



PROJECT NO.
4650A



An Evaluation of the Value of Structurally Enhanced PVC Pipe

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2018

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WRF ISBN: 978-1-60573-338-8

WRF Project Number: 4650A

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ACKNOWLEDGMENTS

This research was performed under the leadership of The Water Research Foundation (WRF), Denver, CO, and American Water (AW), Voorhees, NJ. The researchers are grateful to the WRF for taking the lead in providing funding for this project. We would like to thank Jonathan Cuppett from WRF and the Project Advisory Committee members: Graham Bell from HDR, Barry Usagawa from the Honolulu Board of Water Supply and Frank Lau from EPCOR. Special mention is given to the Missouri American and New Jersey American staff that facilitated the first installations of the iPVC pipe in North America and offered their constructive suggestions with a new product.

EXECUTIVE SUMMARY

KEY FINDINGS

- The results from standard tests considered in this research confirmed that iPVC pipe is suitable for use in the North American water industry.
- Users can expect iPVC pipe to be more robust during handling, installation, and operation than conventional PVC.
- Based on fatigue tests, the pipe is projected to have a very long life.
- A field installation guide was prepared based on insight gained from actual pipe installations.

OBJECTIVES

It is the purpose of this research to capture and report on the strength characteristics of enhanced varieties of polyvinyl chloride (PVC) pipe. This report seeks to provide utilities with a balanced comparison of pipe alternatives and specifically focus on the installation requirements of the PVC materials to place these pipes into service. Despite an AWWA standard for PVC-O (C909; AWWA 2009b), American Water perceives there is a significant gap in the awareness of water utilities about this PVC alternative, as the standard does not highlight much about its significant strength.

This research is intended to identify the pipe characteristics and provide a modified user's manual for the enhanced PVC product. It is also a goal to make utilities aware of significant observations made during the installation process by the experienced PVC pipe installers. Utilities require thorough information about the new breed of structurally enhanced PVC water piping in order to make proper decisions concerning the PVC alternatives. This research seeks to highlight the characteristics and demonstrate the true installation requirements of the structurally enhanced PVC. The focus will be upon iPVC to include installation criteria that match the physical characteristics of the material. The secondary benefit of the project is to introduce a potentially innovative new PVC product into the marketplace.

BACKGROUND

Many U.S. utilities rely upon iron pipe to deliver water through their distribution networks. It has only been in the past 50 years that other pipe materials have penetrated the water utility market. Some water utilities have turned to various cementitious and plastic materials, largely to overcome aggressive soils that can be corrosive to the metallic pipes or in search of less expensive alternatives. Nonmetallic pipe to date has not offered the high strength and ductility of the iron pipe, and many utilities have favored that strength and combat the threat of corrosion through polyethylene lining, cathodic protection, and various coatings on ferrous pipe. With less than 60 years of experience with the pipe, estimates about the useful life PVC pipe vary from 75 to 150 years.

Like iron pipe, PVC pipe appears capable of evolving in its manufacture. Cast iron shifted from pit cast to spun cast to ductile with a resulting enhancement of strength. The introduction of a new structurally enhanced PVC pipe, called iPVC, has added to the variety of PVC pipe options already in the market. The iPVC pipe was developed in South Korea by Pyungwha Pipe Industry

Inc. (PPII) and currently is used for water distribution systems in Japan, China, and South Korea. iPVC pipe has been certified by the National Sanitation Foundation as NSF 61 certification compliant and meeting the American Water Works Association (AWWA) C-900 standard.

PPII manufactures the pipe in South Korea in 4, 6, 8, 10, 12, 16, 20, and 24-inch diameters with dimension ratios of DR 14, DR 18, and DR 25. After PPII approached American Water (AW) about the pipe material, it was decided to pursue funding to explore the iPVC potential. AW applied for and received funding for this project from WRF to perform testing, evaluate the structural properties, and install the pipe. AW partnered with Center for Underground Research and Education (CUIRE) at the University of Texas at Arlington (UTA) to determine the scope of testing to be performed.

APPROACH

The project approach consisted of several defined steps:

- Literature Review – Armed with testing already performed on the iPVC product, the characteristics of various PVC materials were reviewed and compared. American Water’s investigations identified the design characteristics that are key to the installation of PVC pipe. The review provided full familiarity with bedding, backfill, and loading criteria. American Water investigators collected verifiable data from prior material testing of the iPVC and PVC-O products, as well as key material characteristics of ductile iron pipe.
- Testing Preplanning – A regimen of testing to confirm some characteristics of iPVC and to explore criteria directly related to installation practices was prepared. From the time of the proposal, it was thought that selective tests on the pipe would include impact, stiffness, tensile, short-term hydraulic burst pressure, and fatigue testing. What was needed was a form of a field bedding test, preferably prior to pilot installations and operation of the pipe as part of an active system.
- Material Testing – UTA CUIRE met with American Water and agreed on an appropriate regimen of testing, then began performing some of the tests. Owing to the need to perform some testing well past the conventional PVC range and time constraints, AW subsequently divided the material testing for the research project between UTA and Microbac Laboratories, Boulder, Colorado. The goal was to perform the testing in advance of the installation phase.
- Testing Review and Analysis - UTA CUIRE and Microbac reported their findings on the iPVC. The most important function of testing was to see how the results might affect pipe installation. It was also important to convey the data to Missouri American Water (MOAW) to encourage the pipe’s adequacy to function in the distribution system. The iPVC test results were compared to information gleaned from studies on ductile iron pipe and PVC-O pipe.
- Field Installation – MOAW installed 1,500 feet of iPVC (shipped by PPII from Korea, as they do not yet have a United States-based manufacturer in place). MOAW selected a site, drew up plans, and secured permits. The installation was originally planned for summer 2015, but delays pushed the installation into 2016. MOAW staff (installation and engineering) provided key comments on the product, as they are experienced in the installation of PVC.

- Project Output – American Water monitored the field installation and prepared installation guides tailored to the products installed and employing the insights from MOAW staff.

RESULTS/CONCLUSIONS

The literature review contained testing results on the iPVC pipe that showed that the product often exceeded AWWA C900 criteria by at least 10-20%. Researchers were surprised at the lack of actual PVC-O testing information. PVC-O is an extruded PVC (as is iPVC), but there is no evidence of mass testing results by independent laboratories. PVC-O manufacturers were contacted, but they provided little supplemental material testing data. The AWWA C909 standard may not provide performance criteria that would differentiate it from C900 PVC other than the thinner wall dimensions (AWWA 2009b). Consequently, comparison between the PVC materials in the U.S. market was very limited. This would be a matter for AWWA standards committees to consider addressing in the future.

Unlike PVC-O pipe that elected to reduce pipe wall thickness with the added strength of that PVC material, PPII retains the pipe wall thickness to match the pipe wall thickness typical of ductile iron pipe. With less material per foot, PVC-O is less expensive to produce and ship and a lighter weight product to handle and install. iPVC would appear to offer greater strength and more compatibility with fittings and restraints made for ductile iron.

