WATER PIPELINE FAILURES IN THE ACTIVE ZONE

C. Vipulanandan[1], W. Qiao[2] and H. Hovsepian[3]
[1]Professor and Director of Center for Innovative Grouting Materials and Technology (CIGMAT), and Director of Texas Hurricane Center for Innovative Technology, Department of Civil and Environmental Engineering, University of Houston, Houston, Texas 77204-4003; cvipulanandan@uh.edu
[2]Graduate Student, Center for Innovative Grouting Materials and Technology (CIGMAT), Department of Civil and Environmental Engineering, University of Houston, Houston, Texas 77204-4003;
[3] Assistant Director, Public Works and Engineering, City of Houston, Houston, Texas 77002.

Abstract:

It is becoming a challenge to maintain nearly one million miles of drinking water pipelines in the U.S with an asset value of a few trillion dollars. The ASCE Infrastructure Report rates the water infrastructure to be D^- and hence there is need to investigate the conditions of the water pipelines. Based on our recent survey, most of the small diameter water pipelines in the major cities are placed within the top 1.5 m depth below ground surface. Hence the water pipelines that are buried in the active zone will experience notable changes in the soil moisture content over the year. In the active zone, soils would be affected by the environmental conditions.

In this study, national survey results are presented and analyzed to determine the trends in the water pipeline failures. Based on literature review and experience, potential modes of failures for the small diameter water pipelines have been identified. A national survey was conducted by the Center for Innovative Grouting Materials and Technology (CIGMAT) at the University of Houston in collaboration with the City of Houston to document conditions of small diameter (less than 20 inches in diameter) water pipelines in North America. Several major cities and few smaller cities in North America participated in the CIGMAT survey representing a population of 11 million and water pipeline length of over 28,000 miles. In the survey conducted by the U.S. Conference of Mayors (USCM) has shown that 20 cities are reporting over 500 water pipeline breaks per year, and the CIGMAT survey showed that this could be much higher in some cities. A few case studies on water pipeline failures in the active zone in the City of Houston, Texas have been discussed.

Introduction

Most of the water mains installed during the first half of twentieth century were made of cast iron (CI) (DI pipe was first introduced in 1955) and currently have an average age of 50 to 75 years. Asbestos-cement (AC) pipes are also old pipes, which were introduced in the 1930s and are not used presently. The relatively new polyvinyl chloride (PVC) pipes, first introduction in North American in 1951, are widely used today and are considered to have less break rate than pipes made of CI, DI and AC. PVC pipes have high resistance to deterioration and corrosion, can be used in very corrosive environments, but they are likely to be affected by deterioration if they are exposed to weather (UV light), chemical attack or mechanical degradation from improper installation methods (Rajani et al. 2001; Blaga 1973).

There are approximately 200,000 public water systems in the United States. The community water systems, estimated to be 30% of the public water systems, serves primarily residential areas and 90% of the United States population. These water distribution systems are approximately 863,000 miles (1,380,800 km) long with an annual rate of new installations estimated at 11,900 miles (19,040 km) and annual replacement rate estimated at 4,100 miles (6,560 km) (based on extrapolation from American Water Work Association data) (AWWA 1999).

Objectives

The overall objective of this study was to investigate the trends in the small diameter water pipeline failures in the active zone. The specific objectives are as follows:

1. Review the trends observed in water pipeline failures based on national surveys.
2. Document case studies of water pipeline failures in the active zone.

Survey Analyses

(a) CIGMAT Survey

Closely working with the City of Houston, Texas a national survey was undertaken with selected cities. The survey was done during the years 2008 and 2009. The survey represented over 11 million population and 28,000 miles of water pipelines. The survey indicated that 80 to 99% of the water pipelines were 20-inch or less in diameter and were placed within the 1.5 m (5 ft.) depth. The survey also indicated that maximum breaks varied from 0.3 to 12 per day in the cities surveyed.

