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Ductile Iron Wastewater Force Mains Failure Analysis and Service Life Estimation

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ABSTRACT

Unexpected failures of mortar-lined ductile iron force mains have occurred at unspecified high points due to internal corrosion aggravated by microbiological activity. To avoid unexpected failures in the future, a mechanistic understanding of the microbiologically influenced corrosion and degradation and their rates leading to failure is required. In this work, a detailed failure analysis was performed to uncover the mechanisms and typical rates of internal corrosion at unknown high points in mortar-lined ductile iron pipes (MLDIP). A literature review was conducted to identify existing mechanistic models that could be used in this application to estimate the time to failure considering the composition of wastewater, flow rate, and the size of the air-pocket to be used as a benchmark for future improvement. Laboratory experiments were performed to provide an estimate of the deterioration rates of mortar and corrosion rates of the ductile iron upon exposure to sulfuric acid. The combined results of the failure analysis, literature review, and experimental work were then used to develop degradation curves to estimate the time to failure of MLDIP. This work provides the Hillsborough County Public Utilities Department a much-needed tool that could guide future design and repair or replacement works at wastewater conveyance and treatment facilities that can also be leveraged by other organizations.

Key words: microbiologically influenced corrosion, mortar-lined ductile iron, force mains, service life estimation, failure analysis.

INTRODUCTION

Ductile iron pipes have been employed in water and wastewater transport systems for more than four decades. In such applications, the pipe material is usually lined internally with cement or mortar, epoxy, or bituminous paints to protect it from corrosive agents in the flowing fluid. However, in sewage force mains, unexpected corrosion of mortar-lined ductile iron (MLDI) force mains have occurred at certain points.¹ Failures from internal corrosion have been attributed to the effect of hydrogen sulfide released intermittently during turbulent flows from the sewage and intensified by the actions of microbial agents present in slimes at the crown of the sewer pipes.^{2,3} To explain the degradation steps and formulate predictive models, a mechanistic understanding of microbial induced deterioration of the mortar layer as well as the corrosion mechanism and rates of the ductile iron are required.

In the past, models have been proposed to predict service life for utilities assets of concrete and metal-based materials where microbiologically influenced corrosion (MIC) is a major problem. For instance, Jiang et al, identified the prominent roles that certain environmental factors like concentration of hydrogen sulfide, relative humidity, and temperature in sewer environments play during the initial stage of deterioration of fresh concrete sewers.⁴ Davis, measuring the deterioration rate of concrete with time, reported a steady value for concrete deterioration in sewer atmosphere after an initially high rate of deterioration.⁵ The model considers a reaction zone where sulfides are converted to sulfuric acid and reaction of the acid with concrete creates a deteriorated layer which may be removed by flow or gravity. However, the major limitation with the model is its use of a constant flux and pH independent parameters which makes it unsuitable for most practical applications. On the other hand, certain models like Pomeroy, though developed for gravity sewer pipes, presents a relationship between H₂S exposure and deterioration rate but is based on empirical findings that may not be applicable to all concrete formulations.³ Yuan et al. developed a model based on reactive transport equations that may be applicable to all cement types with slight modifications.⁶

Models developed to predict metal MIC have been mostly limited to immersed conditions and neglect environmental influence, or require inputs that are not directly available.⁷ Pot's model, for instance, presents a baseline approach to predict corrosion of metal components in wastewater treatment component, but depends on an extensive set of parameters that require empirical data.⁸ Also, the model does not consider the mechanism through which corrosion could take place. A more simplified approach to Pot's model developed by Maxwell considers only four important variables (sulfides, oxygen, pigging frequency and age).⁹ Melchers and Well's model for anaerobic corrosion in the presence of sulfate-reducing bacteria (SRB) was developed specifically for MIC in seawater and did not account for other environmental variables.¹⁰

As a result of the inherent limitation in ascertaining the integrity of components in wastewater treatment plants, operators of such utilities have often relied on age-based estimates or a history of breaks to predict when to perform proactive replacement. This lack of information regarding the true condition of the pipe and the rates of degradation typically results in catastrophic failures requiring costly emergency repairs. To avoid unexpected failures in the future, a mechanistic understanding of the microbiologically influenced corrosion and degradation and their rates leading to failure is required.

In this work, a detailed failure analysis to uncover the typical rates of internal corrosion at either specified or unknown high points in two failed mortar-lined ductile iron pipes (MLDIP) is presented. In addition, existing mechanistic models that could be used in this application and as a benchmark for future improvement were identified. However, the available models overwhelmingly address concrete sewers and little information exist for predicting internal corrosion damage within ductile iron force mains. Therefore, the information obtained from the damage assessment and the literature along with the results of the exposure studies were used to propose a preliminary model that considers both deterioration of the mortar layer and corrosion of the ductile iron. This preliminary model may be further improved through additional testing and exposure results.

