COMPREHENSIVE LIST OF PARAMETERS AFFECTING WASTEWATER PIPE PERFORMANCE

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Abstract

Risk is the combination of likelihood of failure and consequence of failure. Important variables to assess the likelihood of wastewater pipeline should be collected and compiled for use in risk ranking by the water utilities. There are many parameters that affect the performance and failure of wastewater pipeline infrastructure systems. For the purpose of analysis, design or both, it is necessary to develop a complete understanding of all parameters that have an influencing role in wastewater pipeline performance. Having an understanding of the wastewater pipeline parameters and their effects that lead to pipeline deterioration can aid in comprehensive data collection and better asset-management, decision-making processes. Specifically, the parameters can be used in developing a robust condition or performance index, performance prediction model, prioritizing repair and rehabilitation, prioritizing inspection, planning operation and maintenance, developing capital improvement programs and making high-level decisions. This paper summarized the factors that affect the performance of wastewater pipelines. In addition, a complete list of possible collection methods for each of the parameters is provided.

Introduction

A key to implementing an asset management strategy is a comprehensive understanding of pipeline parameters and their effects that lead to pipeline deterioration. The performance of a wastewater pipeline is determined by analyzing the pipes' characteristics, operational factors and external factors. The pipelines used in municipal wastewater systems are made from a variety of materials, depending on suitability of the pipe location and design purposes. Each pipe material undergoes failure in a different way. Failure in wastewater pipes depends greatly on pipe characteristics, the surrounding environment (internal and external) and operational practices.

Wastewater pipe structural and functional deteriorations have an essential role in pipe asset management, capital improvement planning and renewal planning. The reliability of decision-making tools, such as wastewater pipe deterioration and performance models, depends greatly on a comprehensive understanding of wastewater pipe deterioration parameters, condition and performance.

The parameters that affect wastewater pipe structural deterioration, operation and maintenance have been identified through a series of studies [1-25]. The National Association of Sewer Service Companies' (NASSCO's) Pipeline Assessment and Certification Program (PACP) [4] presented a standardized system to evaluate internal television inspections of wastewater collection assets. Visual defects are identified utilizing key structural and operation and maintenance (O&M) parameters. Collection system assessment through PACP, or other similar methods, can then be recorded and evaluated. Szeliga and Simpson [13] and Makar [27] investigated failure modes and mechanisms of pipes. Factors related to structural condition and influences were noted.

Other studies, conducted by NRC-Canada [5], and the U.S. EPA [20] focused on inspection and condition assessment. NRC-Canada presented guidelines for assessing and evaluating wastewater collection systems. It recommended that information on location, physical dimensions, related land-use areas, operating conditions and applicable structural and operational data should be recorded. Condition assessment of pipes in the system should be rated based on structural integrity, functional integrity and hydraulic adequacy. CARE-S [3] was developed by the European Commission with the goal of producing a decision support system (DSS) to maintain effective management of sewer networks. It takes into account all aspects of rehabilitation decisions with a link to Performance Indicators (PI). Al-Barqawi and Zayed [15], Chughtai and Zayed [17] and Kathula [21], and Mehta [23] proposed condition rating models and identified performance indicators of the wastewater pipes. Decision support systems, such as performance prediction models and maintenance optimization tools, proposed by Stone et al. [6] and Nelson et al. [24] identified and utilized wastewater parameters.

However, many studies focused only on specific utilities or areas. Some studies focused mainly on certain subjects and/or parameters, and they did not provide an inclusive overview of wastewater pipe infrastructure performance and deterioration. A complete list of parameters that affect wastewater pipe does not exist. Hence, there is a need for a comprehensive list of the parameters that affect wastewater pipes to support an asset management strategy, renewal decisions and performance evaluation models. Wastewater pipe infrastructure data frequently have been recorded in several cities and in utilities' documents, such as maps, maintenance records, daily field logs, recorded flow data, as-built (or record) drawings, specifications and survey information. Often, the compilation of all wastewater pipe system information fails due to the lack of proper means to store the information so that it can be retrieved and used easily, and the lack of integration among sections or departments in utilities.

An extensive study was conducted in order to provide a dependable list of pipe parameters from the literature, questionnaires and utility and pipe association interviews. The goal is to eventually create an inclusive list of all parameters that affect the deterioration and performance of pipe infrastructure. This paper summarizes wastewater pipe performance parameters and their influences. In addition, a complete list of possible collection methods for each parameter is provided.