The selection of testing methods for iPVC pipe held very much to those suggested in the original project proposal. The challenge with the testing was to execute sufficiently challenging tests expeditiously. The use of Microbac Labs immediately improved the speed of some testing, as they had the necessary facilities to carry out the impact and stiffness tests at a higher capacity than UTA. They also were able to be a second test location for the tensile and hydrostatic burst tests. UTA extended the fatigue test beyond the proposed 2 million cycles. The bedding test was modified during the project; pipe length, additional sensors, and stabilizing backfill were added before the full test was executed.

The testing confirmed the high strength and ductility in iPVC when compared to conventional PVC pipe. The tensile, impact, hydrostatic burst, and stiffness tests exceeded AWWA standards. It was only when the temperature of the pipe was lowered that the high capacity of the impact test actually fractured the pipe. The stiffness test and bedding test proved most instructive concerning the behavior of the pipe in the trench. The stiffness test showed a pipe withstanding 1,000 psi resulting in full height reduction (to 20% where the bottom and top of pipe touched) without breaking the pipe. The bedding test showed that fully loaded trucks had minimal impacts on an empty pipe, with backfill soils to the crown of the pipe having poor characteristics.

Impact Test

The impact test was performed as per ASTM D2444 (ASTM 2011b) standards with a standard 100-pound tup A (cone-shaped) as the falling weight dropped from a height of 12 feet (maximum height at the lab performing the work). The tup generated maximum impact energy of 1,200 foot-pounds with this height and weight combination. The test was performed on 35 pipe samples with this configuration and failed to fracture any of the samples until the temperature of the iPVC was dropped to 32 degrees Fahrenheit. This test resulted in the breaking of the pipe samples at 1,050 foot-pounds (dropping the 100-pound tup from a drop height of 10.5 feet). The test demonstrated the resilience of the material for field activity borne out by various efforts by

MOAW to damage the pipe and a number of demonstrations available in the company literature. It should be noted that similar demonstrations could be found in brochures provided by PVC-O manufacturers.

Hydrostatic Burst Test

Both UTA and Microbac Lab conducted the short-term burst pressure tests. This test provides a rapid increase in pressure to a pipe sample to the point that the pipe fails. The testing was performed per ASTM D1599. The purposes of the test were to determine the ultimate burst pressure of the iPVC pipe and to study the way this pipe might fail in the field.

Microbac tests had an average pressure of failure of 1,033 psi, taking 123 seconds as an average failure time. The average failure pressure is 40% higher than the AWWA C900 and C909 requirement for DR 18 pipe (755 psi for DR 18 pipe), and the average failure time is 76% more than maximum 70 seconds taken to reach 755 psi. Microbac observed two types of failure: a catastrophic failure in which the pipe shattered into pieces implying some brittleness, and a ductile failure where the pipe expanded in size before ultimately splitting to a far less extent and appearing less brittle. Microbac Lab tests had four ductile and six catastrophic failures of iPVC. What is interesting to note is that a slower pressure increase to failure in some of the Microbac tests resulted in the ductile expansion of the pipe and small leaks, in contrast to faster tests to failure that generated a catastrophic shattering type of failure.

The hydrostatic short-term burst pressure tests demonstrated how strong the pipe is under excessive pressure and offered some clues as to how the pipe might fail in the field. Sudden pressure could conceivably cause fracturing, but it is thought more likely that pressure changes associated with the eventual failure will tend to cause the pipe to expand. Most importantly, the pipe will not split longitudinally.

Stiffness Test

Microbac Lab performed the stiffness tests per ASTM D2412. This test is used to determine the deflection and vertical load resistance of the pipe, a key design element for pipe installation; the maximum load deflection allowed for PVC pipe is 5%. The test places pipe samples between two parallel plates of machine and a controlled load is applied on 8-inch iPVC pipe samples. The behavior of pipe was studied at 5% outside diameter (OD) reduction increments from 95% of pipe height through 20% or until the inner walls of pipe are in contact. Ten samples were tested and the average pipe stiffness at 95% OD deformation loading was 451 psi, exceeding the minimum AWWA (AWWA 2002) requirements of 364 psi at 95% OD deformation by over 23%. At maximum deformation to the point where the top of the pipe met the bottom of the pipe, the pipe did not crack. That maximum deformation was at slightly less than 20% of original OD under an average pressure load of about 7,500 psi.

The stiffness test was the lab test that offered the most insight into how the pipe might perform in the trench. The pipe showed both resistance to vertical load and flexibility when that vertical load was excessive.

Tensile Test

Microbac conducted tensile tests per ASTM D638, Type I dimensions. Each sample was prepared by trimming the mid-wall section of the pipe in the form of standard dumbbell-shape and

was tested under defined conditions of pretreatment, temperature, humidity, and testing machine speed. The average tensile strength observed for the test was 7,930 psi with a calculated modulus of elasticity of 461,000 psi. The calculation was greater than the results provided by PPII. The testing results exceeded the AWWA C900 pipe requirement by 13% in tensile strength and the calculated modulus of elasticity by 15%. The modulus is a major component in design calculations used to define trench requirements. UTA tested samples prepared by PPII that were categorized as Type III samples. The Type I samples were judged to be most appropriate, and UTA did have some technical issues with their equipment.

Fatigue Test

The fatigue test demonstrated the resiliency of the iPVC pipe. A 10-foot pipe section was subjected to two million cycles of pressures between 150 and 225 psi about every 10 seconds. There was only a marginal change in the pipe circumference when the pipe was pressurized, and the pipe remained stable through the process. The manufacturer requested that the UTA test continue for an additional two million cycles, and the pipe completed this additional testing without failure and again minimal change in diameter.

The fatigue test has been used to project pipe life based upon the assumption that cyclic pressure is a primary cause of ultimate failure in PVC pipe. Based upon the results from the first two million-cycle test, a projected life of 122.5 years has been estimated using industry calculations. If cyclic pressure is a primary cause for PVC pipe failure, it does not appear to be a major concern for the iPVC pipe. PPII will be evaluating the ten-foot section of pipe in the near future.

Bedding Test

The formal bedding test allowed for full monitoring of a buried empty pipe under dead and varying live loads. The results show little more than a 1% deflection of the pipe in poor soils with a fully loaded dump truck running (and braking) over the trench. The results confirmed the potential of the pipe to be used in poor soils under normal loading conditions and to meet PVC deflection design criteria. The Spangler equation and Modified Iowa equation both showed good correlation to field results.

Pilot Installation

MOAW provided a site and design for the installation of 1,500 feet of 6- and 8-inch DR 18 iPVC pipe at a St. Louis County location with aggressive high silty clay content soils. The project site was at the southern extreme of St. Louis County, not far from the Meramec River. The project area had highly corrosive silty soils and experienced flooding in January 2016, a few weeks prior to installation.

