Lifecycle Cost and Performance of Plastic Pipelines in Modern Water Infrastructure

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Abstract

The demand on water infrastructure systems continues to grow as populations increase and current freshwater withdrawal sources are depleted. The importance of designing new and future pipelines for life-long performance will be especially critical in the face of rising freshwater demands. Increasingly urbanized population centers have greater exposure to social costs in the event of pipeline failure due to a lack of available freshwater and disruptions resulting from construction activity. Furthermore, public funding for new pipeline construction, operation, and maintenance will become more stringent as more expensive, alternative water sources are employed in response to depletion of current freshwater sources. Plastic material provides pipeline designers with a valuable tool for lowering installation and long-term operation and maintenance costs for new pipeline projects. The advantages of plastic pipe materials are explored through a series of performance and cost analyses. Installation methods, seismic reliability, internal corrosion resistance, and hydraulic flow performance are considered in quantifying the costs associated with typical water pipe materials throughout a standard design life of 75 years. The cost and performance analyses of plastic pipes focus on High Density Polyethylene (HDPE) and Polyvinyl Chloride (PVC) due to their widespread usage in water pipelines. Significant short and long term costs savings can be realized through selection of HDPE and PVC over other historically prevalent materials. The results of the cost analyses are presented for direct, present value, comparisons. HDPE and PVC water pipes are then discussed in the broader, social context of addressing future water infrastructure challenges.

Keywords: Plastic Pipe, Water Pipelines, Underground Construction, Water Infrastructure, Pipeline Reliability

The design and planning requirements for water infrastructure projects are ever-evolving. Engineers and public officials face the difficult task of developing water distribution systems which can meet future demands while limiting immediate and future maintenance, repair, and replacement costs. Rapid population growth and continued urbanization put ever-increasing demands on water conveyance networks. Population and urbanization in the United States are projected to grow at rates of 41.5% and 59.2% respectively from 2010 to 2050 (U.S. Department of Commerce & U.S. Census Bureau, 2010). As a consequence, the national demand for water and wastewater pipe is expected to rise 10% annually through 2016 (Freedonia, 2012). The accelerating rate of urbanization results in the increasingly critical nature of urban water distribution systems.

Water pipeline distribution systems become especially critical in urban regions. The large population serviced by a water pipeline in an urban region leads to higher potential economic and social costs in the event of pipe failure. Quality of life can be significantly impacted by a temporary lack of available water, as well as traffic delays resulting from construction activities required to repair a broken pipe. Severe economic costs are also incurred in the event of an urban pipe failure. Underground construction in urban areas poses additional challenges due to dense, complex systems of existing utilities, which must be avoided or supported during construction activity. Dense property layouts and high traffic volume create additional burdens on contractors by limiting construction access.

Water pipeline designers must account for the future increases in urban demand and the potential consequences of critical pipeline functions serving dense populations. Pipe material selection plays a critical role in controlling pipeline reliability over the design life of a pipeline. The financial consequences incurred by a water agency from repairing a failed pipe can be significant, making shortsighted material selections unacceptable. Both the initial cost of installation, as well as the future reliability of a pipeline, must be considered throughout the design phase.

Background

Critical factors in pipeline material selection

A water pipeline's performance is challenged throughout the life of the pipeline by many factors. A water pipe is subjected to both internal and external corrosion, chemical reactions with its contents as well as the surrounding soil, and constantly varying loading conditions from varying groundwater levels. Possible seismic events and ground movement from construction activities pose additional threats to the long-term viability of underground pipelines. All the while, a pipeline must be designed to adequately transport its contents without disruption or significant degradation in performance over a lifetime of exposure to those challenges. Failures in water pipelines are made intolerable since they cannot be easily replaced or repaired due to their depth below grade.

Plastic pipe market share rise

Pipeline designers have many choices for materials at their disposal. Possible materials include, but are not limited to, steel, ductile iron pipe (DIP), cast iron, reinforced concrete pipe, HDPE, and PVC. The distinct physical and chemical properties of the pipe material have tangible effects on the installation and performance of a pipeline.

In response to rising future pipe demands, designers have increasingly turned to thermoplastic materials over historically traditional materials. A market research report by

Freedonia (2012) titled “US Water and Wastewater Market” states, “Plastic pipe will be the fastest-growing pipe material through 2016, continuing to steadily take share from competing materials in a range of markets” (p. 1). The most prevalently used plastic pipe materials are Polyvinyl Chloride (PVC) and High Density Polyethylene (HDPE) due to their durability and relatively low cost of production.

Cost Differential Analyses

The acceleration in demand of plastic pipes can be attributed to the economic, social, and environmental advantages they provide. The physical and chemical properties of plastic pipes make them better suited than other materials to succeed in the challenging environment that exists below the surface of the Earth.

Plastic pipe materials have significant economic advantages, both at the time of initial construction, and over the life of the pipe. The typical design lifecycle of an underground water pipeline is 75 years, which leaves great potential for pipeline performance degradation and damage resulting from natural events (American Water Works Association [AWWA], 2001). Hypothetical cost assessments are presented to explore the present value costs for a variety of pipeline materials over a life cycle of 75 years. The resulting cost estimates predict the costs associated with a variety of natural phenomena that should be considered in pipeline performance analyses. The results of the analyses allow for direct comparisons between typical pipe materials, quantitatively highlighting many of plastic pipe’s advantages.

Ease and Cost of Installation

Background. The costs of pipeline construction are highly dependent on the region of installation. Pipeline construction in a rural area is significantly less expensive than similar pipeline construction activities in a developed, urban region. The option of excavating open-cut trenches is typically not available in an urban environment due to streets, properties, and existing underground utilities. Urban regions have higher demand for water resources than rural areas, so a greater portion of water pipeline construction occurs in densely populated areas.

Reducing the construction impact on commercial and residential developments along the path of a new pipeline is challenging in urban environments. Trenchless installation methods eliminate the demand for open space required in open-cutting and the need for excavation shoring along the length of the pipeline. Trenchless technology refers to methods, which do not require open trenches or disturb the surface. Trenchless methods have gained wide market share in the United States since their introduction in the early 20th century in response to space limitations from urban growth (Thomson, 1993).