Failure Analysis

A series of ductile iron force main pipe failures has occurred recently within the Hillsborough County (Tampa, FL.) inventory. To understand the primary steps that precede failure of the MLDIP, a detailed failure analysis of two pipe sections from separate lines was performed. The specimens were named mortar lined ductile iron pipe-A (MLDIP-A) and mortar lined ductile iron pipe-B (MLDIP-B). Methods of analysis to understand the failure mode included visual inspection, scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS). The overall objective of the analysis was to determine whether mortar deterioration and ductile iron corrosion occur simultaneously or independently. Additionally, the analysis was used to provide insight into the corrosion and deterioration mechanisms.

Experimental Details

A visual inspection of the MLDIP specimens was performed to ascertain the mechanism through which the samples failed, the degree of degradation, the corrosion products and their morphology and establish the depth of penetration of the degradation. In doing so, such evidence as the origin of the failure and the type of corrosion attack (pitting or graphitic corrosion) were sought. Additionally, whether corrosion in the pipe lead to full penetration of pipe wall or if other factors like external soil pressure or internal fluid pressure resulted in eventual depression of the pipes' walls was determined. An estimate of the size of the air pocket was then estimated from the degree of damage present which may serve as an input in the damage forecasting model.

To understand the nature and morphology of the corrosion products formed in the mortar-line ductile iron pipe samples, microstructural characterization was performed on extracted mortar, metal, and metal corrosion product samples using SEM and EDS techniques. Specifically, the analysis was used to determine the composition of the darker corroded region of Pipe A and whether a similar morphology was present on Pipe B. Additionally, the level and mode of mortar deterioration was assessed.

Small samples of the remaining ductile iron pipe wall were cut from the bulk pipe near the failure zone using an abrasive cutting disc with a coolant to avoid heating up the samples. The cut samples were then further sectioned to smaller 5 mm cross-sections using a low speed saw. These samples were then mounted in a cylindrical mold using a mix of epoxy and hardener in a 3:1 ratio and left to cure for about ten hours. The mounted samples were ground successively with silicon carbide abrasive paper having grits of 120, 320 and 600 using an auto-polisher. Samples were polished with a polishing cloth under a slurry of alumina with particle sizes of 5 μm , 1 μm and 0.05 μm in that order. The samples were then cleaned with DI water, bath-sonicated and cleaned in ethanol to remove small adhering particles from the surface. To enhance conductivity of the sample before viewing in the SEM, the samples were sputter-coated with a Au-Pd coating. Secondary electron (SE) imaging and EDS analysis was performed using a Hitachi S800 (Japan) scanning electron microscope^{1†} fitted with a detector and a computer with an EDAX software analyzer. Imaging were obtained of the metal cross section to observe any through wall microstructural changes using an accelerating voltage of 25 kV, 10 μA emission current and 5.5 kV extracting voltage and a working distance of 5 mm.

Results

Figure 1 shows images of the two mortar-lined ductile iron pipes retrieved from the field. The two pipes, A and B were both underground pipes that transported wastewater. The larger pipe, MLDIP-A (Figure 1 a,b,c) had an outer diameter of 65 cm, a metal thickness of 1 cm and a mortar lining measuring 0.45 cm in thickness. MLDIP-B (Figure 1 d,e,f) was 45 cm in diameter with a 1 cm thick metal portion and a mortar lining of ~0.3 cm thick. In each pipe, the failure point was at the crown of the pipe and seemed to have initiated internally.