(b) U.S. Conference of Mayors (USCM) Report

This report provided information on the status of water systems in America's major cities based on a survey conducted in 2007. In Table 1, the size of the cities

Table 1 Summary of Survey Participants

Range of Populations Served	USCM Survey	
	No. of Cities	Percentage
3,000-50,000	77	26
50,000-100,000	112	38
100,000-200,000	46	15
200,000-500,000	37	12
500,000-1.0 mill	19	6
>1.0 mill	5	2

are based on population that participated in the survey is summarized. A questionnaire was sent to 1200 cities and the response received was about the water system was 293, 27.5% response and represented a population of over 50 million. It is of interest to note that over 60% of the cities that responded had the population less than 100,000, and 5 cities had the population of over one million each.. In the USCM study, 48 cities had water pipelines greater than 1000 miles and another 48 cities had pipelines between 500 to 1000 miles Hence this survey covered cities with wide variation of water pipelines (Table 2).

Table 2. Length of Drinking Water Distribution Systems

Miles of Pipes	**USCM Survey**	
(MILES)	**No. of Cities**	**Percentage**
< 100	**17**	**6**
101-200	**57**	**19**
201-300	**60**	**21**
301-500	**63**	**22**
501-1000	**48**	**16**
>1000	**48**	**16**

In the USCM study, 20 cities have reported over 500 breaks per year. The water pipeline breaks could be due to age, type of pipes, internal pressure fluctuations, externals soil conditions, active zone variations and construction/maintenance practices. Since most of the water pipelines are placed in the active zone, the changes in weather will also have a significant influence on the pipe breaks. The data also showed that there was no direct correlation between the pipe length and the number of breaks per year. It is of interest to note that majority of the cities (55%) had 50 or less breaks per year.

Table 3. Summary of Water Main Breaks

Number of breaks per year	**USCM Survey**	
	No. of Cities	**Percentage**
1-25	**101**	**36**
26-50	**54**	**19**
51-100	**47**	**17**

101-200	**42**	**15**
201-300	**7**	**3**
301-500	**11**	**4**
>500	**20**	**7**

In the City of Houston, with a population of 2.2 million and 7,500 miles of water pipelines, dominant type of failure was circumferential cracking as compared to corrosion or chemical attack in the USCM survey (Table 4). It is of interest to note that in the USCM survey, the joint failures were not included, where as in the City of Houston it was about 20%. As mentioned before, the water pipeline failure is caused by number of factors, especially the type of failure must taken into account the local conditions.

Table 4. Leading Causes of Failures in Drinking Water Pipes

Leading Cause of Deterioration	**USCM Survey**	**City of Houston(Current Study)**
Corrosion	**36**	**20**
Chemical Attack	**1**	
General Wear and Tear	**63**	**55 (Circumferential and Longitudinal cracking)**
Joints	**0**	**25**

(c) Water Pipeline Failures

(i) Failure Causes

Several factors have to be considered into pipeline failure mechanisms because underground water pipelines are affected by the physical, environmental and operational conditions as well as quality of manufacturing and installation. Those influence factors include:

(1) Pipe characteristics such as age, materials and diameter;

(2) External and internal loads exerted by the soil pressure, traffic loading, frost loads, operation pressure and third party interference;

(3) Temperature (external and internal);

(4) Corrosion (external and internal): Considered a major issue with the metallic pipes. Factors accelerating external corrosion in metallic pipes are stray electrical currents, soil characteristics such as moisture content, chemical and microbiological content, electrical resistivity, aeration and redox potential. The internal corrosion is affected by the supply water through its chemical

properties, such as pH, dissolved oxygen, free chlorine residual, and alkalinity, as well as temperature and microbiological activity. However, concrete corrosion is directly attributed to the presence of inorganic or organic acids, alkalis or sulfates in the soil (Rajani et al. (2001)).

(5) Chemical and mechanical degradation, oxidation and biodegradation of plasticizers and solvents for PVC or other polymer pipes are not well studied in the literature because these mechanisms are typically slower than in metallic pipes and also because PVC pipes have been used commercially only in the last 35-40 years.