Both microtunneling and horizontal directional drilling (HDD) are popular trenchless methods. Microtunnelling involves the installation of pipe sections by pushing off from a “jacking backboard” at the end of a shored “bore pit”. The end of the pipeline terminates at the “receiving pit” location, which is another shored excavation (Najafi & Gokhale, 2005). Figure 2 depicts a typical microtunneling “bore pit”. This method can be used to install many different types of pipe materials, but it requires significant mobilization costs and primarily installs pipe sections at constant gradients. This can be a problem in densely populated areas due to the high density of existing underground utilities. The HDD method succeeds in areas where microtunneling cannot. Only shallow entry and exit pits are required for HDD and the drill rig is significantly more mobile and less expensive than the bore machine required for microtunnelling. The most unique capability of HDD is the ability to constantly control the direction and gradient of the pipeline being installed. HDD allows a driller to snake the pipeline around underground utilities, difficult drilling soil and rock layers, and travel deep below railroads and rivers before traveling back closer to the surface. A typical HDD bore path is demonstrated in Figure 1.

The HDD method results in significant cost savings over microtunneling. However, the pipe materials HDD can install are far more limited than those of microtunneling. Steel and ductile iron pipes are sometimes installed with HDD, but plastic pipes make up 66.8% of all pipe materials (43.9% HDPE, 22.9% PVC) (Rubeiz, 2012). This discrepancy in pipe materials is due to the lightweight and flexibility of plastic pipes. The lightweight of plastic pipes allows for greater ease of installation. Less weight translates into less frictional resistance along the bore path and a lower overall pull load requirement on the drill rig. The flexibility of plastic pipe gives both the engineer and the driller better ability to vary the pipe's path to avoid existing utilities and difficult drilling layers. A bend in a stiffer pipe material causes higher initial pipe stresses. The flexibility of plastic pipe results in a minimum acceptable pipeline radii of 100 x D compared with 40 x D for steel pipes, with "D" representing the outside diameter of the pipe (Faughtenberry, Fissel, & Hutson, 2001).

Figure 1 **Typical HDD Installation**

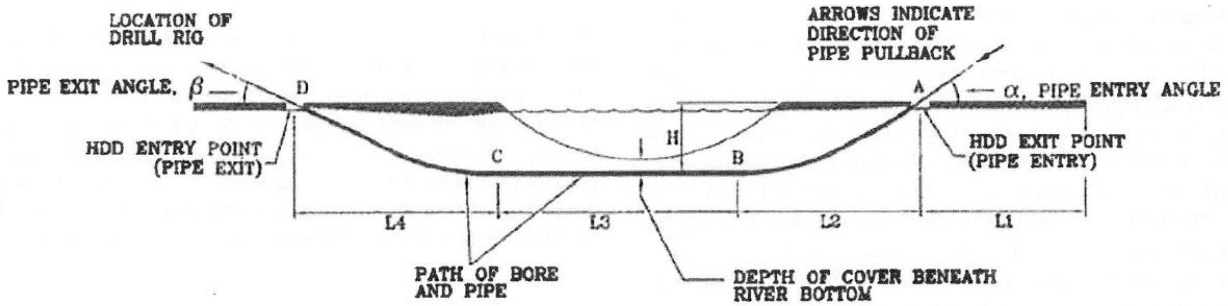

Figure 1. Typical bore path for horizontal directional drilling underneath a river. Adapted from *Standard Guide for Use of Maxi-Horizontal Directional Drilling for Placement of Polyethylene Pipe or Conduit Under Obstacles, Including River Crossings,* p. 2, by American Society for Testing Materials. Copyright 2005.

Figure 2 **Microtunneling Bore Pit**

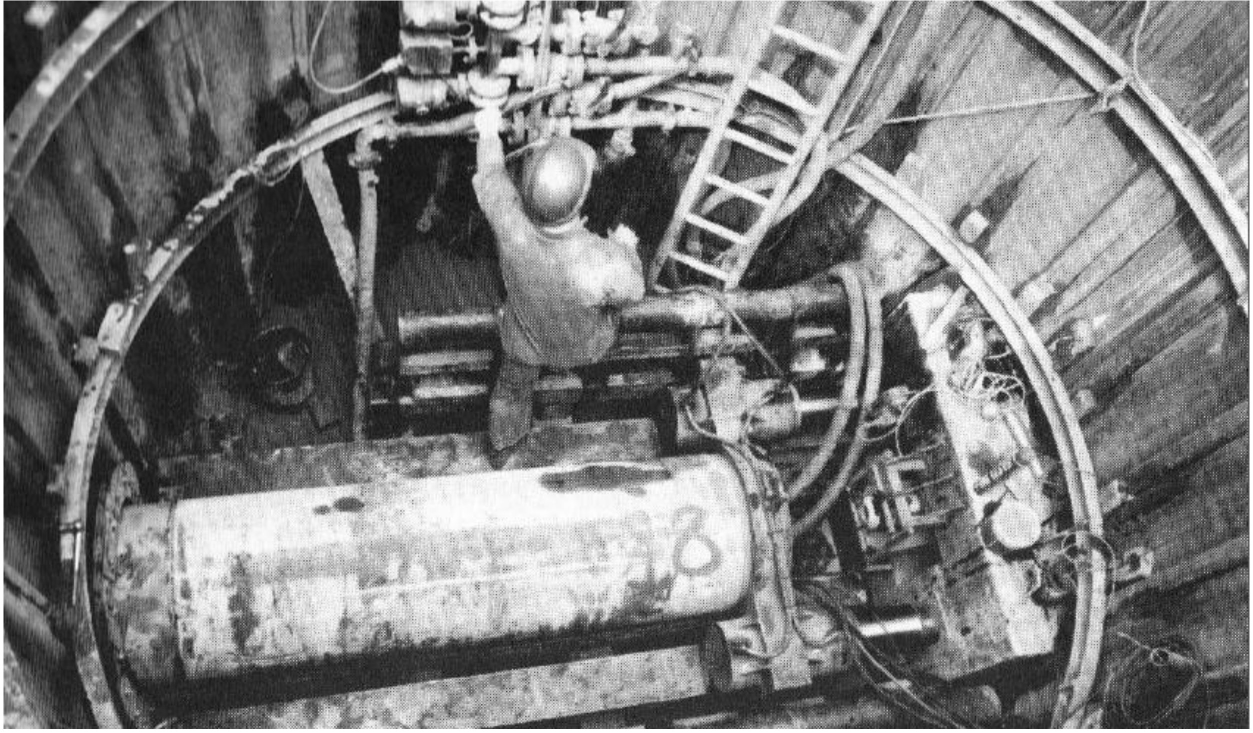

Figure 2. Shored bore pit to facilitate the installation of an underground pipe by the micotunneling method. Adapted from *Pipejacking and Microtunneling,* p. 4, by J. Thomson. Copyright 1993.