Pipe Infrastructure System

Pipelines are major assets of wastewater collection systems. Most buried pipeline networks were installed using open-trench construction methods [26]. This construction method typically consists of placing pipes on bedding material and backfilling the trench. Studies have shown that the structural performance and behavior of the buried pipe is dependent on the type of backfill placed around the pipe, the construction sequence, compaction control, surface loads and the type of pipe material (flexible or rigid) [27-32].

The pipelines used in municipal wastewater systems are made of different types of material depending on the location and design. Commonly, wastewater pipes are made of concrete (reinforced and non-reinforced), clay and PVC, though a small number of metal pipes and brick sewers do exist. Each pipe material fails differently. Rigid pipe is designed to resist external loads by its inherent strength, whereas flexible pipe relies on the capacity of the surrounding soil to carry the load and provide stability. All types of pipe can perform well, but the conditions for satisfactory long-term performance vary. Furthermore, the performance criteria are different for pipe type: the severity of cracking is the main performance criterion for rigid concrete pipe, whereas the degree of deflection is the main performance criterion for flexible pipe. For the purpose of analysis or design or both, it is necessary to develop a complete understanding of the failure modes and mechanisms.

There are many parameters affecting wastewater pipe infrastructure systems and their failure. Examples of these parameters are structural—such as pipe diameter, age and material—and environmental—such as soil properties and external loading. Figure 1 shows some of these parameters which affect pipe deterioration over both the short term and long term. Changes in one parameter will also affect the others. For example, in concrete pipe, excessive loadings along with poor pipe bedding can cause pipe cracks and fractures. Cracks and fractures in the pipeline will cause infiltration and exfiltration.

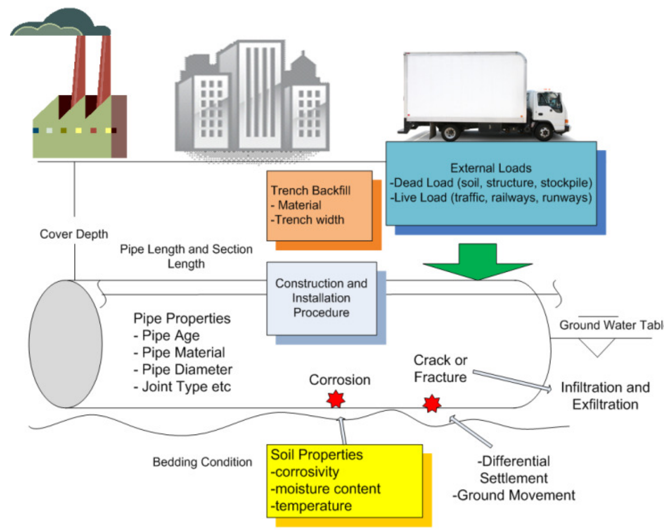

Figure 1. Factors Affecting the Condition and Performance of Buried Pipes

Buried pipes present many challenges:

- Buried pipes are not readily accessible for inspection and defect detection.
- Buried pipes are subject to degradation mechanisms from the outside (soil side) as well as from the inside (fluid side).
- The external environment of buried pipeline has loading, chemical, geotechnical and soil-pipe structural considerations that can be unique to each installation and/or site.
- Pipe bedding materials can also vary by their nature and degree of inspection or verification during the installation process.
- Buried pipes encompass a wide range of materials and a wide range of sizes.
- Buried pipes may be bare or they may have a variety of external coatings and internal linings.
- The design formulas and corresponding design margins for soil and surface loads are not well defined for wastewater buried pipes.

Pipeline Parameters

A comprehensive list of parameters and their influence on pipeline performance for all wastewater pipe materials is presented below in alphabetical order.

A

Age: The length of time since the asset was installed. Age may or may not be a strong indicator of pipeline deterioration and can be a function of the material type and other factors. Typically, it is assumed that older pipes have sustained longer stresses and may be subject to deterioration with age. The unit of this parameter is *year*. This parameter is important for all pipe materials.

B

Backup Flooding: Sewer overflow occurs when the pipe is blocked, which results in backup flooding into building basement or street through inlets and manholes. Usually, backup flooding is catastrophic and may contaminate the environment. The unit of this parameter is *yes/no.* This parameter is important for all pipe materials (see Overflow).