(ii) Failure Criteria

Based on the literature review and experience, water pipeline failures can be broadly classify into 3 categories (Table 5). The failure attributed to corrosion and environment, the failure due to excessive stresses and the failure at the joints. Many times the failure occurs as a combination of different types. Corrosion of the pipe can occur both from inside and from the outside of the pipe. Corrosion is an electrochemical process that results in gradual atonement of the metal or degradation of the polymer and hence the loss of strength of the pipe wall. The pitting failure corresponds to the type where there is localized external corrosion that leads to formation of small 'pitting holes'. Graphitization relates to process where the metal constituents of the pipe degrade, eventually leaving only a carbon shell, which is not as strong as the original pipe hence making the pipe wall vulnerable to bursts. Unsaturated bonds in the polymers can be vulnerable to degradation by chemicals in the soils and dechlorination compounds in the water.

Corrosive soils are generally classified as with low pH, low resistivity and significant presence of sulfate reducing bacteria. Other secondary reasons leading to external corrosion are the stray currents that the pipe conducts from the ground, hydrogen embrittlement resulting from unintended or misapplication of cathodic protection. The failure due to external corrosion has been extensively studied by Seica et al. (2004) and Doyle et al. (2001). The nature of internal corrosion depends of the aggressive water properties and its chemical composition and its interaction with the internal pipe wall. Other type of failure is attributed to excessive hoop or axial stresses resulting from the Ambient temperature differences, transient conditions leading to 'water hammer' effects, freeze-thaw or moisture changing effects due to changing seasons, ground movement/settlements or expansions periodically. The failure at the joints results as a combination of different stresses, ground movement and/or corrosion conditions.

(d) Pipe Length (L)

It has been reported in the literature that length is a factor to the breaks (Rajani 2001). Total length of pipelines in the system for each city is shown in Figure 8, and the pipe length varied from 500 to 7500 miles. The variation of daily breaks with pipe length for various cities is shown in Figure 9. The nonlinear relationship (Model 4) was as follows:

$$PB = 0.295e^{0.0005L} \quad (L \leq 7500 \text{ miles}) \tag{1}$$

where PB= Average No. of Breaks per Day

L = Total Length of Pipelines in Each City (mi) (≤7500 miles)

The coefficient of correlation (R) was 0.77, which was the highest among the parameters investigated. The total length of pipelines included in this study was over 28,000 miles.

Table 5. Types of Failures (Vipulanandan et al. 2008)

Failure type	**Modes of Failure**	**Causes of failure**	**References**
Type I Corrosion and environment	Pitting Holes	Corrosive soils(low pH, resistivity), microbiological influence, stray currents, external stress corrosion	Doyle, Seica and Grabinsky et al; Rajani.B, Zhan.C, Kuraoka.S
	Graphitization	Corrosive soils, hydrogen embrittlement, stray currents, anaerobic bacteria	Garry Doyle, Michael Seica et al, Jeffrey Packer, Grabinsky, Hamilton et al
	secondary effects	hydrogen embrittlement, chlorides from the water, sulfates from the soil, coating damage, dissimilar soils with different concentrations, stress corrosion and ground movement.	Romer et al, Seica et al, Grabinsky et al, Szeliga et al.
Type II Stress failure	Longitudinal break/split	Ambient temperature differences, transient conditions, Freeze Thaw effects	Rajani et al, Manfredi et al, Seica et al.
	Tensile break	Circumferential stress, Thermal stresses, Transient conditions, mechanical stresses, soil swelling or settlements	Seica et al, Manfredi et al, Rajani et al.
Type III Joint failure	Brittle failure (cracking)	graphitization, hydrogen embrittlement, dissimilar metals at joints, coating damage	Packer et al, Hamilton et al, Andrew E. Romer, Hardie et al
	connection failure	Defects in welding material, thermal stresses, fatigue weakening, Galvanic reaction at dissimilar metal/plastic joints, plastic pipe connections	Zhou et al, Rajani, Zhan et al, Marshall Parker
	Joint burst	Transient conditions, soil swelling or settlements, differential thermal expansion/contraction.	Seica et al, Rajani et al