Cost analysis. The following analysis predicts the cost of a hypothetical pipeline installation underneath a river. The depth of the river precludes installation of the pipe at a shallow depth. This is a typical application of HDD, which is used for rivers, railroad crossings, and busy streets to negate construction impacts on the area. The pipe material costs are not included, as the goal of the cost analysis is to explore the operational cost differential. This does not skew the results, as the difference in pipe material costs is insignificant in comparison with the costs of installation. The results of the cost analysis can be seen in Figure 3.

Figure 3 **Comparison of HDD and Microtunneling Installation Costs**

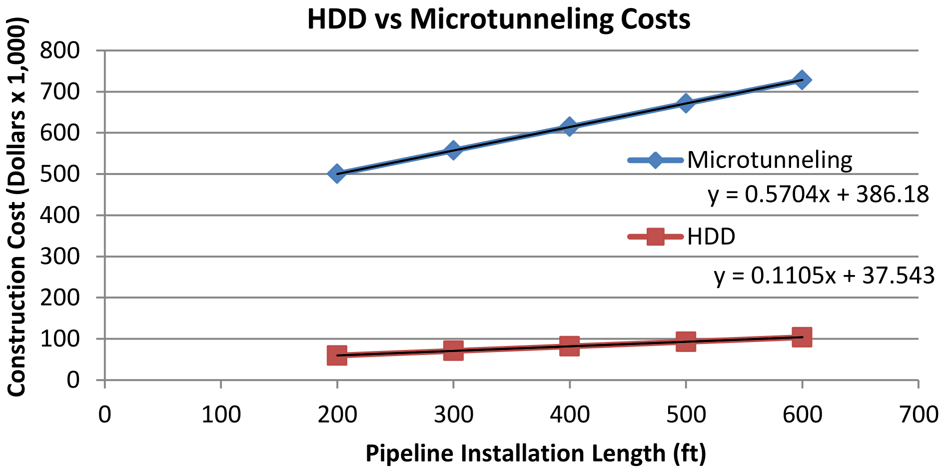

Figure 3. See the appendix for a breakdown of unit costs, analysis parameters, and assumptions that were used in the cost analysis. See Appendix A for a breakdown of unit costs, analysis parameters, and assumptions that were used in the cost analysis.

Cost of Installation Best Fit Linear Equations:

Microtunneling: $$Cost\ (\$) = 570.4(Drill\ Length) + 386{,}180, \quad (1)$$

HDD: $$Cost\ (\$) = 110.5(Drill\ Length) + 37{,}543, \quad (2)$$

The mobilization costs of microtunneling are substantially higher than those for HDD. Deep bore pits are required for such installations which can require substantial excavation shoring, depending on the site conditions. This difference is reflected by the high initial starting costs in the second terms of Equation 1 and Equation 2 ($386,180 and $37,543 respectively). Additionally, the cost per linear foot of drilling is significantly higher with microtunneling due to the use of expensive Microtunneling Boring Machines (MTBM). The cost difference per foot can be seen in the first terms of Equation 1 and Equation 2 with a cost per foot of $570.40 and $110.50 respectively. The installation costs increase linearly with increased bore length at a rate equal to the cost of drilling per foot.

This hypothetical scenario is typical, given the urban environments where water pipelines are often constructed. The typical scenario demonstrates the significant construction savings that plastic pipe materials can provide, due to the methods with which they can be installed. This analysis can also apply to less densely populated areas having rivers and railroads which must be crossed without disruption. Further, the light weight of plastic pipes leads to easier pipe handling and lower shipping costs to a construction site. The light weight of plastic pipes can also bring cost savings by eliminating the need for heavy duty equipment required to handle heavier pipe materials. Table 1 lists some weight and flexibility characteristics of some typical pipe materials. The weight of a typical 24 in. diameter pipe is considered, based on standard dimensions for length and wall thickness.

Table 1

List of Physical Properties of Various Pipe Materials

Physical Characteristics of Pipe Materials				
Pipe Material	Density (pcf)	Modulus of Elasticity (ksi)	Wall Thickness (in.)	20’ Pipe Section Weight (lbs)
Steel	490	31,000	3/8	1,894
RCP	160	2,000-6,000	2-3/8	3,586
DIP	440	56	3/8	1,701
HDPE	60	*110	1.4 (SDR 17.6)	828
PVC	81	*400	1.43 (DR 18)	1,140

Note. *Denotes Short Term Conditions. Adapted from *Recommended LRFD Specifications for Plastic Pipe and Culverts*, p. 5, by T.J. McGrath and V.E. Sagan. Copyright 2010.

Seismic reliability

Background. Seismic events pose substantial risk to underground utilities, which often experience a high incidence of breaks and leaks after earthquakes. The vulnerability of a pipe to ground movement induced failures is a function of its material stiffness. Flexible pipe materials have significantly lower rates of failure during seismic events than stiffer materials. This cause is derived from unstable crack propagation that occurs in stiff materials, making them brittle in the face of cyclic ground movements. Table 2 presents the strain levels at pipe failure for some typical water pipe materials.

Ground movement induced pipe failures occur from crack propagation within a pipe’s walls. Every pipe has voids and imperfections resulting from the fabrication process, environmental wear, and stress cracks. Stress concentrations exist locally around internal voids, with their intensity depending on the size and shape of the void. Flexible materials are able to redistribute concentrated stresses to adjacent fibers, while stiffer materials tend to maintain the concentrated stresses. Higher stresses cause localized cracks to propagate from the edges of the internal flaws. Small, dispersed cracking is tolerable for the pipe to perform acceptably without leaks. However, unstable crack propagation leading to coalescence of micro cracks into wide cracks leads to leakage and eventual failure through the pipe’s cross section.

Cost analysis. A comparison between plastic pipe and a number of common pipe materials is presented in the form of a hypothetical case study with the results presented in Figure 4, Figure 5, Table 3, and Table 4. The analysis predicts the anticipated repair costs associated with earthquake damaged pipe sections for a 10 mile section of pipeline in a seismic region. The pipeline repair costs are analyzed based on the anticipated number of breaks resulting from an array of potential fault rupture magnitudes over a time period of 75 years (typical design pipeline life). The rate of required repairs is based on a loss algorithm presented by which is formed from a rigorous statistical analysis of historical pipe performance data resulting from seismic events (Technical Council on Lifeline Earthquake Engineering, 1991). The pipeline characteristics are assumed to be the same for all pipe materials with the exception of the pipe strain at failure. The material flexibility is the property that greatly affects the predicted reliability of the pipeline after a seismic event.