Bedding Condition: A pipe is not made to act as a load-bearing beam and must be supported through adequate bedding. The bedding should be a uniform support made up of clean backfill that is properly tamped to reduced settling and shifting (see Non-Uniform Bedding and Trench Backfill). Uneven support due to lack of proper bedding conditions can lead to beam stress on the pipe [3. The unit of this parameter is *condition level.* This parameter is important for all pipe materials.

Blockage: Blockage makes pipe networks inoperative, and wastewater systems no longer function as designed. Blockage may be caused by unintended objects getting into the system or parts of the broken or collapsed pipe blocking the flow. Smaller diameter pipes are more likely to have a blockage. The units of this parameter are *yes/no* and *condition level.* This parameter is important for all pipe materials.

C

Cathodic Protection: Cathodic protection is a technique used to control the corrosion of a metal surface by adjusting the electric potential of a pipe. The most common protection method is the sacrificial anode method which uses galvanic anodes of zinc and magnesium. In the presence of stray currents, these active metals oxidize more easily that lead to corrosion of the sacrificial anodes and not of the protected metal (see Stray Currents). The active materials must oxidize almost completely before the less-active metal will corrode. This parameter only is applicable for metal pipes. The unit of this parameter is *yes/no.* This parameter is important for metal pipes.

Closeness to Trees: A pipe in close proximity to trees may be subject to root intrusion, if there is a crack or a hole presented in the pipe. Tree roots may also seep through an open or separate joint. The unit of this parameter is *ft*. This parameter is important for all pipe materials.

Coating: An external coating is an approach used to provide protection of the pipeline from external corrosion. If properly applied, a coating can provide resistance to soil corrosivity, hazards of pipeline transportation and fluid penetration or absorption (see Soil Corrosivity). This coating can only be applied during the manufacturing process [3. The unit of this parameter is *yes/no.* This parameter is important for metal pipes.

Condition: Pipe condition can be determined by different types of inspection. Typical inspection methods used to examine pipes are CCTV inspection, smoke test and dye test. The unit of this parameter is *condition scale 1-5*. This parameter is important for all pipe materials.

Connection Density: The required wastewater capacity is dependent on the number of service connections. The pipe size and flow rate of the collection mains must be adequate to transport wastewater to the treatment plants. The unit of this parameter is *number of lateral connection/100ft*. This parameter is important for all pipe materials (see Diameter and Flow Velocity).

Cover Depth: The pipe depth can play a factor in the amount of stress applied to the pipe as a result of live and dead-load loading. As the soil cover increases, the load pressure decreases [5. The amount of cover can also influence the type of failure mode and mechanism. For example, if the pipe is buried at sufficient depth, it is more likely to develop localized buckling than beam buckling [3. A shallow pipe depth may also be a factor for third-party damages. The unit of this parameter is *ft*. This parameter is important for all pipe materials.

D

Design Life: The period of time that the pipe is expected to operationally function. A high design life typically indicates a longer life expectancy; however, other influencing parameters may reduce the expected life. In contrast, the pipe can also be functional past the design life. The unit of this parameter is *year*. This parameter is important for all pipe materials.

Diameter: The diameter of a pipeline is typically classified by the nominal diameter or outside diameter rather than the inside diameter. Small-diameter pipe are more susceptible to beam failure than larger pipe diameters. In relation to pipe capacity, smaller diameters are easy to be blocked by objects, root intrusion or built-up sediment. The unit of this parameter is *inch*. This parameter is important for all pipe materials.

Dissimilar Materials/Metals: When dissimilar metals are connected and exposed to an electrolyte, galvanic corrosion will occur since the metals have different properties. The galvanic difference within the metals causes one metal (anode) to release electrons to another metal (cathode). The metal that discharges the electron can result in pipeline corrosion, while the metal accepting the electron is protected from corrosion [3. The unit of this parameter is *yes/no.* This parameter is important for metal pipes.

Disturbances: Third-party disturbances to the pipeline can lead to direct or indirect damage. For example, construction disturbances due to excavation can lead to direct damage, which results in the equipment physically breaking the pipe or indirect damage due to soil movement close to the pipe. Disturbances in the pipe bedding or alignment can lead to beam failure if the pipe is not adequately supported and/or the pipe depth is not sufficient [3. The unit of this parameter is *yes/no*. This parameter is important for all pipe materials.

E

Exfiltration: Exfiltration refers to wastewater getting out of the system through cracks, holes, separated joints and/or opened joints. Exfiltration may contaminate the surrounding environment and water sources. The unit of this parameter is *level*. This parameter is important for all pipe materials.

