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Water Main Breaks - High Time to Learn from Mistakes and Avoid Further Breaks

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ABSTRACT

Water main failures are very expensive for municipalities because they typically result in expenses associated with repair costs, flood damage, and loss of revenue to affected businesses. Water main failures also interrupt the operation of vital services, such as medical care and fire-fighting operations. Currently, millions of dollars are spent annually by the water utility industry and by municipalities on the repair of failed components of the water distribution infrastructure, such as components that are made from gray cast iron or “gray iron” pipe and ductile cast iron or “ductile iron” pipe. The rate of municipal water main failures is expected to increase as the existing cast iron infrastructure continues to age. The cost of repairing damages caused by broken water mains (and subsequent flooding damage) may become an important item in many municipal budgets. It is important to develop a corrosion program to prevent catastrophic failures of water mains. This paper presents a plan consisting of several phases including preassessment, indirect assessment, direct assessment, and integrity assessment of failed water mains. We will elaborate on the failure mechanisms, failure analysis protocols, and corrosion mitigation strategies for water mains that experience breaks. Water main breaks are mainly due to corrosive soil, pipe material, galvanic action, stray current corrosion, or microbiological induced corrosion (MIC). This paper provides an overview of corrosion issues commonly experienced by water main pipes, presents specific case histories involving graphitic corrosion, galvanic corrosion, stray current corrosion, and MIC. In this paper, we will introduce a graphitization sensor for condition assessment of water mains. This sensor can identify the location and extent of graphitization on water main.

Keywords: Water Main Break, Ductile Iron Pipe, Backfill, Polyethylene (PE) Encasement, Corrosion, Graphitic Corrosion, Galvanic Corrosion, Stray Current Corrosion, Microbiological Induced Corrosion (MIC).

INTRODUCTION

Ductile iron (DI) pipe manufacturers claim a service life more than 100 years. Research indicates that an average service life of water main pipeline is around 50 years. However, we worked on several water main projects where water main pipeline has failed in 20 – 30 years; well below what most manufacturers claim.

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The cost of repairing damages caused by broken water mains (and subsequent flooding damage) may become an important item in many municipal budgets. According to a study by AWWA ⁽¹⁾ conducted in 2012, the United States must invest more than \$1 trillion in underground water infrastructure work for over 25 years. The amount could go beyond \$1.7 trillion over the next 40 years. Avoiding or hampering the investment could result in catastrophe both in terms of water main breaks and the cost associated. This would especially apply to pipe installed without an increased investment in condition assessment, pipe monitoring and adequate corrosion control measures.

Prior to failure, water main pipe appears sound, so failures are not often recognized as corrosion but are usually referred to merely as “water main breaks”. Some of the causes of water main breaks are poor design, improper installation, surge or water hammer, soil movement, manufacturing defects, impact, internal corrosion, and external corrosion. This paper focuses on the external corrosion of the water main. Figure 1 shows some of the possible causes of the cast iron pipe.

Graphitic corrosion is the most common cause of water main break. In water industry, graphitic corrosion and graphitization are interchangeably used. However, they are different forms of corrosion. Graphitic corrosion—deterioration of cast iron wherein the metallic constituents are selectively leached or converted to corrosion products, leaving the graphitic particles intact. Graphitization¹—the formation of graphite in iron or steel, usually from decomposition of iron carbide at elevated temperatures. “When in Rome, do as the Romans do”. So, keeping water utility in mind, both graphitic corrosion and graphitization are considered as same in this paper.

CASE HISTORY 1: GRAPHITIZATION OF CAST IRON WATER MAIN

INTRODUCTION

A 36 inch (91.44 cm) diameter cast iron (CI) water main failed catastrophically. Water from the leak covered many blocks. The CI pipe was reported to be approximately 90 years old.

FIELD TESTING

Visual Examination

The broken sections of the pipe are shown in Figure 2. Visual examination indicated that the initial failure of the pipe had resulted in a large window section having broken out. This would result in a large volume of water escaping from the pipe every second. The window section was measured to be 36 inches (91.44 cm) long and 18 inches (45.72 cm) wide.

Conditions within the trench is shown in the Figure 3. After visual examination of the failed water main in the trench, soil samples were collected from several locations within the trench and near the pipe for laboratory analysis. Testing was also performed to look for the presence of stray currents.

Stray Current Corrosion Determination by Potential Measurements

One of the factors that could contribute to the external corrosion of the water main pipes is the presence of stray currents in the soil. Soil is a conductive ionic electrolyte. Stray currents can enter a water main pipe at one location (pick-up area) and leave (discharge area) at another location along the pipe. Stray currents can cause severe corrosion of water main pipes at the point of current discharge.