Table 2

List of Strains at Failure for Various Pipe Materials

Pipe Material	Max Strain At Failure
Steel	0.012
Reinforced Concrete	0.004
Ductile Iron Pipe	0.010
HDPE	0.050
PVC	0.035

Note. Adapted from *Recommended LRFD Specifications for Plastic Pipe and Culverts,* p. 5, by T.J. McGrath and V.E. Sagan. Copyright 2010. Adapted from *Seismic Loss Estimates for a Hypothetical Water System*, Monograph No. 2, p. 6-38 – 6-43, by Technical Council on Lifeline. Copyright 1991.

Figure 4 **Number of breaks in pipeline over a 10 mile span**

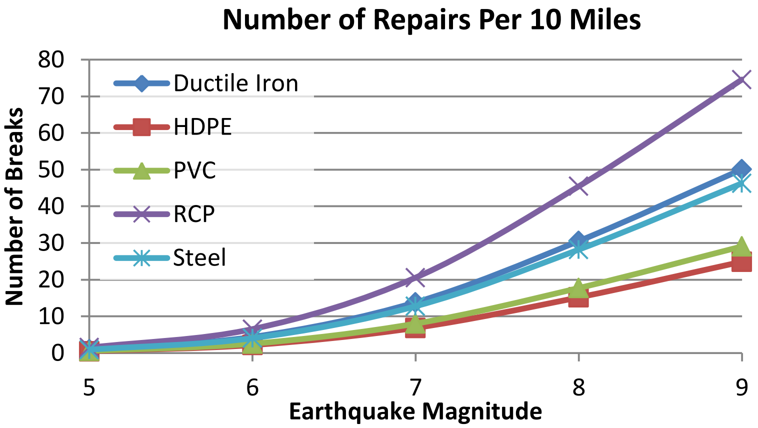

Figure 4. See Appendix B for a breakdown of unit costs, analysis parameters, and assumptions that were used in the cost analysis.

Figure 5 **Cost of repairing pipeline breaks over a 10 mile span**

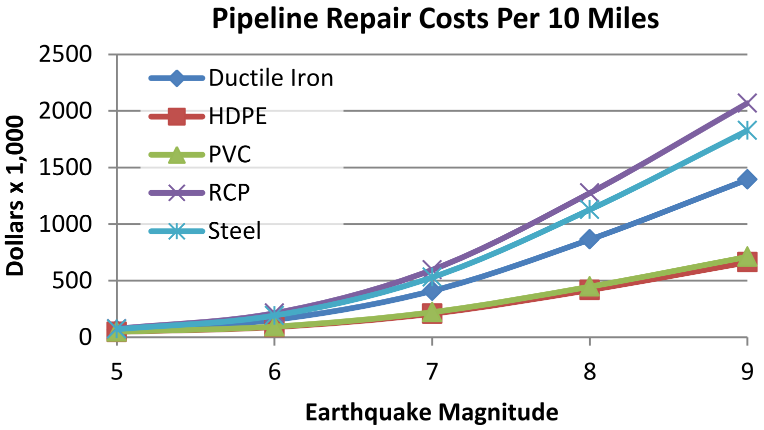

Figure 5. See Appendix B for a breakdown of unit costs, analysis parameters, and assumptions that were used in the cost analysis.

Table 3

Total Repair Costs (Dollars)

Pipe Material	Mag 5	Mag 6	Mag 7	Mag 8	Mag 9
HDPE	47,617	90,129	208,187	417,445	662.279
PVC	48,572	94,365	221,534	446,940	710,667
Ductile Iron Pipe	62,051	154,131	409,841	863,085	1,393,385
Steel	70,606	192,061	529,347	1,127,186	1,826,661
Reinforced Concrete	75,369	213,179	595887	1,274,233	2,067,904

Note. Cost of repairing pipeline breaks over a 10 mile span. See Appendix B for a breakdown of unit costs, analysis parameters, and assumptions that were used in the cost analysis.

Table 4
Normalized Repair Costs

Pipe Material	Mag 5	Mag 6	Mag 7	Mag 8	Mag 9
HDPE	1.0	1.0	1.0	1.0	1.0
PVC	1.02	1.05	1.06	1.07	1.07
Ductile Iron Pipe	1.30	1.71	1.97	2.07	2.10
Steel	1.48	2.13	2.54	2.70	2.76
Reinforced Concrete	1.58	2.37	2.86	3.05	3.12

Note. Normalized cost of repairing pipeline breaks over a 10 mile span based on HDPE. See Appendix B for a breakdown of unit costs, analysis parameters, and assumptions that were used in the cost analysis.

The results from the cost analysis predict significant differences in structural reliability among the different pipe materials. Both HDPE and PVC pipes are predicted to similarly outperform their counterparts. The results of the cost analysis may be extrapolated to predict repair costs for large, urban networks of pipes by directly scaling the costs for the total length of pipeline desired. The cost estimates are given in terms of earthquake magnitudes so the values can be correctly applied to a region based on a fault's "Maximum Credible Earthquake", which can be determined with the International Building Code, as well as other credible sources.

Internal corrosion resistance

Corrosion poses lifelong threats to the flow and environmental performance of underground pipelines. Material selection for a pipeline is the most significant tool in combating corrosive damage.

The effects of internal corrosion in steel and ductile iron pipes on water quality can be startling to public water customers. If the water being transported contains either a deficiency or excess of calcium carbonate, iron oxide (rust) is produced from the electrochemical reaction with the pipe material. Rust is easily removed from the corroded pipe's walls and is transported in the flowing water to the customer. The result is red water, which stains plumbing fixtures and laundry. Although safe for human consumption, water discolored by rust is not appealing due to the metallic taste and odor it produces (Smith, 1989).

Internal pipe corrosion significantly affects hydraulic flow performance. Metallic pipes suffer from tuberculation, a process in which corrosion products accumulate around the site of a corrosion cell. The layering of corrosion products protrude from the pipe's wall to form a tubercle, as seen in Figure 6, and creates flow turbulence. While the tubercle extends into the flow area, the reaction removes iron from the pipe wall and creates structural deficiencies. Concrete pipes face similar challenges when exposed to aggressive water. Excessive alkalinity pick-up (leaching) can occur during periods of low flow or stagnation, which results in the deposition of solids in plumbing and possible ingestion of the leached particles (Smith, 1989).