New Jersey American Water provided a second site for installation. A contractor with New Jersey American Water placed the pipe in existing streets. The contractor completed a 2,000-foot installation under suburban streets. There were 47 service connections made on the pipe. This pipe also featured Trelleborg gaskets, which provided more range of motion for the pipe installed. This led to an expectation that the iPVC pipe could be deflected at the joint, though the extent of the change was not evaluated in this study.

The field installations served multiple functions for the researchers and PPII. Installation processes included handling, cutting, trimming, tapping, and connecting to various fittings and other pipe materials. PPII representatives on site learned about improved ways to package the pipe for shipment. The iPVC pipe was flushed, pressure tested (200 psi), and disinfected per AWWA C605 guidelines. The service connections were achieved by hot tapping the pipe using appropriate tapping and saddle. Both MOAW and New Jersey American Water confirmed that the installation of the iPVC pipe was no different from the conventional PVC pipe installation. One difference in the New Jersey installation was a new thinner gasket that allows deflection. The manufacturer is exploring the feasibility of deflection, but if it is similar to PVC-O a deflection of at least 3 degrees should be acceptable.

APPLICATIONS/RECOMMENDATIONS

As water utilities are confronted with aging infrastructure, they are looking to replace pipe with materials that will last as long as some of the original pipe placed in the ground over a century ago. At the same time, there is a need for all water utilities to be more enlightened about the developments in pipe materials in general. In this case, the introduction of a new product from Korea allows more light to be shed upon a product largely unused by U.S. utilities, the structurally enhanced PVC-O. The two products offer an interesting contrast. With increased strength, PVC-O has mimicked the path of iron pipe by going to a thinner wall when a technique to make the material stronger is put in place. PPII has elected to maintain the pipe wall thickness and offer increased comparable strength. We believe that the iPVC alternative is appropriate for PVC and, if so, utilities stand to benefit.

The testing results from this project suggest that the new iPVC addresses some of the weaker aspects of PVC: robustness during handling, installation, and operation; improved resistance to surge; avoidance of the tendency to fail longitudinally; and greater strength that translates into fewer constraints for backfill. Further study by the manufacturer that bears watching includes the potential ability to deflect pipe at the joints and resistance to earthquakes.

A preliminary analysis based on expected economies in backfill, installation time, and other factors should encourage utilities. However, the product's strength and ductility offers the most important feedback to utilities looking for a longer lasting pipe that resists corrosion. It should be illuminating to the water utility industry that innovation of plastic pipe has not stopped. This could motivate manufacturers of all pipe products to continue to enhance their products. Finally, WRF will continue to be associated with innovation in materials and be valued by water utilities as a place to go to learn of new products.

Throughout the testing of the iPVC pipe, there was a strong desire on the part of the researchers to make comparisons with other products, particularly the thinner walled extruded PVC-O pipe. It was somewhat surprising to find a lack of published testing results on the plastic products given the performance of PVC pipe in the water industry. This project was heavily invested in describing the character of iPVC and not the other products. It is recommended that WRF engage in some comparative testing, but the researchers believe it is incumbent upon the manufacturers to make third party testing available, particularly if the product significantly exceeds AWWA standards.

The latest information from the vendor is that progress has been made to bring the product to the U.S. by manufacturing it in North America. The development of the pipe to better suit the U.S. and continue innovation (as demonstrated by a change in the way gaskets are made) and look

at the development of fittings made with the same material bear watching by utilities and the entire pipe industry.

RESEARCH PARTNERS

This Tailored Collaboration project was partially sponsored by American Water. The state operations of Missouri American Water and New Jersey American Water participated in field installations.

RELATED WRF RESEARCH

- Impact of Hydrocarbons on PE/PVC Pipes and Pipe Gaskets (project #2946)
- Long-Term Performance Prediction for PVC Pipes (project #2879)
- State of the Science of Plastic Pipe (project #4680)
- Vinyl Chloride and Organotin Stabilizers in Water Contacting PVC Pipes (project #2991)

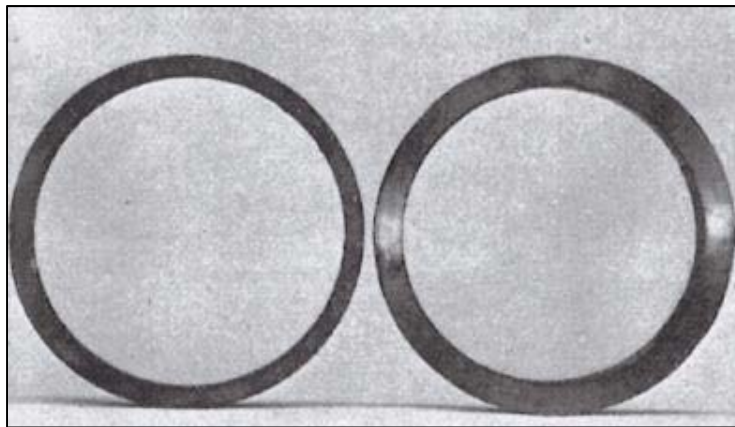
CHAPTER 1

INTRODUCTION

1.1 WATER PIPE HISTORY

Pipe has slowly evolved in North America over 250 years. The first pipelines in the United States were installed before the country was established, using British technology of hollowed out logs. Cast iron was first manufactured in the early 1800's in New Jersey. Philadelphia was the first city to begin widespread use of cast iron in its distribution system but the primary pipe through the first half of the nineteenth century was wood pipe.

The original forms of cast iron were brittle and to provide a perceived need for strength to hold water under pressure, pipe with thick walls was manufactured. Early in the 20th century, the process of annealing and the use of a spinning process made cast iron considerably stronger and the resulting product featured a thinner wall thickness (lighter) pipe (See Figure 1.1). Cement lining was introduced to resolve significant drawbacks of poor water quality and reduction of internal diameter from tuberculation. Further modification occurred with the introduction of ductile iron pipe in the 1950's as iron and steel remained the material of choice for use in the water distribution system. Combinations of cement and steel were used for larger diameters pipelines.



Source: Reprinted with permission from Gillespie, P., 1922. A Departure in Pipe Foundry Practice, *Journal AWWA*, 9:5:709. Copyright © American Water Works Association.

Figure 1.1 Difference in thickness of spun and pit cast pipe

New products emerged for use in distribution pipe beginning with asbestos cement (AC) first installed on the west coast in the 1940's and finally came east primarily in the 1960's and 1970's. Polyvinyl chloride (PVC) pipe was invented and used in Germany in the 1940's and eventually found its way into the US market in the 1970's as health concerns about asbestos pipe in both manufacture and use arose. In fact, some manufacturers of AC pipe migrated to PVC manufacturing. Polyethylene pipe was developed in the 1950's and evolved from low to high density and has been in the market for almost 50 years though it is more commonly found in larger pipe and service lines.