Extreme Temperatures: A change in climate can result in stresses that occur to the pipe itself and the soil surrounding the pipe. As a result of hot and cold temperatures, the pipe endures dimensional changes due to the expansion and contraction of the material. These dimensional changes create increased axial loads in the pipe. Furthermore, the soil can create a downward pressure due to the expansion of water freezing within the soil pores during cold temperatures while contracting when the water content is reduced during hot temperatures [3. The unit of this parameter is *degree Fahrenheit*. This parameter is important for vitrified clay pipes.

F

Failing Utilities: Failed utilities located in the vicinity of the wastewater pipeline can result in soil disturbances and possible changes in bedding configuration, ultimately leading to wastewater pipe failure. The unit of this parameter is *yes/no*. This parameter is important for all pipe materials.

FOG: FOG also known as fats, oils and grease. FOG build-up in the system can cause blockage and overflow. The units of this parameter are *yes/no,* and *condition level.* This parameter is important for all pipe materials.

Flooding: Flooding can impact the pipe and soil equilibrium causing the pipe to collapse or float out of alignment. Aggressive waters and/or constant water in contact with the pipe can increase the external corrosion rate [3. The unit of this parameter is *occurrence level*. This parameter is important for all pipe materials.

Flow Velocity: The flow of the fluid through the wastewater pipe. Flow velocity can determine the pipe capacity and required pipe diameter during pipe design. Velocities should not be less than 2 ft/s, which causes sediment to build up. However, excessive velocities are not recommended because they lead to mechanical surface wear and exposure of aggregates in concrete pipes. The unit of this parameter is *ft/s*. This parameter is important for all pipe materials.

Frost Penetration: Frost penetration is the depth to which frost can penetrate the soil. The greater depth of frost penetration increases the earth loading on the pipe. The increase in dead load results in a compressive stress or crushing force which acts on the pipe, leading to potential longitudinal cracks [3. The unit of this parameter is *yes/no*. This parameter is important for all pipe materials.

Function: Different uses of a sewer may deteriorate at different rates. Whether it is a combined sewer, separate sewer or forced main, different parameters are considered in performance evaluation. The unit of this parameter is *type (e.g., gravity sewer, force main).* This parameter is important for all pipe materials.

G

Groundwater Table: The location of the groundwater table can affect the pipe-soil relationship. If the pipe is located at or below the water table, floatation may occur if proper measures are not considered such as a greater soil cover or a weighting system. Constant contact with groundwater may lead to external corrosion in metal pipes [3. The unit of this parameter is *ft*. This parameter is important for metal pipes and reinforced concrete pipes when cracks are present.

H

Hydrogen Sulfide Gas (H_2S): High levels of H_2S concentration can severely cause pipe corrosion and eventually lead to structural failure. Sulfuric acid that corrodes the pipe near the crown is formed by hydrogen sulfide gas in sewage. H_2S usually occurs in shallow-slope pipes. The unit of this parameter is *level* or *ppm*. This parameter is important for metal and concrete pipes.

I

Inflow and Infiltration (I&I): I&I refers to outside water getting into the wastewater system through cracks, holes, separated joints and/or opened joints. I&I may cause surrounding soil erosion and unnecessary increases in flow volume. The unit of this parameter is *condition level* or *Gallon/min*. This parameter is important for all pipe materials.

Installation: Poor installation can result in inadequate bedding and/or possible damage to the pipe itself. Prior to the 1930s, installation specifications required the pipe end bells to be placed on top of solid supports; however, over the years, it was determined that such supports can lead to uneven support and excessive beam stress. Also, the general construction practice consisted of refilling the trench with the excavated soil. Today, practice requires clean backfill to protect the pipe from uneven bedding and reduce the chances of corrosion potential [3. The unit of this parameter is *level*. This parameter is important for all pipe materials.

J

Joint Type: Joints for the various material types have evolved over the century. Today, many of the available joints provide a greater amount of flexibility and versatility. The flexibility of the joint can also compensate for ground movement. Typical joint types for concrete pipe are lined joint, rubber gasket joint and steel endring joint. The unit of this parameter is *type*. This parameter is important for all pipe materials.

L

Lateral: A lateral pipe refers to a small pipe connecting a mainline to a household. If the lateral is not properly connected, I&I can occur. The unit of this parameter is *number of connections*. This parameter is important for all pipe materials.