Figure 6 **Tubercle Formation Process**

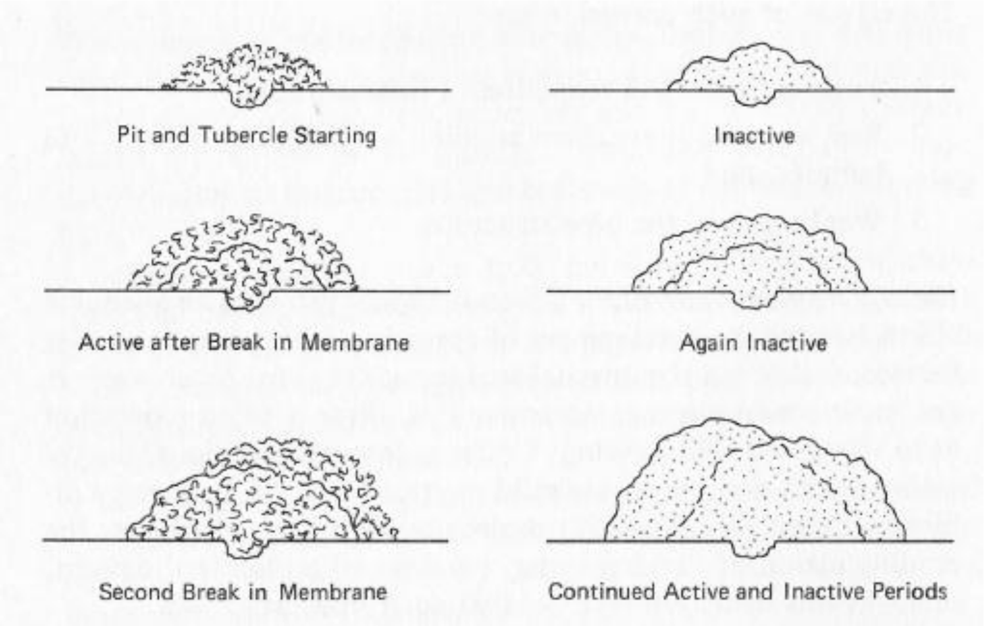

Figure 6. The formation process of a tubercle in the wall of a pipe. Adapted from *Corrosion Management In Water Supply Systems,* p. 38, by H. Smith. Copyright 1989.

Plastic pipelines are virtually immune from internal corrosion due to their lack of electric conductance. This is why plastic material is often used for internal liners in new and existing pipes to protect against corrosion and improve water quality. The installation of plastic liners requires additional expense over the raw material cost of the pipe, often making it economical to select plastic pipe over its electrochemically reactive counterparts at the time of construction.

Hydraulic flow performance

Background. The most basic function of a pipeline is to deliver its contents to its destination at the flow rate required. One of the challenges to water pipeline function is the loss of pressure head over the length of the pipeline. Hydrostatic head is the driving force behind pipe flow. The loss of pressure head can result from both elevation changes as well as frictional forces that develop from the pipe material boundary and its dynamic contents. Loss in hydrostatic head must be overcome by additional pump power for pressurized pipelines, which can add significant costs to a project.

Surface roughness coefficient. The surface roughness coefficient is an empirically determined factor that relates pipe materials to the frictional resistances they impart on their contents. The theoretical framework for modeling hydraulic pipe flow is based on zero fluid flow along the perimeter of the pipe. While the flow velocity is zero at the edges for all pipe materials, resulting in some head loss even for a perfectly smooth pipe, the material roughness produces viscous shear stresses within the fluid, which are proportional to the roughness coefficient. Smoother pipe materials lead to less frictional loss from viscous shear forces.

Plastic pipes such as HDPE and PVC have surface roughness coefficients approaching zero. For practical pipe flow analysis, designers typically use a surface roughness coefficient of zero due to the smoothness that plastic pipe manufacturing produces. Table 5 displays typical roughness coefficients for various pipe materials under new conditions, which are used in pipeline design.

Table 5

Roughness Coefficients for Various Pipe Materials

Pipe Material	**Equivalent Roughness, ε**
Riveted Steel	0.003-0.03
Concrete	0.001-0.01
Cast Iron	0.00085
Galvanized Iron	0.0005
Commercial Steel	0.00015
Plastic, Glass	0.0 (Smooth)

Note. Adapted from *Fundamentals of fluid mechanics (5th ed.),* p. 433, by B.R. Munson, D.F. Young, and T.H. Okiishi. Copyright 2006.

Internal corrosion frictional losses. Internal pipe corrosion occurs when the pipe material chemically or electrochemically reacts with its contents. Internal corrosion severely impacts a metallic pipe's roughness by wearing away cross sectional area and creating a rough surface. Plastic pipe cannot conduct electricity and is therefore not susceptible to electrochemical corrosion. While chemical reactions can lead to internal corrosion of plastic pipes, the levels of such chemicals (primarily chlorides, acids, and hydrocarbons) that can lead to this corrosion are not seen in water pipelines in such quantities (Smith, 1989).

The Hazen-Williams equation is an empirically based equation predicting pipe pressure head loss. The method uses a material coefficient much like the "Equivalent Roughness" values shown in Table 6. The values displayed in Table 6 are the Hazin-Williams Coefficients for surface friction of typical pipe materials at various durations after installation.

Table 6

Hazin-Williams Coefficients "C_w", for Various Pipe Materials

Pipe Material	New	25 Years	50 Years	Badly Corroded
PVC	150	140	140	130
Smooth Concrete	150	130	120	100
Galvanized Steel	150	130	100	60
Cast Iron	130	110	90	50
Riveted Steel	120	100	80	45

Note. Adapted from *Pipeline Design For Water Engineers (3rd ed.*), p. 19, by D. Stephenson. Copyright 1989.

While the rate of corrosion typically remains constant, its degradation of a pipe's smoothness accelerates over time (Liu & Meeker, 2012). This is due to the compounding effect of altering a previously altered surface. A rough surface is more easily worn by fluid flow as it causes local turbulence, causing further wear. The most efficient method to limit the rate of degradation over time is to limit the pipe's initial corrosive wear. Plastic pipe's lack of electrochemical potential leads to negligible corrosion over time as demonstrated in Table 6.

Cost analysis. A cost difference analysis has been performed to explore the expense of multiple pipe materials over a 75 year lifecycle due to pressure head loss in the pipeline. The hypothetical scenario is based on a 10 mile section of 24 in. diameter water supply pipe. The head loss due to friction from inherent pipe roughness properties and corrosive degradation over time are accounted for in the analysis. The results of the analysis are presented in Figure 7, Figure 8, Table 7, and Table 8.

The Colebrook Method was used for the initial pipe material friction losses using the coefficients listed in Table 1 and the Hazen-Williams Method was used to model the friction losses over time due to corrosion, using the values listed in Table 2. The effective costs incurred result from extra pump horsepower required to overcome the pressure loss.