With these options, it is well known that the water industry seldom jumps quickly to the "next best thing." The water utility industry is often described as conservative and utilities are slow to change materials to be placed underground. This may be due in part to the lengthy history

of cast iron pipe that has demonstrated a century or more of service in many instances. To date there is no perfect product as each material: cementitious, resin, plastic or ferrous materials have advantages and limitations. Arguably, the strongest of the pipe materials is ductile iron yet this pipe does have some history of pipe failure with well under a century of use. Kleiner and Rajani (2002), Rajani and McDonald (1995), Folkman (2012), Paradkar (2012), describe utilities experiencing premature failure from DI pipe well before the end of their useful life. Therefore, as the search for better materials continues, it is important for utilities to make the best most informed decisions about investments they hope will last 100 years or more.

According to report published by Paradkar et. al. (2012), utilities based their selection of materials upon, the practice, history of material used in the past and resulting qualifications utilities specify. The importance of utilities to understand the pipe environment is critical to make the best choices. In the case of ductile iron pipe, still thinner than the spun cast iron pipe it replaced was more susceptible to corroding through the reduced pipe wall.

Utilities are also aware of pipe materials that have not lived up to expectations. The recent history of pre-stressed concrete cylinder pipe experiencing failures at 50 years, premature failures of early versions of fiberglass pipe and the failures of polybutylene pipe provide reason for utilities to be conservative when considering change. Complicating the issue of pipe material performance are manufacturing errors and installation mistakes that inevitably become associated with the material employed.

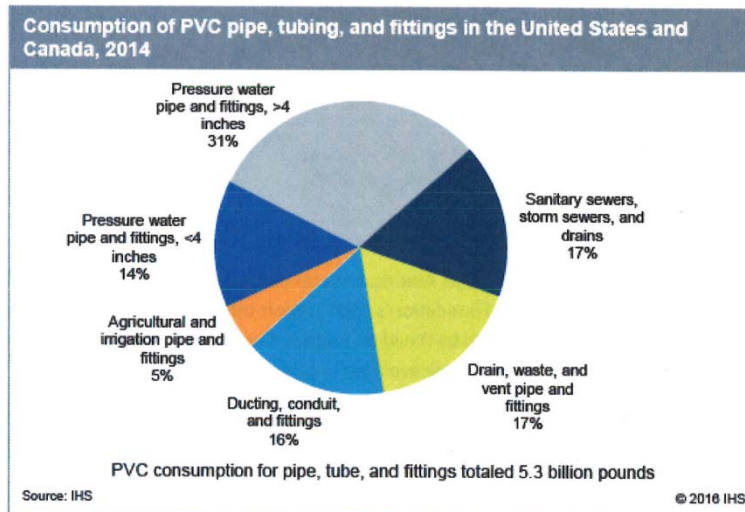
1.2 INTRODUCTION TO POLYVINYL CHLORIDE (PVC)

Polyvinyl chloride (PVC) is a versatile thermoplastic material. Industry employs PVC resin for the production of hundreds of day-to-day products that consumers use. PVC resin is also found in products used in construction, electronics, healthcare, and other industries. The low cost and desirable physical and mechanical properties are some of the reasons for its widespread use. Figure 1.2 identifies the consumption of PVC resin in U.S. and Canada pipes in 2014 (American Chemistry Council, 2016).

PVC pipe can be heated and reshaped, an important property in the belling operation of the pipe. One end of the pipe is heated and placed in a belling machine to form the bell end of the pipe along with a groove reserved for a gasket. The bell end is then cooled to maintain the shape (Howard, 2015). Aside from the Korean iPVC, there are three types of PVC available in worldwide markets:

- PVC (un-plasticized/ PVC-U and commonly called PVC),
- PVC-O (oriented) and
- PVC-M (modified) pipe (Burn et al. 2005).

Each pipe is distinguished by their chemical structure, raw material used and manufacturing process involved in extraction of pipes. PVC-M is a product developed in the Pacific area. It has an “impact modifier added to its formula and like PVC-O it has a thinner pipe wall. The product has not penetrated the US market.



Source: Reprinted with permission from The Economic Benefits of Polyvinyl Chloride in the United States and Canada. Copyright © July 2016 American Chemistry Council.

Figure 1.2 PVC pipe use in the United States and Canada

1.2.1 Conventional PVC (PVC-U) Pipe

PVC-U (un-plasticized) is referred to as uPVC in some parts of the world and as PVC in North America. PVC is the currently the most widely used piping material in North America for water applications. The molecules are arranged randomly in long chains and do not display any definite directional orientation. It has been observed that PVC tends to crack longitudinally, a significant failure when compared to circumferential breaks. PVC used for pipe does not have plasticizers like some other PVC products that need to be more flexible (as in membranes, bags, gloves, and toys). It does have UV inhibitors to reduce the impact of direct sunlight. As per AWWA and ASTM standards, PVC pressure pipe must meet or exceed a tensile strength of 7,000 psi, modulus of elasticity of 400,000 psi and have a hydrostatic design basis of 4,000 as per ASTM D2837-13e1 (Najafi and Gokhale, 2005). PVC-U pipe will be referred as PVC throughout this research project for simplicity.

1.2.2 PVC-O Pipe

Oriented PVC pipe has been manufactured since 1974. PVC-O pipe demonstrates superior performance qualities over standard PVC pipe. The molecular orientation in PVC-O pipe is achieved by increasing the diameter of the conventionally extruded pipe at elevated temperature and then cooling it rapidly. The orientation of molecules is in a circumferential (or hoop) direction along the length of the pipe, which increases the strength of the pipe in the circumferential direction (West and Truss, 2011).

Either an inline or an offline process is followed to manufacture PVC-O pipe. A rigid small diameter thick-walled PVC pipe called the stock pipe is heated to temperatures between 175 °F and 250 °F in the offline process. During the heating, the pipe transits into a rubbery flexible state and then the pipe is inflated within the mold. This process reorients the random molecules in the PVC pipe to align parallel to circumferential direction. The inline process pulls the pipe over a conical die to expand the diameter during the extrusion process of the pipe. The expansion of the

pipe reduces the thickness of the wall while increasing the diameter size and reorienting the molecules in circumferential direction. (Chapman and Agren, 1998).

The reduced pipe wall thickness required a separate AWWA standard and that occurred in 1998. The C909 standard does not vary in performance requirements from the C900 standard except for the hydrostatic design basis (7,100 psi in place of the 4,000 standard PVC criteria) and the related hydrostatic design basis (3,550 psi versus 2,000 psi). Sustained test pressure, burst test pressure, temperature coefficients, flattening and addressing surge appear identical in the standards. Some of the material advantages of the C909 over C900 pipe are impacted by choosing to reduce the pipe wall thickness. Thinner pipe has significant advantages in terms of less material to use and ship and ease of handling during installation. PVC-O pipe is found in other parts of the world notably Europe and Australia. It should be noted that standards and manufacturing processes can differ in various parts of the world so assuming a characteristic of a type of pipe from other countries with those made in North America are somewhat limited.