Length: There are two lengths regarding wastewater pipeline: a section length between joints and a node length between manholes. An increase in pipe section length can lead to increased stresses as a result of differential ground movement transverse to the pipe axis. A pipeline that is not properly supported can result in beam stresses. Excessive beam stress can lead to circumferential cracking [3. A pipe with a node length greater than 500 ft is considered difficult to maintain, due to maintaining the equipment operating length. The unit of this parameter is *ft*. This parameter is important for all pipe materials.

Lining: The internal surface of a pipe can be covered by a coating to improve resistance from tuberculation and corrosion. The lining is also used to prevent inflow/infiltration of water from soil and exfiltration of wastewater into the environment if cracks and fractures are present. This lining can be applied during the manufacturing period or installed to an existing pipe. Common types of linings consist of mortar linings and epoxy coatings. The units of this parameter are *yes/no* and *type*. This parameter is important for all pipe materials.

Live Load: Live loading from traffic can cause compressive forces on the pipe wall. This downward pressure is a factor of the pipe depth, soil type, type of pavement (rigid or flexible) and the type of vehicles (see Cover Depth and Soil Type). Excessive crushing forces can lead to longitudinal cracks on the pipe wall. Bending stresses are also present within the pipe if the pipeline is not evenly supported (see Bedding Condition). Excessive bending stress can lead to circumferential cracking [3. The units of this parameter are *average daily traffic (ADT)* or *level*. This parameter is important for all pipe materials.

Location: A pipe in urban, suburban, rural or coastal area may be subject to different loads and conditions. A pipe serving a dense population area needs more capacity. A pipe in an industrial zone may be subject to highly acidic or alkaline conditions as well as other chemicals that may corrode the pipe. The unit of this parameter is *type (e.g., residential)*. This parameter is important for all pipe materials.

M

Manhole: Rigid connections frequently exist when the pipeline is connected to a structure such as a manhole. A manhole experiencing differential settlement can create high bending moments and shearing forces on the pipe [3. The units of this parameter are *condition level* and *type (e.g., material, type A)*. This parameter is important for all pipe materials.

Manufacture: The pipe material quality can vary based on the pipe manufacture. Errors due to manufacturing can result in a defective material that is more vulnerable to pipe failure. The unit of this parameter is *type*. This parameter is important for all pipe materials.

Material Type: The metallurgy of the pipe material type can dictate the resilience of strength and also the resistance to corrosion. Different pipe material types are designed for various service types and vary in design life, thickness, diameter, etc. The unit of this parameter is *type*.

Moisture Content: Soil moisture content indicates the amount of water present within the soil. The fact that moisture content can vary throughout the year should be taken into consideration. Prevailing moisture content can lead to soil corrosion [3. The unit of this parameter is *percent*. This parameter is important for metal pipes.

O

Odors: Odors in the system may be contributed by solid build-ups, poor system hydraulics and flat grade. The units of this parameter are *yes/no* and *level* (see H_2S). This parameter is important for all pipe materials.

Operational Pressure: Internal pressure is maintained at an effective level by the use of valves and pumps. The pressurized system results in a tensile stress (hoop stress) that acts on the pipe. This stress is a function of the operational pressure and the pipe diameter and wall thickness (see Diameter and Thickness). Excessive hoop stress can lead to longitudinal cracks in the pipe wall. The operational pressure causes a different type of stress on the pipe's bends and valves known as axial stress. Excessive pressure on these appurtenances can lead to circumferential cracking [3. This parameter is only applicable for force mains. The unit of this parameter is *psi*.

Overflow: Overflow may inundate surrounding soil and change loading on the pipe. Overflow occurs when the pipe is blocked or the system is overloaded, and results in backup flooding into building basement or street through inlets and manholes (see Backup Flooding). The units of this parameter are *yes/no* and *level*. This parameter is important for all pipe materials.

P

Precipitation: A large amount of precipitation can lead to possible flooding, an increase in the groundwater table, soil moisture content and soil erosion (see Flooding, Groundwater Table and Moisture Content). Extended external exposure of water to a pipeline can promote external corrosion, while the erosion of the soil can result in inadequate bedding conditions or landslides (see Bedding Condition). If there are cracks and holes in the pipe, a large amount of precipitation can lead to inflow/infiltration and exceeding capacity, and results in sewer overflow. The unit of this parameter is *inch/year*. This parameter is important for all pipe materials.