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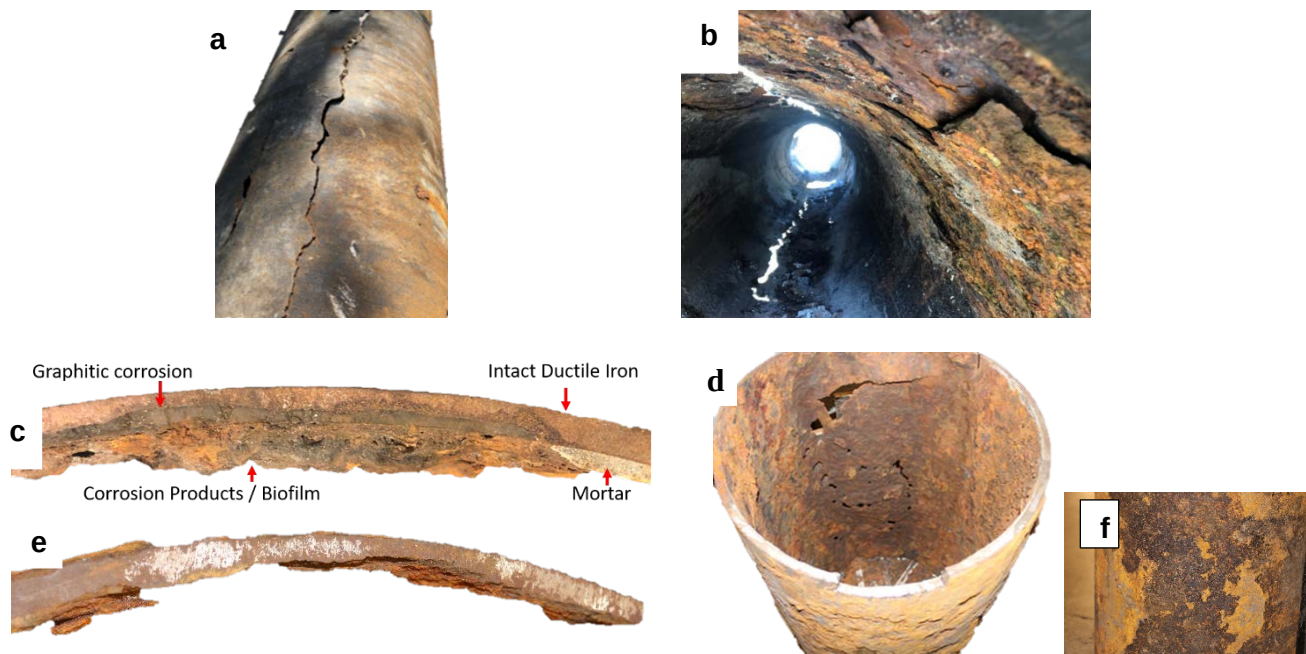


Figure 1: Optical image of failed mortar-lined ductile iron pipes a) Longitudinal crack in MLDIP-A b) Internal corrosion in MLDIP-A c) Graphitic corrosion in MLDIP-A d) Failure in MLDIP-B e) Cross-section image of a part of MLDIP-B f) Uniform corrosion on external surface of MLDIP-B

The size of the air pocket was estimated based on the degradation pattern of each pipe. For MLDIP-A, approximately 60% of the pipe's circumference was severely deteriorated as indicated by complete absence of the mortar layer and corrosion of the ductile iron. A longitudinal crack along the crown of the pipe, as shown in Figure 1a, likely suggests that the pipe failed due to the line pressure as a result of the thinned pipe wall. The smallest pipe wall thickness measured along the crack was 1.30 mm. An image of the cross section of the pipe near the failure zone is shown in Figure 1c. On the right end of the image, the ductile iron is completely intact and lined with the original mortar layer designed to protect against corrosion. At the left end of the image, three material layers are present, including a biofilm layer that seems to be mixed with iron corrosion products, a dark corrosion layer, and the original ductile iron. Upon extraction of a small sample for analysis, it became clear that the dark corrosion layer had lost its strength. Since there does not seem to be corrosion underneath the intact mortar layer, visual inspection suggests that the mortar layer deteriorates completely prior to the initiation of the ductile iron corrosion.

In MLDIP-B, severe corrosion can be seen both internally and externally on the pipe surface. While corrosion on the outside surface of MLDIP-B in contact with the soil was mainly uniform as seen from Figure 1f, the internal pipe structure suffered severe corrosion within the failure region. Severe pitting at random spots within the failure region seem to have led to full penetration of the pipe wall. Subsequent collapse around the failure zone can be added to be due from soil pressure as the pipe continued to thin to a point where its strength could no longer hold. This is evidenced from the inward dent of the pipe.

SEM micrographs of the metal samples of MLDIPA and MLDIPB show nodules of graphite distributed in a steel matrix (Figure 2) within the unaffected portion of the metal. Regions affected by the exposure conditions as indicated by darker shades in the micrographs may be used to ascertain the corrosion mechanisms. Interestingly, the darker shaded region of the pipe A sample does not show graphite nodules, while the darker region of the pipe B sample does. This could indicate that the exposure conditions may result in different modes of attack.