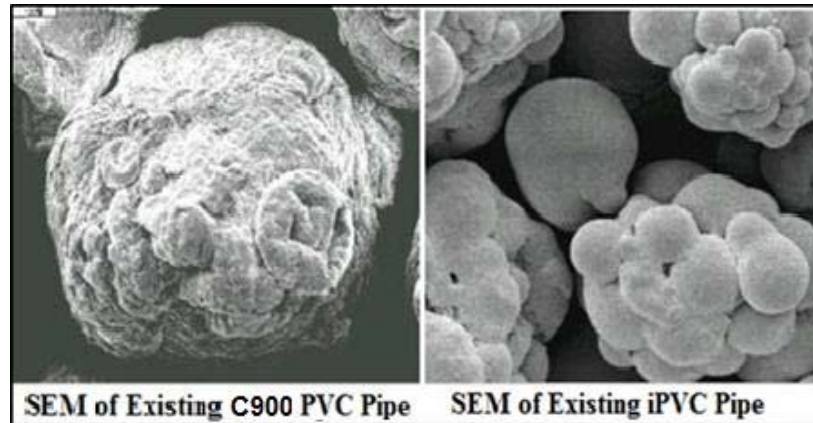
1.2.3 PVC-M Pipe

Modifying the PVC resin molecular weight and adding an additive (impact modifier) to PVC resin can yield dramatic changes in the processing characteristics and physical properties of PVC resin (Tseng et al. 1991). PVC-M pipe is manufactured by adding ‘impact modifiers’ during the manufacturing process. Additives can improve the impact strength and flexibility of PVC. The impact modifiers added are either elastomeric or rubbery in nature and have a lower modulus than the PVC. Acrylonitrile butadiene styrene (ABS) and chlorinated polyethylene (CPE) are the two most used impact modifiers to improve regular un-plasticized PVC (Plastics Additives and Compounding, 2004). This pipe is found in Europe and Australia and is not distributed in U.S. for buried applications (Najafi and Gokhale, 2005).

1.3 INTRODUCTION TO iPVC PIPE

In 2014 American Water, Voorhees, NJ, met with representatives of Pyungwha Plastic Industry System Inc. (hereafter PPII), a leading PVC pipe manufacturer from Korea to discuss its PVC pipe product and possible potential in the American market. The product is known as iPVC pipe and is available in 4, 6, 8, 10, 12, 16, and 24-inch diameter size and with conventional dimension ratios of DR 14, DR 18, and DR 25.

The iPVC pipe is manufactured in Asia, operating out of three plants in Korea and one plant in China and marketed in Japan, China, and South Korea. The iPVC pipe is manufactured using the extrusion process. The high strength resin is produced by mixing raw material in different proportions along with additives during the polymerization process. Figure 1.3 illustrates the molecular structure snapshot of a regular PVC (C900) and iPVC pipe from scanning electron microscope (SEM).



Source: PPII 2015.

Figure 1.3 PVC and iPVC pipe structure under SEM

1.4 INTRODUCTION TO iPVC PIPE PROJECT

This pipe evaluation project was a tailored collaboration between WRF and American Water. The research was financed by WRF (\$100,000) and American Water (\$100,000). American Water selected CUIRE at the University of Texas at Arlington, Arlington, TX to assist with selection of testing methods and to conduct testing. During the project, Microbac Laboratories, Denver, CO was added to conduct testing. The performance evaluation in the field was conducted by installing the iPVC pipe by American Water in St. Louis County, Missouri and at the end of the project at a New Jersey American water site in Manville, NJ.

1.4.1 Research Needs

After viewing demonstrations of the pipe and reviewing test results it was evident that iPVC pipe could offer features in strength and flexibility to rival other extruded PVC pipe but with increased thickness may perform better in the trench. Testing is a clear need for iPVC pipe. The engineering properties and strength characteristics of iPVC pipe to be tested were expected to exceed the AWWA standards requirements set for PVC pipes. American Water perceives there is a significant gap in the awareness of water utilities about this and other conventional PVC alternatives. This research is an opportunity to introduce iPVC pipe to U.S. water utilities.

1.4.2 Project Objectives

The premise for this research is that utilities require more thorough information (and better communicated) about the new varieties of structurally enhanced PVC water pipe to allow them to make appropriate decisions concerning these PVC pipe alternatives. This research is seeking to highlight the characteristics and demonstrate the true installation requirements required of the structurally enhanced PVC pipe. iPVC pipe (structurally enhanced PVC pipe) is looking to have installation criteria defined that match the physical characteristics of the material. The secondary benefit of the project is to introduce a potentially innovative new PVC pipe product and spur innovation in the North American marketplace. Specifically, this research will evaluate the following properties of iPVC pipe to be applied to design. Analysis will include study of engineering properties and strength characteristics. This will foster real testing of behavior of iPVC pipe installation in poor (clayey) soils that will be demonstrated through pilot installations in actual

conditions. If successful, the project will create awareness amongst water utilities about iPVC pipe potentially bring an improved PVC pipe product to the US.

1.4.3 Project Methodology

The WRF and American Water funded the project. The completed tasks accomplished under this project include a complete assessment of tensile performance, iPVC pipe bedding needs, fatigue resistance, impact resistance, pipe stiffness and short-term burst pressure test on the iPVC pipe to evaluate performance characteristics of iPVC pipe. CUIRE performed fatigue test, tensile test, and the hydrostatic short-term burst pressure test. Microbac carried out impact tests, stiffness tests, and tensile tests. The second phase of the project addressed how the pipe would function in the trench. This include field installations by American Water and a bedding test conducted by UTA. The installation crew of Missouri American Water in St. Louis County placed the first iPVC pipe in January 2016 and by a contractor for New Jersey American in Manville, NJ in October 2016. Conclusions and recommendations are presented at the end of this report along with recommendations for future research. Figure 1.4 presents a methodology flow chart for this iPVC pipe project.