S

Seismic Activity: Seismic activity can result in increased pipe stresses and disturbances in the pipe-soil relationship, and cause failure. Pipe floatation may also occur due to liquefaction of the soil [3. The units of this parameter are *yes/no* and *level (e.g., frequent and magnitude)*. This parameter is important for all pipe materials.

Slope: The pipe slope affects the velocity of a gravity-flow sewer and may result in blockage, sediment and corrosion (see Velocity). Pipe slope may be derived from upstream invert elevation, downstream invert elevation and pipe length. The unit of this parameter is *gradient*. This parameter is important for all pipe materials.

Slope Stability: Soil stabilization is influenced by the slope of the ground. Earthquakes, reservoir draw-downs, heavy precipitation and floods can result in soil erosion or landslide potential, which can affect the pipe bedding condition and the alignment of the pipe (see Precipitation, Flooding and Bedding Condition). Anchor and/or thrust blocks may also be used to stabilize the pipe on a steep slope [3. The unit of this parameter is *yes/no*. This parameter is important for all pipe materials.

Soil Corrosivity: Soil corrosivity cannot be directly measured and is a function of several soil properties such as soil redox potential, soil pH, soil resistivity, soil sulfides, moisture content, etc. [4 (see Soil Redox Potential, Soil pH, Soil Resistivity, Soil Sulfides and Moisture Content). The corrosivity level of the soil can result in corrosion of the pipeline. The unit of this parameter is *level*. This parameter is important for metal and concrete pipes.

Soil pH: Soil pH is a measure of the soil acidity or alkalinity. A low pH represents an acidic soil promoting corrosion and is also a soil that serves well as an electrolyte. High alkaline conditions can also lead to corrosion of a ferrous material pipeline since it will be a soil that is high in dissolved salts, which yields a low soil resistivity [3. The unit of this parameter is *pH level* (see Soil Resistivity). This parameter is important for metal and concrete pipes.

Soil Redox Potential: Redox potential (also known as the reduction potential) is a measure of the tendency of the soil to attain electrons. Substances that accept electrons are capable of reducing or having a negative redox potential, which indicates an anaerobic condition. Soils that are anaerobic are regarded as potentially corrosive, predominately in ferrous material pipelines [3. The unit of this parameter is *mV*. This parameter is important for metal and concrete pipes.

Soil Resistivity: Soil resistivity is a measure of the soil to serve as an electrolyte and is often measured in the presence of ferrous material pipelines. The lower the resistivity value, the more likely the soil will serve as an electrolyte, which relates to an increase in soil corrosion activity. The soil temperature does have an impact on the soil resistivity; as the temperature decreases, the soil resistivity increases. Soil resistivity is also a function of the soil moisture content; the higher the moisture content, the lower the soil resistivity [4. The unit of this parameter is *Ohm-cm level* (see Moisture Content). This parameter is important for metal and concrete pipes.

Soil Sulfides: Soils containing sulfide indicate that there is a problem caused by sulfate-reducing bacteria. Soils with positive sulfide content are more prone to pipeline corrosion [3. The unit of this parameter is *percent*. This parameter is important for metal and concrete pipes.

Soil Type: The soil dead load and change in soil volume can be attributed to differing types of soil. The unit weight of the soil and depth of the pipe determine the total dead load resulting from the soil (see Cover Depth). This external load is usually accountable for ring deflection of the pipe. Soil types that are compressible can result in a greater pipe deflection, due to additional loading. Certain soil types are also more prone to expansion and contraction of soil, due to the wetting and drying cycles. In particular, the expansion of the soil can cause the external soil load to increase, which can result in axial and/or beam loads on the pipeline [3. The unit of this parameter is *type (e.g., clay, sand)*. This parameter is important for all pipe materials.

Stray Currents: Stray currents are caused by a local direct current (DC) flowing through the earth. These stray currents can be present if the pipe is near a transportation system such as a railway, or if other utilities are close to the pipe. Often these stray electrical currents can cause electrolytic corrosion in metal pipelines if they are not properly protected. Cathodic protection is the most common protection method of metal pipelines as a result of stray currents. The unit of this parameter is *yes/no* (see Cathodic Protection).

Surcharging: Surcharging in a gravity sewer in dry and wet weather should be monitored. Surcharge is described as a condition when the sewer flows full and under pressure. Surcharge occurs as a result of under design capacity or changing of system conditions such as deposit or blockage. Surcharging usually occurs during storms, due to high groundwater tables. Surcharging is usually measured in hydraulic head level (ft). The units of this parameter are *yes/no* and *ft.* This parameter is important for all pipe materials.