Figure 7 **Pressure head loss over 10 miles**

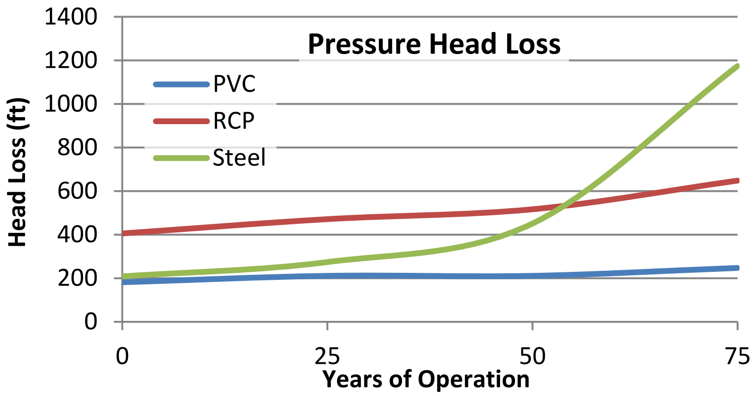

Figure 7. See Appendix C for a breakdown of unit costs, analysis parameters, and assumptions that were used in the cost analysis.

Figure 8 **Required pumping costs to overcome friction losses over 10 miles**

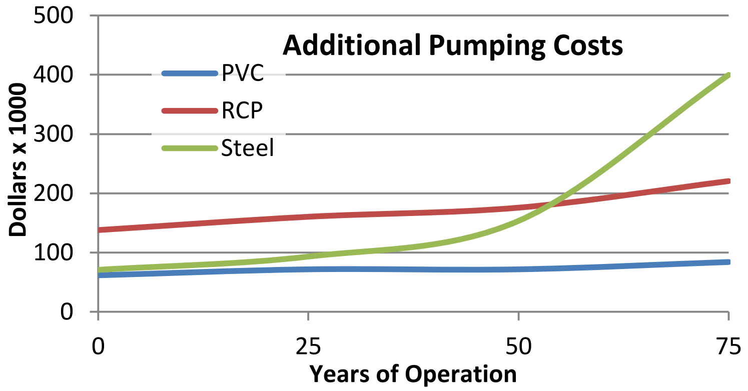

Figure 8. See Appendix C for a breakdown of unit costs, analysis parameters, and assumptions that were used in the cost analysis.

Figure 7 and Figure 8 demonstrate the significant impact that material properties can have on pumping costs for pressurized pipelines. The most significant driving force behind pipe corrosion is the electrochemical reaction involving metallic components of a pipe. Steel and reinforced concrete pipes are suseptable to internal, electrochemical corrosion, while plastic pipes are not. The initial flow performance of steel and plastic pipe is initially comparable, while reinforced concrete pipe causes an initial pressure loss increase by roughly a factor of two. However, over time the flow characteristic performance of steel pipe is eclipsed by that of reinforced concrete pipe. Reinforced concrete pipe electrochemical corrosion is due to the presence of steel reinforcement. The difference in quantity of steel between reinforced concrete and steel pipes is what causes the corrosion of steel pipe to drastically outpace its counterparts. Throughout the lifecycle of the hypothetical pipelines, plastic pipe's flow performance remains relatively unchanged. From the time of pipe installation to the end of the pipe's lifecycle, the plastic pipe's flow performance exceeds the other materials'.

Table 7

Required Pumping Costs (Dollars) Per 10 Miles / Pumping Power (HP)

Pipe Material	0 Years	25 Years	50 Years	75 Years
HDPE/PVC	61,765 / 41.2	71,831 / 47.9	71,831 / 47.9	84,173 / 56.1
RCP	137,062 / 92.0	160,470 / 107.0	175,846 / 117.2	220,661 / 147.1
Steel	70,930 / 47.3	93,338 / 62.2	153,530 / 102.4	399,738 / 266.5

Note. Required pumping costs to overcome frictional losses over 10 miles and the corresponding pumping power. See Appendix C for a breakdown of unit costs, analysis parameters, and assumptions that were used in the cost analysis.

Table 8

Normalized Additional Pumping Costs

Pipe Material	0 Years	25 Years	50 Years	75 Years
HDPE/PVC	1.00	1.00	1.00	1.00
RCP	2.24	2.24	2.45	2.62
Steel	1.15	1.30	2.14	4.75

Note. Normalized pumping costs to overcome frictional losses over 10 miles based on HDPE and PVC pipes. See Appendix C for a breakdown of unit costs, analysis parameters, and assumptions that were used in the cost analysis.

The results of the cost analysis may be extrapolated to predict repair costs for large networks of pipes by directly scaling the costs for the total length of pipeline desired. The scalability of the results have been maintained by remaining independent of elevation changes and external factors which are constant for all of the pipe materials.

The anticipated drop in pressure head over the life of the pipe must be considered when designing a pump station. Initially accounting for future pressure loss can be expensive since the typical cost of constructing a pump station is $1,500/foot of pressure head (Menon, 2012).

Plastic pipe provides the benefits of low initial pressure loss due to its smooth surface as well as high resistance to internal corrosion over time. Significant cost savings can be realized over the life of the pipeline, making plastic pipe materials the most attractive material choice for many new water pipeline projects.

Discussion

Plastic materials are valuable tools in the design and construction of pipelines. The cost analyses performed demonstrate significant cost savings associated with the use of plastic pipes over more historically prevalent materials. While dollar for dollar comparisons demonstrate the significance of plastic pipe's advantages, such comparisons undervalue the totality of advantages that plastic pipe material brings. The direct economic pipeline costs are highly interconnected with social consequences among the greater public.

Water distribution systems are municipal by nature so the costs associated with municipal water pipelines are shared among a combination of public sources. The funding for public pipeline projects is derived from customer rate increases, state and local tax revenues, grants, loans, bond sales, and federal funding for projects deemed the most critical (Loera & Pridmore, 2011). The recent worldwide economic climate has highlighted the difficulties, which social budgets can experience when tax revenues falter and less funding is available for public works projects. Under such circumstances, the costs of public works projects can have a profound effect on public budget allocations.