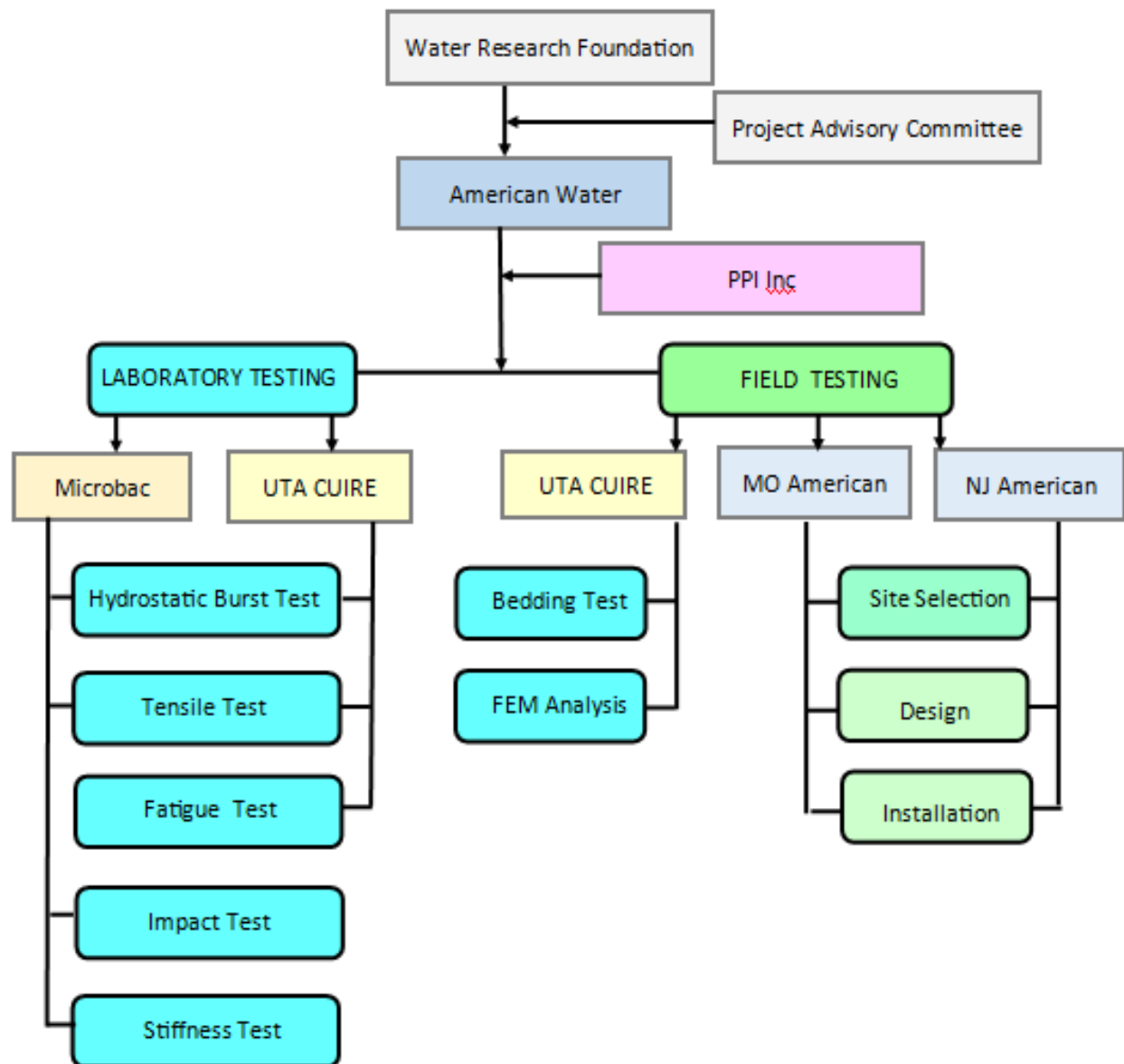


Figure 1.4 Project approach

CHAPTER 2

LITERATURE REVIEW

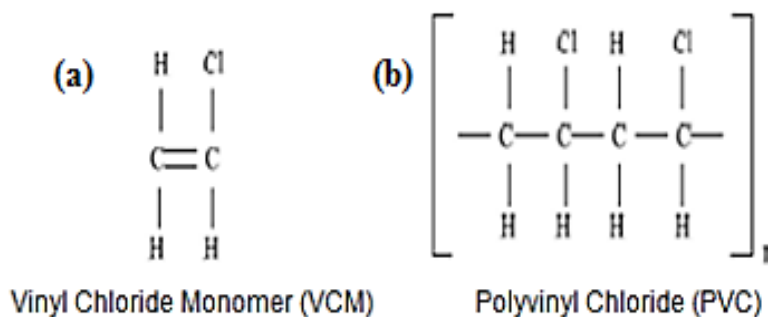
This chapter consists of a detailed review of findings from an extensive literature search. The literature search provided additional information about PVC pipe behavior and testing and provided some contrast the behavior of other pipe materials for different tests. The subjects covered in this chapter include previous experimental field and lab studies conducted on pipe materials and their results, as well as previous testing conducted on iPVC pipe.

2.1 INTRODUCTION TO PVC PIPE

2.1.1 Development of PVC Compound

Polyvinyl chloride pipe (PVC) material was an accidental discovery in the 19th century made by German scientists when vinyl chloride gas was being observed and an off-white accumulation of solid material was formed when exposed to the sunlight. Several attempts were made to understand this compound during 19th century. It was in 1904 three scientists Zacharias, Klatte, and Rollet from Chemische Fabrik Griesheim Elektron derived PVC from mixture of acetylene and chlorine. A process proposed by Klatte was tedious and the resulting product was unstable and degraded during the processing. According to Mulder & Knot (2001), the discovery of PVC compound was accepted in 1912 when the material was patented a year later. Although the production of PVC products was completely halted after World War I as the material was considered low quality in comparison with other materials, scientists continued to research PVC fibers. In Germany, the IG Ludwigshafen laboratory developed the PVC compound polymerization process. Polymerization reduced the melting temperature of PVC compound without altering its flexible nature. These polymerizations led to yet another era in PVC product development.

Researchers continued their attempts to improve the stability of the product. In 1928, IG Farben manufactured first PVC fiber and later in 1931, Schonburg discovered a process for making high performance resin and PVC films derived from chlorine in Germany. The material was not advanced significantly until revisited by Henri Regnault in 1935. During the 1930's the market flourished with PVC products from cable insulation to tooth brushes and frames overtaking the rubber industry. By end of 1930's PVC pipes were manufactured to convey water and other liquids. A vinyl-chloride molecule consists of hydrogen, carbon, and chlorine as shown in Figure 2.1. Table 2.1 illustrates the important milestones of PVC pipe in North America.



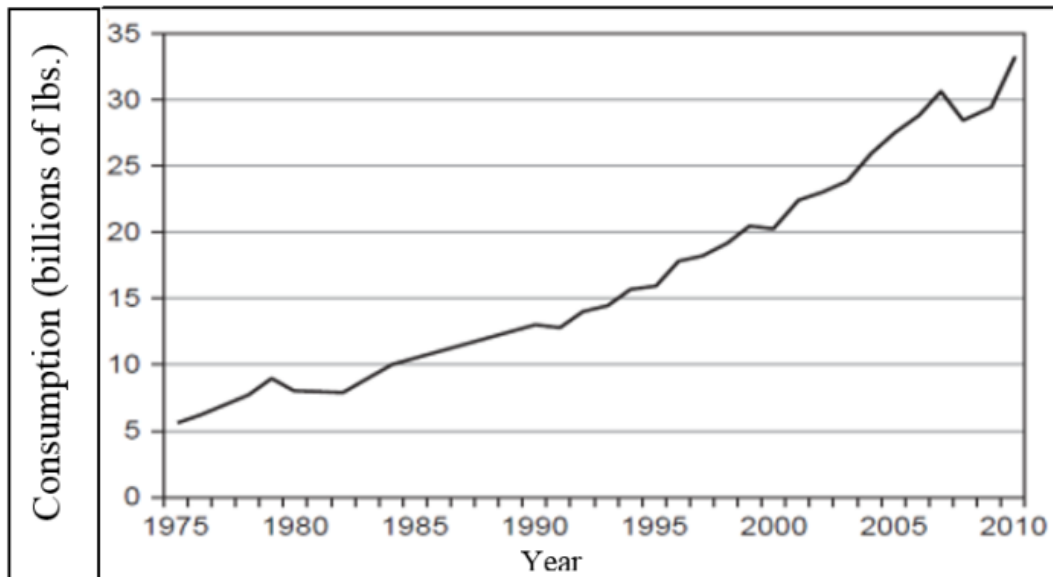
Source: Deshmukh 2012.

