0.64
201-300 m	0.55	0.76
301-400 m	0.64	0.75
401-500 m	0.59	0.77
501-1000 m	0.47	0.71
>1000 m	0.50	1.00

In general, the earlier the pipes were placed in the ground, the greater the probability of them breaking a first time at a younger age (Tables 22.13 and 22.14). This is demonstrated by higher probabilities for pipes breaking in the 1960s and 1970s up to 15 y old for both Scarborough and Etobicoke. This is likely to be the result of changes in placement practices and pipe manufacturing.

Table 22.13 Probability that a pipe will experience an initial failure within a 5-y period, given the decade that the pipe was placed in the ground, Scarborough.

Decade pipe laid	Age of pipe at first break (y)								
	1-5	6-10	11-15	16-20	21-25	26-30	31-35	36-40	41-45
1960-1969	0.06	0.10	0.12	0.09	0.07	0.03	0.05	0.03	0.01
1970-1979	0.01	0.05	0.06	0.04	0.03	0.02			
1980-1989	0.00	0.01	0.01	0.01	0.01				

Table 22.14 Probability that a pipe will experience an initial failure within a 5-y period, given the decade that the pipe was placed in the ground, Etobicoke.

Decade pipe laid	Age of pipe at first break (y)							
	1-5	6-10	11-15	16-20	21-25	26-30	31-35	36-40
1960-1969	0.07	0.09	0.08	0.06	0.06	0.06	0.05	0.02
1970-1979	0.02	0.05	0.03	0.03	0.05	0.03		
1980-1989	0.02	0.02	0.02	0.01				
1990-1999	0.00	0.03						

For a second break (Tables 22.15 and 22.16), the probabilities vary depending on the time period in which the second break occurs. Older pipes are more likely to break in both Scarborough and Etobicoke, with the exception of pipes that break between 11 and 20 y (Scarborough) and 11 and 15 y (Etobicoke). Pipes breaking in these time periods are more likely to be pipes placed in the decade 1970-1979. Specifically, pipes placed in Scarborough between 1970 and 1979 have a 0.25 probability of breaking a second time between 11 and 15 y after placement. Pipes breaking during the same time period, but placed in the decade 1960 to 1969, have a 0.14 probability (Table 22.15).

The final model demonstrates the effect of pipe material, pipe diameter, and soil type on the probability that a pipe will break in any subsequent 10-year period after being placed in the ground. Tables 22.17 to 22.20

demonstrate the model for Scarborough using cast iron and ductile iron pipes for first and second breaks. For example, from Table 22.17, a decision-maker can determine that if a 150 mm cast iron pipe is 10 y old and placed in silt/clay, it has a 0.52 probability of failure in the next 10 y. That same pipe placed in sand/gravel has a 0.47 probability of failure and if it was a 300 mm pipe, the probability of failure drops to 0.24. If the pipe has already broken once, the probability for a second failure in the next 10 y is 0.41. This information enables an informed decision when deciding on pipe replacement in conjunction with other infrastructure projects in the same location, allowing economies of scale to be maximised.

Table 22.15 Probability that a pipe will experience a second failure within a 5-y period, given the decade that the pipe was placed in the ground, Scarborough.

Decade pipe laid	Age of pipe at second break (y)								
	1-5	6-10	11-15	16-20	21-25	26-30	31-35	36-40	41-45
1960-1969	0.03	0.07	0.14	0.18	0.11	0.10	0.05	0.05	0.02
1970-1979	0.01	0.10	0.25	0.17	0.08	0.05	0.01		
1980-1989	0.00	0.12	--	0.18	0.12				

Table 22.16 Probability that a pipe will experience a second failure within a 5-y period, given the decade that the pipe was placed in the ground, Etobicoke.