When public funding sources are at a premium, the high cost of municipal pipeline construction and maintenance can degrade the availability of funds for other public works projects and social services. Plastic pipe materials have excellent performance and reliability characteristics, which can leave more room in public budgets. While pipeline maintenance costs are inherently variable, the reliability of plastic pipe materials allows for more accurate long-term cost forecasts. The greater reliability of plastic pipe also limits the number of emergency repairs required over the life of a pipe. The price per foot of pipe for emergency pipe repairs is often high, as mobilization costs are spread over smaller, finite lengths of construction compared with the initial, large construction length. The costs of unanticipated pipe repairs can contribute to local budget shortfalls since proper funding cannot always be secured in such short time periods. The high cost of pipeline construction can also lead to a project being deemed cost ineffective, leaving the public with aged water systems that must process water flow rates exceeding their design quantities over time. An overstressed pipeline has a greater likelihood of developing leaks and a need for repairs, ultimately running up long-term maintenance costs and exposing water customers to environmental hazard. Plastic water pipelines deliver superior environmental performance due to their resistance to corrosive and chemical attack.

The availability of public funding to deliver sufficient water infrastructure investment will likely be challenged more with time. Water agencies are faced with the challenge of delivering increasing quantities of water to match pace with population demand. All the while, the availability and ease of withdrawal from fresh water sources is on a downward trend. The most cost effective freshwater withdrawal sources have historically been from rivers and large surface bodies of water. However, those resources are already being drawn from at critical levels. Lake Mead is among the largest freshwater withdrawal sources in the United States, supplying Southern Nevada, Arizona, and Southern California with drinking water. At current rates of withdrawal and decrease in snow pack from increased regional temperatures, there is a 50% probability that minimum live storage levels will be reached by 2021 (Barnett & Pierce, 2008). Such scenarios are not isolated to Lake Mead, but are faced by hydrological regions nationwide.

In the near future, surface water sources will need to be supplemented and replaced by deep groundwater pumping and alternative sources such as desalination of non-freshwater sources. These challenges are further compounded by increased groundwater pumping, which often lowers the local groundwater table when ground infiltration recharge cannot keep pace with withdrawals. This has a dramatic effect, which can be seen with the Ogallala Aquifer across vast agricultural regions of Texas. The groundwater depth has increased by 100-150 feet over the past sixty years, which has greatly increased the difficulty of groundwater pumping (Postel, 2012). Areas experiencing rapid urbanization are further vulnerable to groundwater depletion, as the ability for surface water to infiltrate the earth is limited due to impermeable asphalt and concrete at the surface (Center for Sustainable Systems, University of Michigan, 2011). As an aquifer becomes depleted, the water table lowers and the costs of withdrawal increase due to the additional required depth and pumping power required. The cost of withdrawal from these sources is exceedingly expensive, but will soon become cost-effective as demand continues to increase.

The cost savings resulting from choosing plastic pipe materials will help to offset increases in the cost of water withdrawal as current water sources become depleted. Plastic pipe selection is not only beneficial for the construction and maintenance of a pipeline, but also is a positive investment in the sustainability and reliability of a modern water infrastructure. The reliability, flow performance, and low long-term costs of plastic pipe materials make them an important piece of a complex solution to address future water demands.

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Appendix A

Microtunneling vs HDD Installation Costs

Description of pipeline. The pipeline being installed is a 12 in. diameter municipal water pipeline. The HDD method of installation is more feasible with HDPE or PVC plastic materials while microtunneling is more conducive for other pipe materials such as steel, ductile iron pipe, or concrete.

Primary installation obstacle. The pipe must be installed underneath a river. The depth of the river is only moderately deep at 10 ft requiring a minimum of 9 ft of cover above the proposed pipe. The maximum depth of the pipeline will be 20 ft to account for the required cover and pipe diameter.

Construction cost values. The following costs are given in dollars per unit. The drilling length varies for both microtunneling and directional drilling to explore the effect of the drill length. Also, the directional drilling cost per foot estimate accounts for the multiple reaming passes that are required.

Table A.1.
Construction cost values

Construction Activity	Unit, Quantity	Material	Labor	Equipment	Total	O&P
Microtunneling						
Drilling Costs (50 ft/day)	LF, Varies	X	X	X	415	457.50
MTBM Rental	Month, 1.0	X	X	X	92,000	101,000
Operating Technician	Day, 12	X	X	X	610	680
Mobilization / Demobilization	Job, 1.0					
Minimum		X	X	X	40,000	45,000
Maximum		X	X	X	420,000	462,000
Average		X	X	X	230,000	253,500
Directional Drilling (HDD)						
Drilling Costs (50 ft/day)	LF, Varies	0.03	2.63	3.6	6.29	8.04
Unit Setup Per Drill	Each, 1.0	X	230	315	545	695
Mobilization / Demobilization	Each, 1.0	X	460	630	1090	1395
Mud Trailer	Day, 8	X	360	310	670	880

Note. Adapted from *RSMeans Heavy Construction Cost Data*, by Reed Construction Data. Copyright 2012.

General estimate method and assumptions. Only the operational cost differences between the two methods were explored in this analysis. Some factors not included in the analysis include pipe material costs, dewatering, traffic control, and fill/compaction costs at the bore and receiving locations. These were not included in the analysis because they do not have significant effects on the difference in total installation costs. While direct pipe material costs are not significantly different in this analysis, the means of installation is dependent on pipe material, which drastically affects the construction costs.

Appendix B

Seismic Performance Study

Description of pipeline. The pipeline being installed is a 24 in. diameter municipal water pipeline. The pipeline is in a seismically active region and has a depth of 12 in. to its spring line. The analysis is performed based on a 10 mile section of the pipeline. The results of the analysis can be accurately scaled proportionally to longer or shorter pipe lengths.

Primary operational challenge. The pipeline will be subjected to seismic events of varied magnitude. The seismic events result in a number of breakages per unit length of pipeline, which must be repaired and replaced at each location.

Table B.1.
Construction cost values

Construction Activity	Unit	Material	Labor	Equipment	Total	O&P
Excavation /Repair Work						
Earthwork, 1.5 CY Excavator	CF	X	1.38	2.00	3.38	4.30
Dewatering Sump w/12in. Pipe	LF	24.00	13.15	4.77	41.92	51.75
Bedding Placement	LCY	31.5	6.15	2.23	39.88	46.3
Bedding Compaction	ECY	X	3.12	0.36	3.48	5.19
Structural Backfill	LCY	X	1.13	1.60	1.95	
Crushed Rock Base	TON	18.90	1.97	1.85	22.72	26.03
Asphalt Replacement	SY	11.55	22.00	1.86	35.41	48.50
Temporary Traffic Barriers	EA/DAY	X	X	X	X	4.33
Trench Shoring Equipment						
8 ft x 24 ft Trench Shield	EA/WK	X	X	X	X	400
6 ft x 24 ft Trench Shield	EA/WK	X	X	X	X	200
Pipe Materials						
HDPE, Mech. Joints, 24 in.	LF	67	16.05	10.7	93.75	109.8
PVC, DR 25, 24 in.	LF	43	12.75	X	55.75	66.4
DIP, Mechanical Joints, 24 in.	LF	82	32	13	127	152.8
Steel, 3/8 in. Walls, 24 in.	LF	240	66	43	349	411
RCP, 24 in.	LF	114	16.65	5.45	136	156
Design Services						
Surveying	EA	X	X	X	X	2,000
Geotechnical Investigation	EA	X	X	X	X	5,000
Total Engineering Design	EA	X	X	X	X	22,000
Field Personnel						
Field Engineer	EA/WK	X	X	X	X	1,750
Super Intendant	EA/WK	X	X	X	X	2,650