Figure 2.1 (a) Vinyl chloride molecule and (b) molecular chain in PVC

Table 2.1
Milestones of PVC pipe in North America

Year	Milestone
1935	PVC pipes were manufactured in Germany
1936	Installation of PVC pipes for water distribution system
1952	PVC pipe was introduced in U.S.
1955	First PVC pipe for water use was installed
1966	AWWA appointed a committee to study and report on the adaptability of plastic pipe for use in the water industry
1968	The AWWA Standards Committee on thermoplastic pressure pipe was established
1975	First edition of AWWA C900 Standard was published
1980	AWWA published Manual 23 - PVC pipe design and installation
1988	Publication of AWWA C905
1991	Publication of AWWA C901
1994	AWWA approves and publishes C605
1998	Publication of C909

Source: Adapted from sewerhistory.org and Uni-Bell PVC Pipe Association



Source: Uni-Bell 2012.

Figure 2.2 PVC pipe and fittings worldwide consumption

PVC pipe has worldwide status and continues to grow in the market (Figure 2.2). The European and Asian market recognized PVC pipe two decades prior to penetrating the U.S. market as reflected in Table 2.2. Due to highly corrosive soils, several Australian utilities have employed PVC pipes in their distribution systems since the 1970's following years of cement lined iron and steel installations. A recent study from the Freedonia Groups, Inc., a Cleveland based industry market research firm, predicts an annual growth rate of 6.2 percent for PVC pipe in US through 2018.

Table 2.2
PVC installation in selected countries prior to 1960

Country	Amount of Pipe		Years of Experience
Japan	64,000 km.	40,000 miles	10
Italy	36,000 km.	22,500 miles	12
Germany	16,000 km.	10,000 miles	25
Holland	8,000 km.	5,000 miles	9

Source: Data from Heathcote 2009

2.1.2 Making PVC Resin

Figure 2.3 illustrates the process used to make PVC resin at manufacturing plants common to all PVC pipe. The resin fabrication equipment consists of batch polymerization reactors, a blow-down vessel, and downstream processing equipment, which includes a stripper, decanters, and a fluid bed dryer.

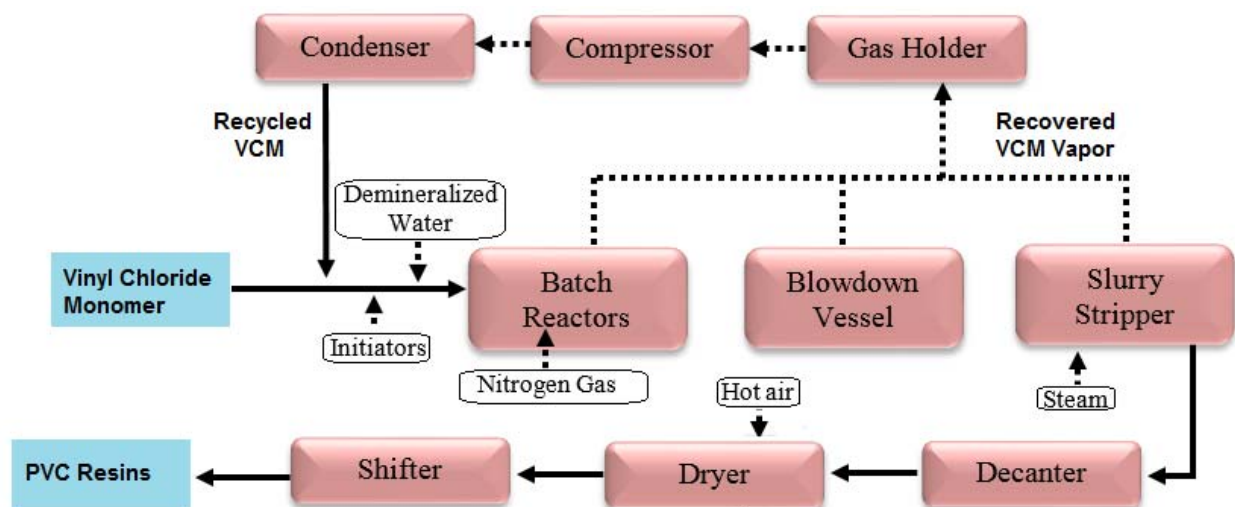


Figure 2.3 Process flow diagram for PVC resin manufacturing

The raw materials used for the polymerization process are demineralized water, a mixture of fresh vinyl chloride monomer (VCM) and recycled VCM (received from blowdown vessel and stripper), initiators and suspending agents. The polymerization process takes place in the batch reactors. The demineralized water along with suspending agents are charged into the reactor followed by initiators. After completion of water charge, the reactor is purged with nitrogen to ensure no oxygen is present in the reactor. The nitrogen is removed from the reactor by vacuuming. After the VCM and water are added to the reactor, the optimum operating temperature and pressure are achieved. The exothermic polymerization process continues for 7.5 hours and the generated product is a slurry consisting mainly of PVC, water, and some byproducts such as unreacted VCM, initiators, suspending agent and traces of contaminant (Chan et al. 2007).