T

Tidal Influences: Tidal influences within coastal areas can influence the soil groundwater table. As the wave progresses inland, as a result of high tide, the groundwater table can fluctuate [4. The unit of this parameter is *yes/no* (see Groundwater Table). This parameter is important for all pipe materials.

Thrust Restraint: Unbalanced hydrostatic or hydrodynamic forces are known as thrust forces which can result in joint separation. These thrust forces are often controlled with the use of thrust blocks or restrained joints [4. This parameter is only applicable for force mains. The unit of this parameter is *yes/no.*

Trench Backfill: The trench backfill is responsible for providing sufficient surrounding support for pipe stability. Settlement of the backfill and/or pipe can create shearing or friction forces at the sides [3. The unit of this parameter is *type (e.g., Class A).* This parameter is important for all pipe materials.

Trench Depth: The trench depth should be dug accordingly for minimum cover to protect the pipe from possible loading and the frost line. The depth of the trench may be governed by existing utilities or other possible conditions [3. The unit of this parameter is *ft.* This parameter is important for all pipe materials.

Trench Width: The trench should be wide enough to provide adequate pipe support from the bedding and backfill (see Bedding Condition and Trench Backfill). Settlement of the soil or pipe can create shearing or friction forces at the side of the pipe [3. The unit of this parameter is *ft.* This parameter is important for all pipe materials.

Type of Cleaning: Some type of cleaning may damage the pipe. Typical cleaning methods used for wastewater pipe are water jetting, bucketing and chemical. The unit of this parameter is *type (e.g., jetting).* This parameter is important for all pipe materials.

V

Vintage: The pipe vintage can determine the metallurgy, uniformity, thickness, pressure class and available diameters of the various pipe materials (see Thickness, Pressure Limit and Diameter). For example, cast-iron pipe was initially pit cast; however, over the years, this casting method was changed to centrifugally spun cast. These variances due to pipe vintage can control the resiliency of the pipe material. The unit of this parameter is *year.* This parameter is important for all pipe materials.

W

Wall Thickness: The pipe wall thickness often governs the operational pressure of the pipe and is variable on pipe diameter and material type (see Operational Pressure, Diameter and Material Type). The magnitude of potential pipe stresses in relation to loading and depth of pipe can also be a function of the wall thickness (see Live Load and Cover Depth). Thickness is also a variable in analyzing the potential of corrosion and can dictate the amount of time corrosion pitting can be detrimental towards the pipe lifespan [4. The unit of this parameter is *inch.* This parameter is important for all pipe materials.

Wastewater Quality: Wastewater quality cannot be directly measured. It is a function of several properties such as wastewater pH, BOD, COD, temperature and chemical. The wastewater quality is thought to have an effect on the corrosion. This parameter is important for all pipe materials.

Wet/Dry Cycles: The wet/dry cycles as a result to climate can lead to expansion and/or contraction of the soil. The expansion of the soil can cause the external soil load to increase, which can result in axial and/or beam loads on the pipeline. Increased loading is also related to the shrinkage of the soil. The unit of this parameter is *yes/no* (see Soil Type). This parameter is important for all pipe materials.

Parameter Collection Protocol

Wastewater pipe infrastructure data has been previously recorded in municipality documents such as maps, maintenance records and daily field logs. In addition to the city

Table 1. A to L Parameter Sources

Parameter	Utility Records	Construction Specification	Hydraulic Model	Product Standards	Pipe Sample	Geotechnical Records	Aerial Photography	Customer Complaints	Other Testing	Online Database
Age	X	X								
Backup Flooding	X		X					X		
Bedding Condition	X	X							X	
Blockage	X		X					X	X	
Cathodic Protection	X	X								
Closeness to Trees	X						X			
Coating	X	X		X	X					
Condition	X									
Connection Density	X	X								
Cover Depth	X	X							X	
Design Life	X			X						
Diameter	X	X		X	X					
Dissimilar Materials/Metals	X	X								
Disturbances	X									
Exfiltration	X		X						X	
Extreme Temperatures	X								X	X
Failure Utilities	X									
FOG	X							X		
Flooding	X						X			X
Flow Velocity	X		X						X	
Frost Penetration	X								X	X
Function	X	X								
Groundwater Table	X					X			X	X
H_2S	X								X	
I&I	X		X						X	
Installation	X									
Joint Type	X	X		X						
Lateral	X	X								
Length	X	X								
Lining	X	X		X	X					
Load	X								X	

and utility documents mentioned above, staff interviews, survey questionnaires and informal meetings are always good sources for information. Often, compilation of this information is in paper format, which limits accessibility. Today, the most effective format for storage wastewater pipe infrastructure data would be an electronic overall base map such as Geographic Information System (GIS).