Decade pipe laid	Age of pipe at second break (y)								
	1-5	6-10	11-15	16-20	21-25	26-30	31-35	36-40	41-45
1960-1969	0.04	0.08	0.09	0.12	0.11	0.09	0.09	0.05	0.02
1970-1979	0.00	0.05	0.12	0.08	0.09	0.13	0.00	0.00	0.00
1980-1989	0.04	0.04	0.04	0.00	0.00	0.00	0.00	0.00	0.00

Table 22.17 Probability of First Break of Cast Iron pipes after construction in specified duration of time for the City of Scarborough.

Diameter	150 mm		200 mm		300 mm	
Soil Type Pipe break in:	Sand / Gravel	Silt / Clay	Sand / Gravel	Silt / Clay	Sand / Gravel	Silt / Clay
next 10 y	0.26	0.30	0.16	0.21	0.14	0.13
next 20 y	0.47	0.52	0.38	0.41	0.21	0.24
next 30 y	0.55	0.63	0.46	0.53	0.29	0.33
next 40 y	0.59	0.71	0.51	0.61	0.29	0.37

Table 22.18 Probability of Second Break of Cast Iron pipes after construction in specified duration of time for the City of Scarborough.

Diameter	150 mm		200 mm		300 mm	
Soil Type Pipe break in:	Sand / Gravel	Silt / Clay	Sand / Gravel	Silt / Clay	Sand / Gravel	Silt / Clay
next 10 y	0.12	0.16	0.05	0.09	--	0.11
next 20 y	0.56	0.41	0.30	0.35	0.75	0.37
next 30 y	0.61	0.60	0.55	0.63	0.75	0.57
next 40 y	0.63	0.71	0.80	0.73	0.75	0.67

Table 22.19 Probability of First Break of Ductile Iron pipes after construction in specified duration of time for the City of Scarborough

Diameter	150 mm		200 mm		300 mm	
Soil Type Pipe break in:	Sand / Gravel	Silt / Clay	Sand / Gravel	Silt / Clay	Sand / Gravel	Silt / Clay
next 10 y	0.12	0.12	0.07	0.06	0.06	0.03
next 20 y	0.19	0.33	0.09	0.20	0.13	0.13
next 30 y	0.23	0.38	0.09	0.23	0.15	0.18
next 40 y	0.24	0.39	0.09	0.24	0.15	0.18

Table 22.20 Probability of Second Break of Ductile Iron pipes after construction in specified duration of time for the City of Scarborough

Diameter	150 mm		200 mm		300 mm	
Soil Type Pipe break in:	Sand / Gravel	Silt / Clay	Sand / Gravel	Silt / Clay	Sand / Gravel	Silt / Clay
next 10 y	0.33	0.15	0.80	0.06	0.25	0.08
next 20 y	0.67	0.62	1.00	0.58	0.38	0.34
next 30 y	0.76	0.76	1.00	0.65	0.63	0.59
next 40 y	0.81	0.79	1.00	0.69	0.63	0.63

22.3 Conclusions

The model, as developed based on quantified breakage frequency, provides useful input to decision-making for indicating likelihood of failure of individual pipes, given the type of pipe, soil material and age in the ground. Only pipes placed since 1960 have been included in the analyses.

Generally, silt and clay soils demonstrate the greatest likelihood of first failure for both Scarborough and Etobicoke, especially for smaller diameter pipes. This could be the result of the increased potential for corrosion in these soils, although resistivity measurements are not available. Alternatively, the cause could be the result of poorer pipe-bedding foundations. Factors such as poor drainage and low electrical resistivity contribute towards this increase in corrosion capabilities. Furthermore, silt and clay soils are more likely to heave, during extreme freeze thaw cycles as experienced in southern Ontario winters.

The findings of the research demonstrate that first failure is more likely in cast iron pipes, as opposed to other pipe types. Once a pipe has failed, it is highly likely to fail a second time. Pipe material and soil type play a smaller role in second failures than in first breaks. Additional observations include: the older a pipe, the greater the probability of it failing; and, maximum failure rates will vary according to pipe material, diameter and soil type, even for pipes of the same age.

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