The corrosion caused by stray current is more serious than soil corrosion under normal conditions. Potential measurements are one of the test methods used to identify the presence of stray currents. Pipe-to-soil potential measurements showed -449 mV CSE (Copper Sulfate Electrode) which is in the native potential range. There was no evidence of more electropositive or more electronegative potential readings which indicates the absence of stray current pick-up and discharge areas.

On-Site Soil Resistivity Measurements

The test method followed for on-site soil resistivity is ASTM ⁽²⁾ G57.² Field measurements involved the use of four equally spaced metallic pins driven into the ground. The instrument supplied a current to the soil through two outer pin electrodes and the voltage difference was read between the two inner pin electrodes. A set of 2, 4, 6, 8, and 10-foot pin spacing measurements were taken. The data is shown in Table 1. Soil resistivity measurements revealed that soil around the pipeline is corrosive as per Table 2.

Table 1
Soil Resistivity (ohm-cm) and Barnes Layer Analysis from Field Measurements

Location	A at failed location, along pipe	B close to failed location, 3 feet from pipe	C 10 feet from failed location, 3 feet from pipe	D 10 feet from failed location, 3 feet from pipe	E 50 feet from failed location, 3 feet from pipe	F 100 feet from failed location, 3 feet from pipe
Pin Spacing	Soil Resistivity Results from Field Testing (ohm-cm)					
2 feet	460	3830	3256	7660	53,623	16,853
4 feet	245	4903	3600	3677	44,431	19,917
6 feet	115	3792	2873	125,248	25,279	14,938
8 feet		1992	1272	735	19,917	8426
10 feet		1341	1417	1341	12,257	3064
Layer Depth	Soil Layers Resistivity (ohm-cm) by Barnes Layer Calculation					
0 – 2 feet	460	3830	3256	7660	53,623	16,853
2 – 4 feet	167	6809	4027	2419	37,929	24,343
4 – 6 feet	56	2609	2046	1923	13,576	9959
6 – 8 feet		822	476	185	12,172	3651
8 – 10 feet		581	2614	585	4828	864

Table 2
Classification of Soil Corrosivity Based on Resistivity³

Resistivity Range (ohm-cm)	Corrosivity
0 - 1000	Very severe
1,001 – 2,000	Severe
2,001 – 5,000	Moderate
5,001 – 10,000	Mild
>10,000	Very mild

LABORATORY INVESTIGATION

Soil Analysis

Five soil samples were collected from the excavation trench near the failed pipe. Each soil sample was tested for: soil resistivity in the as received condition and again in the moisture saturated condition; moisture content in the as received condition; pH; sulfate content; sulfide content; chloride content; and redox potential. A linear polarization resistance (LPR) corrosion rate measurement was also performed for each sample versus a ferrous steel electrode. Soil test specifications are shown in Table 3 and laboratory soil analysis results are shown in Table 4.

The soils in immediate contact with the top and bottom surfaces of the pipe were found to be very corrosive due to their low pH, low soil resistivity values, and moderately high chloride contents.

Table 3
Soil Test Specifications

Test	Specification
Soil Resistivity	ASTM G57
Moisture Content	ASTM D2216
pH	ASTM G51
Sulfates	ASTM C1580, AASHTO T290
Sulfides	Colorimetric
Chlorides	ASTM D512, AASHTO T291
Redox Potential	ASTM G200
LPR Corrosion Rate	ASTM G102

Table 4
Laboratory Soil Analysis Results

Test	Soil Sample No. 1	Soil Sample No. 2	Soil Sample No. 3	Soil Sample No. 4	Soil Sample No. 5
Location of Sample	top of pipe	3 feet from North side of pipe, 4 feet from surface	3 feet from North side of pipe, from surface	bottom, in contact with pipe	3 feet from South side of pipe, 6 feet from surface
Soil Resistivity (ohm-cm) As Received	1738	246	1488	1730	2356
Moisture Content (wt%) As Received	14	27	20	18	18
Saturated Soil Resistivity (ohm-cm)	1098	98	1415	1496	2270
pH	5.99	7.06	7.8	3.32	7.13
Sulfates (ppm)	740	773	61	290	118
Sulfides (mg/l)	0.06	0.57	0.10	0.05	<0.04
Chlorides (ppm)	94.10	78.47	185.00	160.00	31.20
Redox Potential (mV)	556.8	719.3	667.4	578.6	560.4
LPR Corrosion Rate (mpy)	6.34	>40.00	3.19	10.62	5.57

SEM/EDS Analysis of Soil Samples

The elemental composition of sample no. 2 with the lowest resistivity of the five soil samples was determined using a scanning electron microscope (SEM) equipped with an energy dispersive x-ray fluorescence spectrometer (EDS). The visual appearance of soil sample no. 2 is shown in Figure 4. The material within soil sample no 2 appeared to be black in color and hard in texture. The EDS spectrum shown in Figure 5 indicates it is most likely a slag with a high carbon content.