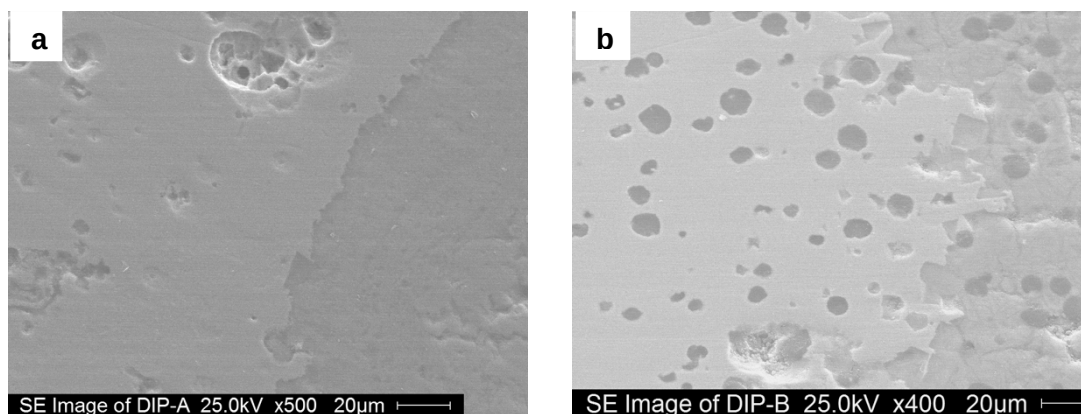


Figure 2: SEM of cross-section of metal taken from failed zone of: a) MLDIPA; b) MLDIP-B

EDS composition analysis was performed throughout the depth of the material to identify how the corroded region differed in composition to that of the unaffected region. The results are shown in Figure 3 which include EDS line scans of the percent weight of iron and carbon as a function of depth with the atomic element as a parameter. A depth of zero reflects the portion of the sample closest to the exposure surface. A high presence of oxygen and a lower amount of iron within this region indicates corrosion taking place. The oxygen concentration decreases away from the exposure surface and the depth of corrosion reaches ~500 µm. The initial decrease in the amount of Fe in the corroding zone of metal components in both pipes can be attributed to the influence of graphitic corrosion which results in selective leaching of Fe (Figures 1c, 3a and 3b). Graphite nodules are more noble than the surrounding ferrite matrix such that galvanic couples form at the nodule matrix interface resulting in preferential corrosion around the nodules which releases them from the matrix.¹¹

Further EDS analysis of the corrosion products on the metal portion of pipe A around the failure region revealed the presence of aggressive agents like Cl (0.10% Cl) which may be attributed to the influence of H₂S within the sewage atmosphere. This is similar to the observation made by Hernandez-Rodriguez et al. where corrosion scales that exhibited sulfur content were related to the presence of H₂S which promotes iron sulfide formation (Fe_xS_x).¹²

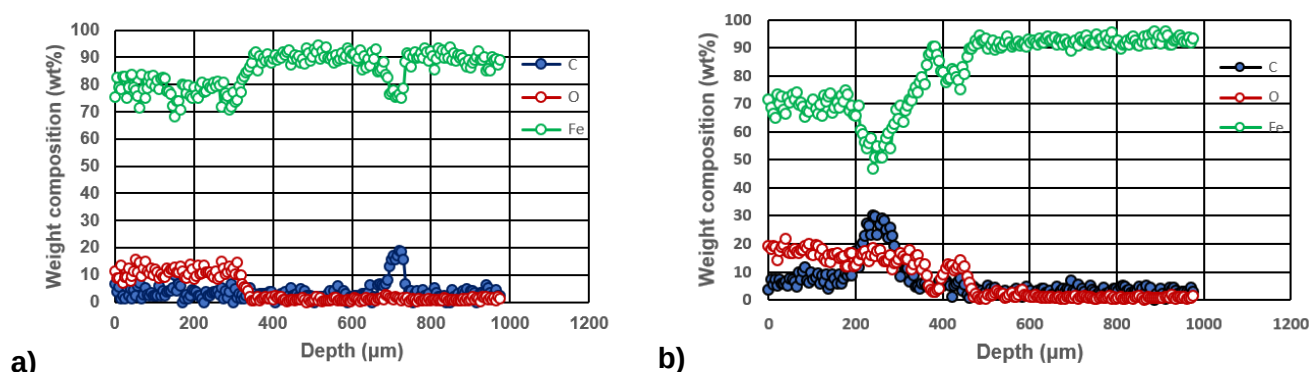


Figure 3: EDS line scan of ductile iron samples taken from failure zone of the failed pipes: a) MLDIP-A b) MLDIP-B.

Table 1 lists the EDS results for intact mortar lining at the bottom of pipes and the failed zone of the mortar at the top of the MLDIP-A and MLDIP-B. The samples were taken from the cross-section of the mortar layer adjacent to the surface layer. Since the mortar lining at the base of the pipe is not exposed to sulfuric acid and is only in contact with the wastewater, it is not prone to acid attack. However, high