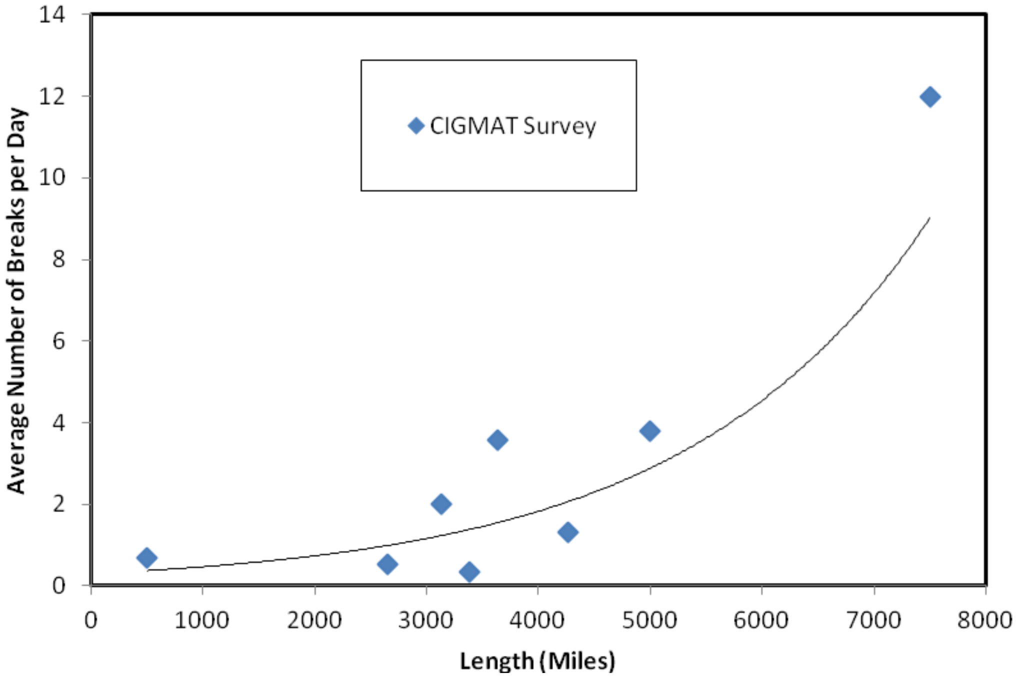

Figure 1. Correlation between Pipe Length and Average No. of Breaks per Day

(e) <u>Case Study</u>

It was critical to visit field sites where water pipeline failures were reported during the period of 2007 September to 2009 August. The City of Houston coordinated the efforts with the field crew to accommodate the UH research team in the field. The field study was focused on collecting information about the type of water pipeline failures, method of repairs and also collecting soil samples and failed pipes for limited laboratory study. The data on the soils at the locations of water pipeline failures was used to determine any trends in the water pipeline.

Over 100 field sites were visited over a period of two years. Based on our field study, the most common failure was circumferential cracks (Type 2 failure) which were usually observed in 6” and 8” diameter A.C. and cast iron pipes. These pipes were placed at depth range of 2 feet to 6 feet below ground. The age of the failed pipes were in the range of 12 to 70 years. Nearly 55% of the failures were due to circumference cracking. Circumferential cracks could be partial or total around the circumference. Those cracks usually observed in CI and AC pipes. The cracks are due to combination of corrosion, ground movement and thermal effects. With age, CI and AC pipes were weakened by corrosion. They could easily fail when they subjected to the bending forces and thermal forces. In this study 59% and 41% of the failures were in CL and CH soils. Active zone in the City of Houston varied from near surface to 3 m (10 ft.).

Case 1: Circumferential Cracking in AC Pipe

About 47% of the failures were observed in the AC pipes. Typical AC pipe failure is shown in Fig. 1, where a 29 year old 8 in diameter AC pipe has circumferential crack. The pipe was located at a depth of 4 ft below the ground in clayey soils in the active zone.