(Table B.1. Continued)

Project Manager	EA/WK	X	X	X	X	2,875

Note. The following costs are given in dollars per unit. Adapted from *RSMeans Heavy Construction Cost Data*, by Reed Construction Data. Copyright 2012.

General estimate method. The number of breaks is predicted using the loss algorithm presented in "Seismic Loss Estimates For A Hypothetical Water System" released by the Technical Council on Lifeline Earthquake Engineering (Technical Council on Lifeline Earthquake Engineering, 1991). The loss algorithm is based on a rigorous statistical analysis based on historical performance data and is as follows:

$$Log[\bar{Y}] = \alpha_S \alpha_o I - \beta_s \beta_o - \beta$$

With "I" Determined By The Following Linear System:

$$Log[PHA] = -3.073 + 0.293I + 0.142S_2$$

$$ln[PHA] = -3.303 + 0.85M - 1.25ln[R + 0.0872e^{0.678M}] - 0.0059R + 0.41S_1$$

Pipeline analysis assumptions.

- Pipeline Section Length = 10 Miles
- Pipe Diameter = 24 in.
- Pipe Spring Line Depth = 12 ft
- Pipeline Section Length = 20 ft
- 50 percent of breaks occur within street or sidewalk areas.
- 50 percent of breaks occur at the pipe joints.
- Trench Depth = 14 ft

- Trench Width = 8 ft
- Bedding Thickness = 12 in.
- Compacted Fill Depth = 3 ft
- Crushed Base Rock Depth = 6 in.
- Time of Repair Per Break = 1 Week Including Hydro-Testing
- Distance From Active Fault = 5 Miles

Appendix C

Flow Performance Study

Description of pipeline. The pipeline being installed is a 24 in. diameter municipal water pipeline. The pipeline is part of a pressurized system which is driven by hydraulic pumps. The analysis is performed based on a 10 mile section of the pipeline. The results of the analysis can be accurately scaled proportionally to longer or shorter pipe lengths.

Primary operational challenge. The required pressure head of the pipeline will need to overcome the initial friction loss associated with its material. Additionally, friction losses will increase over time due to internal corrosion. In order to overcome lifetime pressure head loss, the hydraulic pumping power must be adequate to cover current and future pressure head losses.

Hydraulic flow analysis methods.

Initial friction losses. The initial pipe material friction loss is determined using the Darcy-Weisbach Equation. The expression requires the use of a frictional resistance coefficient, “f”. The friction coefficient is determined by the Colebrook Formula, which is valid for all nonlaminar flow.

Darcy-Weisbach Equation: $h_L = f \frac{l}{D} \frac{V^2}{2g}$

Note. Adapted from *Fundamentals of fluid mechanics (5th ed.),* p. 433, by B.R. Munson, D.F. Young, and T.H. Okiishi. Copyright 2006.

Colebrook Formula: $\frac{1}{\sqrt{f}} = -2Log\left[\frac{\varepsilon}{3.7D} + \frac{2.51}{Re\sqrt{f}}\right]$

Note. Adapted from *Fundamentals of fluid mechanics (5th ed.),* p. 433, by B.R. Munson et al. Copyright 2006.

Corrosion induced friction losses. The impact of corrosion over time on the pipeline's friction loss is estimated by the use of the Hazen-Williams Method.

Hazen-Williams Equation: $S = K\frac{V}{C_w}^{1.85}\frac{1}{D^{1.167}}$

Note. Adapted from *Pipeline Design For Water Engineers (3rd ed.*), p. 19, by D. Stephenson. Copyright 1989.

Required pump horsepower.

Pump Power: $P = \gamma Q h_P$

Note. Adapted from *Fundamentals of fluid mechanics (5th ed.),* p. 433, by B.R. Munson et al. Copyright 2006.

Pipeline analysis assumptions.

- Pipeline Section Length = 10 Miles
- Pipe Diameter = 24 in.
- Pump Station Construction = $1,500 Per Foot of Pressure Head

Note. Adapted from *Liquid Pipeline Hydraulics,* p. 454, by E.S. Menon. Copyright 2012.

- Pipe Flow Rate = 2 $\frac{lb}{ft^3}$

Appendix D

Notation List

α_o	Slope of Seismic Loss Algorithm
α_S	Slope Modifier For Seismic Loss Algorithm Based on Soil Condition
β	Modification Factor For Seismic Loss Algorithm Soil Modifier
β_o	Y-Intercept For Seismic Loss Algorithm Based on Soil Condition
β_s	Soil Modifier For Seismic Loss Algorithm
γ	Soil Density, $\frac{lb}{ft^3}$
ε	Pipe Strain At Failure
C_w	Hazin-Williams Friction Coefficient
D	Inner Diameter of Pipe, ft
I	Modified Mercalli Intensity
K	Hazin-Williams Dimensional Coefficient, 3.03 (U.S. Customary Units)
M	Earthquake Magnitude
P	Hydraulic Pump Power, $\frac{ft \times lb}{s}$
PHA	Peak Horizontal Ground Acceleration, $\frac{ft}{s^2}$
Q	Hydraulic Flow Rate, $\frac{ft^3}{s}$
R	Distance Away From Fault Rupture, $mile$
Re	Hydraulic Flow Reynolds Number
S	Pressure Head Loss Gradient, $\frac{ft}{ft}$
S_1	Site Factor For Soil Depth
S_2	Site Factor For Soil Type
V	Hydraulic Velocity, $\frac{ft}{s}$
$\bar{Y}$	Probability of Pipe Failure For Seismic Loss Algorithm
f	Frictional Resistance Coefficient
g	Acceleration Due To Gravity, $32.2\frac{ft}{s^2}$
h_L	Hydraulic Pressure Head Loss Due To Friction, ft
h_P	Hydraulic Pressure Head, ft