X-Ray Diffraction Analysis of Soil Samples

Portions of each soil sample were dried and pulverized to a fine dust consistency. Each soil sample was then subject to a powder x-ray diffraction analysis to determine the mineral compounds present. The results are given in the Table 5.

Table 5
X-Ray Diffraction Results for Soil Samples

Compound	Formula	Sample No. 1	Sample No. 2	Sample No. 3	Sample No. 4	Sample No. 5
Silica	SiO ₂	73.9	34.7	61.6	63.0	68.7
Muscovite	KAl ₂ (AlSi ₃ O ₁₀)(F,OH) ₂	13.3	4.1	11.4	19.5	22.0
Kaolinite	Al ₂ Si ₂ O ₅ (OH) ₄	3.6	1.7	3.4	6.1	2.0
Microcline	KAlSi ₃ O ₈	3.4	-----	2.3	1.3	1.6
Albite	NaAlSi ₃ O ₈	3.0	-----	-----	2.7	3.6
Clinocllore	(Mg ₅ Al)(AlSi ₃)O ₁₀ (OH) ₈	1.8	-----	2.7	6.1	1.9
Hematite	Fe ₂ O ₃	0.7	-----	2.5	1.3	0.2
Calcite	CaCO ₃	0.3	-----	4.6	-----	-----
Mullite	Al ₆ Si ₂ O ₁₃	-----	49.0	9.3	-----	-----
Magnetite	Fe ₃ O ₄	-----	6.3	2.2	-----	-----
Gehlenite	Ca ₂ Al(AlSiO ₇)	-----	4.2	-----	-----	-----
Goethite	FeO(OH)	-----	-----	-----	-----	-----
Akaganeite	FeO(OH,Cl)	-----	-----	-----	-----	-----
Schreibersite	Fe ₃ P	-----	-----	-----	-----	-----
Siderite	FeCO ₃	-----	-----	-----	-----	-----

Silica is a component of some rocks and also occurs as sand. The minerals muscovite, microcline, albite, clinocllore and gehleneite are rock forming minerals from backfill material. Kaolinite is a clay mineral. Mullite is a ceramic mineral in the backfill. Hematite, magnetite, goethite, akaganeite and siderite are corrosion products of iron. Schreibersite, (iron phosphide) is a constituent of the cast iron pipe.

Microbiological Testing of Soil

The five soil samples were tested for five types of microbiological bacteria that may be present and could contribute to corrosion of the pipe. The five types of bacteria analyzed for are shown in the Table 6. Commercially available MIC kit was used for the microbiological analysis. All five soil samples tested positive for each of the five types of bacteria. Iron oxidizing bacteria are harmful because they metabolize iron and therefore can directly attack the pipe. Sulfate reducing bacteria are harmful because their metabolic waste products are highly acidic and can cause acid attack of the iron.

Table 6
Microbiological Analysis Test Results

Bacteria Type	Positive/Negative
Low Nutrient Bacteria	Positive
Iron Related Bacteria	Positive
Anaerobic Bacteria	Positive
Acid Producing Bacteria	Positive
Sulfate Reducing Bacteria	Positive

Laboratory Visual Examination of Failed Pipe

Along one of the fractured edges of the window and the cross-section extracted from the pipe, the depth of corrosion can be seen as shown in Figure 6. The pipe wall thickness in the non-corroded areas was measured to be 1-1/4 inches (3.175 cm). Partial corrosion was also observed to have occurred at the inside diameter (ID) surface of the pipe underneath the cement lining as shown in these photographs. The minimum remaining non-corroded wall thickness for these cross sections was measured to be 1/4 inch (0.635 cm).

Chemical Analysis of Pipe

A quantitative chemical analysis was performed on the failed cast iron pipe and the results are given in the Table 7. For comparison, the modern chemical requirements of ASTM⁽³⁾ A74⁴ "Standard Specification for Cast Iron Soil Pipe and Fittings" is also given in the table below.

Table 7
Chemical Analysis (wt%)

Element	Failed Pipe	ASTM A74
Total Carbon	3.61	
Graphitic Carbon	1.87	
Manganese	0.28	-----
Phosphorus	0.48	0.38 Maximum
Sulfur	0.12	0.15 Maximum
Silicon	1.22	-----
Chromium	0.25	0.50 Maximum
Nickel	0.10	-----
Molybdenum	0.013	-----
Aluminum	0.004	0.50 Maximum
Titanium	0.061	0.10 Maximum
Lead	0.018	0.015 Maximum
Copper	0.22	-----
Carbon Equivalent	4.177	4.10 Minimum

Metallographic Examination

Transverse cross sections through the cast iron pipe were prepared for subsequent metallographic examination. The graphitic corrosion of the outside diameter surface of the pipe is shown in Figure 7. In graphitic corrosion, localized galvanic corrosion cells form between the graphite flakes and the iron matrix

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