Wastewater pipeline data can be collected by direct or indirect methods; for example, direct methods such as various inspection methods, and indirect methods such as hydraulic modeling. For example, one of the most widely used inspection techniques for collecting internal wastewater pipeline information is called Closed-Circuit Television (CCTV). From CCTV images, the defects in the pipe such as cracks, fractures and holes are captured. Root intrusions through the cracked or broken pipe, Infiltration/ Inflow (I/I) and exfiltration can be detected via this technique as well. Other effective inspection techniques include smoke test, dye test and manhole inspection.

Data collection of pipe parameters can be time consuming and require expensive testing; therefore, selection of parameter collection techniques should be considered. To aid in the collection methods and protocols, a comprehensive list of parameter sources was compiled to give users the various collection techniques. Tables 1 and 2 illustrate each wastewater pipe parameter and list of possible collection sources.

Table 2. M to Z Parameter Sources

Parameter	Utility Records	Construction Specification	Hydraulic Model	Product Standards	Pipe Sample	Geotechnical Records	Aerial Photography	Customer Complaints	Other Testing	Online Database
Manhole	X	X								
Manufacture	X	X								
Material Type	X	X			X					
Moisture Content	X					X			X	
Odors	X							X	X	
Operational Pressure	X		X						X	
Overflow	X		X					X	X	
Precipitation	X									X
Seismic Activity	X									X
Slope	X	X					X			X
Soil Corrosivity	X					X			X	
Soil pH	X					X			X	
Soil Redox Potential	X					X			X	
Soil Resistivity	X					X			X	
Soil Sulfides	X					X			X	
Soil Type	X					X			X	X
Stray Currents	X	X				X			X	
Surcharging	X		X							
Tidal Influences	X					X	X		X	X
Thrust Restraint	X	X		X	X					
Trench Backfill	X	X							X	
Trench Depth	X	X							X	
Trench Width	X	X							X	
Type of Cleaning	X									
Vintage	X	X		X						
Wall Thickness	X			X	X					
Wastewater Quality	X								X	
Wet/Dry Cycles	X									X

Conclusion

An extensive study was conducted in order to provide a dependable list of pipe parameters taken from published studies, questionnaires and utility and pipe association interviews with the goal of creating a comprehensive list of all parameters which have an effect on wastewater pipe performance.

This paper summarized wastewater pipe performance parameters and their influences. A comprehensive list of wastewater pipe parameters presented in this paper aims at the broad understanding of the wastewater infrastructure system. Consideration of each pipeline parameter aids in determination of overall pipeline performance, as each factor has its own influencing role. Along with the prioritization of pipeline performance, financial costs as a result of compiling and collecting these parameters should also be taken into consideration in making asset management decisions. Additionally, collection of each parameter may be unreasonable due to cost and time constrains; therefore, a list of essential parameters should be given priority as the utility manager deems necessary.

Acknowledgements

This research project is funded by the Water Environmental Research Foundation (WERF). The authors would also like to acknowledge the contributions of the participating United States Environmental Protection Agency (US EPA), as well as the following utilities and pipe associations.

<u>Participating Utilities</u>

- City of Atlanta, Atlanta, Georgia; Mr. John Griffins
- Seattle Public Utility, Seattle, Washington; Mr. Terry Martin
- Orange County Sanitation District, Fountain Valley, California; Mr. Kevin Hadden
- Pittsburgh Water and Sewer Authority, Pittsburgh, Pennsylvania; Mr. Michael Lichte
- VPI Sanitation Authority, Blacksburg, Virginia; Mr. Ray Smoot, Mr. Michael Vaught and Ms. Katherine Smith

<u>National Pipe Association Participants</u>

- American Concrete Pipe Association; Ms. Kim Spahn
- National Clay Pipe Institute; Mr. Michael Van Dine
- UniBell PVC Pipe Association; Mr. Robert Walker
- Ductile Iron Pipe Research Association; Mr. Gregg Horn

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