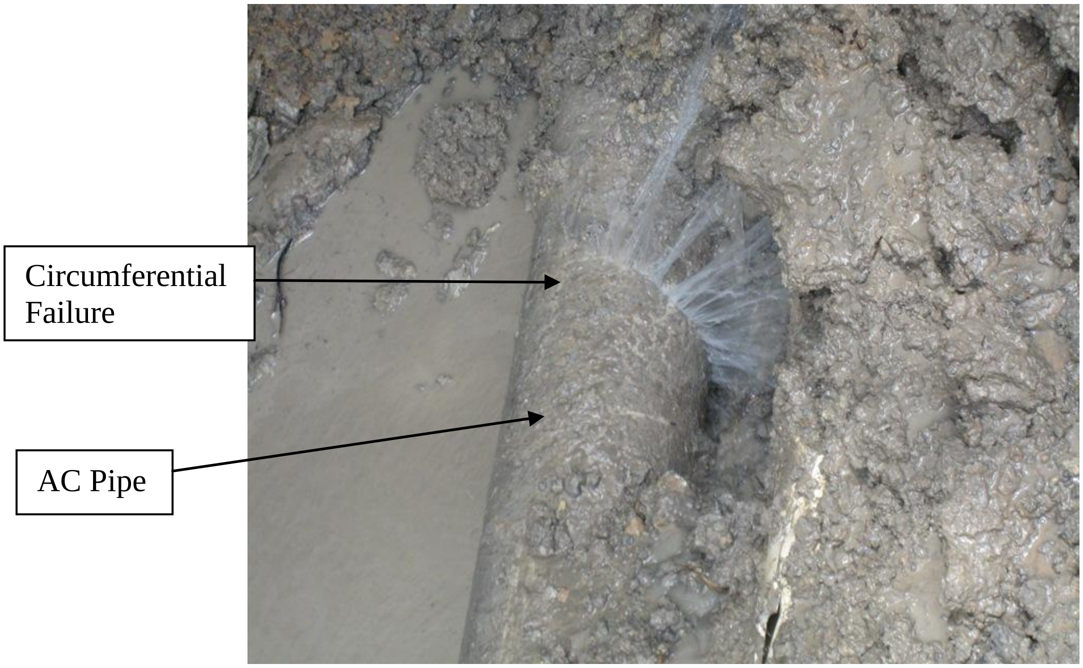

Figure 1. Circumferential Crack in 8” diameter AC Pipe

Case 2: Circumferential Cracking in CI Pipe

About 37% of the failures were observed in the CI pipes. Typical CI pipe failure is shown in Fig. 2, where a 8 in diameter CI pipe has failed by circumferential cracking (Type 2 failure). The pipe was located at a depth of 4 ft below the ground in clayey soils in the active zone.

Case 3: Longitudinal Cracking in CI Pipe

About 37% of the failures were observed in the CI pipes. Another type of CI pipe failure is shown in Fig. 3, where a 2 in diameter CI pipe has failed by longitudinal cracking (Type 2 failure). The pipe was over 40 years old. The pipe was located at a depth of 1 ft below the ground in CL clayey soils in the active zone. The longitudinal cracking might be due to the internal water pressure, active zone changes in temperature and age.

Figure 2. Circumferential Crack for 8" CI Pipe

Figure 3. Longitudinal Crack 2" CI Pipe (325 W. 27th Street)

Conclusions

Based on national surveys and field studies on the performance of small diameter (< 20-inch) over a period of two years, following can be concluded:

(1) Water pipeline breaks are a major issue for small and large cities. There are no models to predict the water pipeline breaks in active zone.

(2) Aging CI, DI and AC pipes are of major concern related to pipe breakage. Limited information is available on the performance of plastic pipes.

(3) Water pipeline failures, based on the influencing factors, can be broadly grouped into three categories: (1) Type I – Corrosion and Environment; (2) Type II – Stress Induced and (3) Type III- Joint Related. In general, the failures in water pipelines are due to more than one factor.

(4) Based on the city size (population and pile length), USMC survey findings may not be directly applicable to the City of Houston. Current survey (CIGMAT/UH survey) will better represent the large city conditions.

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