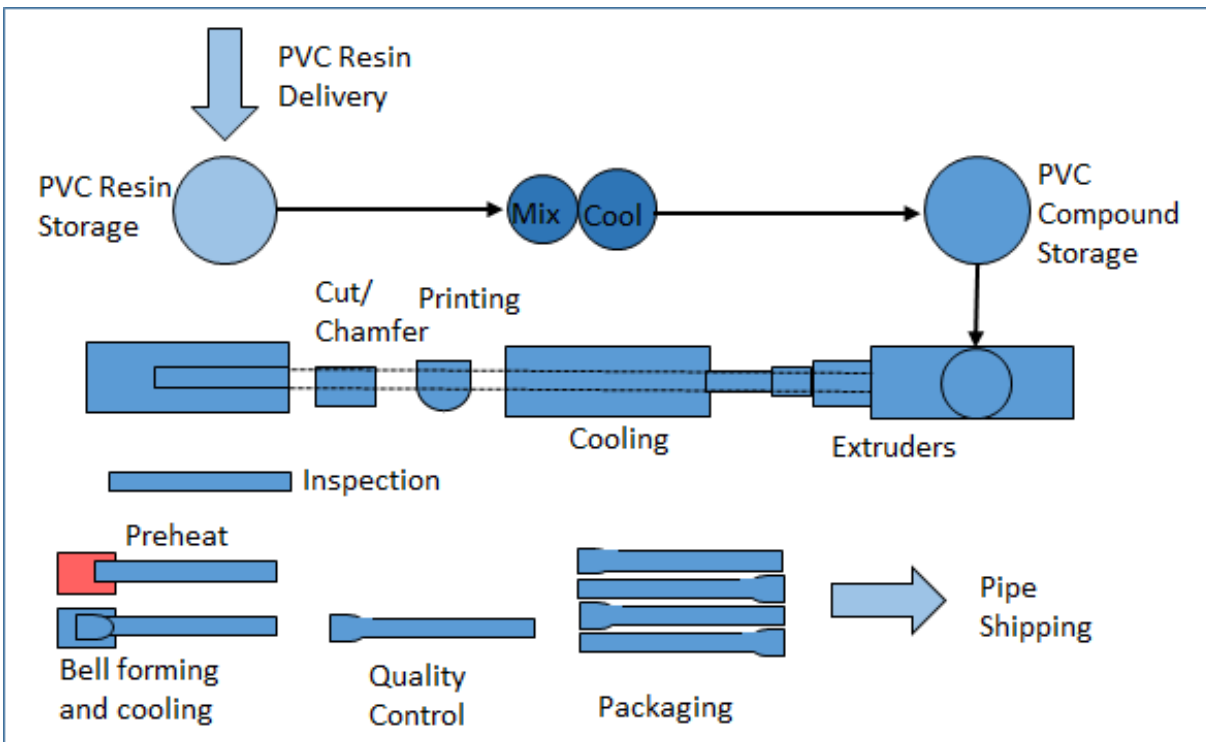
The slurry is discharged intermittently from the reactors to the blowdown vessel, which further transfers the slurry to the downstream processing equipment. The blowdown vessel traps the unreacted VCM vapor and compresses it, condenses it into liquid form and sends it back to the reactors for polymerization. The effluent from the blowdown vessel enters the stripper to remove any remaining unreacted VCM from the slurry. Steam is introduced at the end of the stripper to remove the VCM vapors. The stripped slurry then reaches the decanters, which removes approximately 80% of the water from the slurry. Wet cakes are formed after removal of water. They are then dried and transported to the shifter. Fine resins that pass through the shifter are sold as a product and coarse resins sold as low-grade resins (Chan et al. 2007).

2.1.3 Types of PVC Pipe as per Manufacturing Process

Since the first PVC pipes were installed in the 1950's, some enhancements in the product were made to improve the product from a brittle material to a more flexible material. PVC pipe is a traditional bell and spigot pipe but is available as a fusible product.

PVC pipe is manufactured by integrating PVC resin as described above with the addition of stabilizers, pigments, lubricants, and additives followed by heating the mixture to 400 °F. The heating causes the components to fuse properly and convert to a malleable state. The material is mechanically extruded in its molten form. After the extrusion, the pipe is allowed to cool. Another method of manufacturing PVC pipe is injection molding. In this process, the molten polymerized polymer is forced into pipe molds and then water cooled (Rahman, 2004). Figure 2.4 illustrates

the process of PVC pipe manufacturing by extrusion. The different types of PVC pipes manufactured are as described in Chapter 1.



Source: Adapted from Uni-Bell 2012.

Figure 2.4 PVC pipe manufacturing process

2.1.4 Types of Joints for PVC Pipe

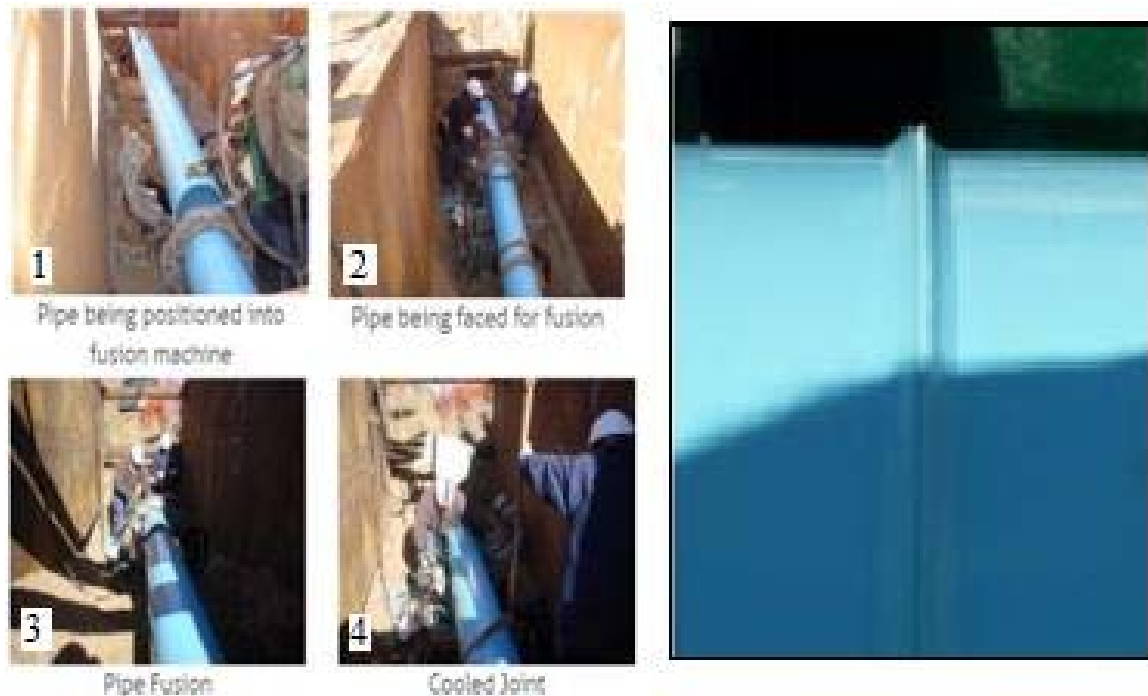
2.1.4.1 Gasketed Joint

An elastic gasket is fitted at joints and compressed between the bell end of one pipe and the spigot end of another pipe around the circumference of the pipe to form a tight seal. Gasketed joints can be in the form of restrained or unrestrained. Unrestrained joints are known as push-on joints. Gasketed joints are unrestrained joints when the joint allows movement of one pipe relative to another pipe. The bell end of the pipe faces the direction of laying pipe during installation so that installers can insert the spigot end of the new pipe into the bell end of the pipe previously laid. A restrained gasket system prevents the movement from one pipe to another and involves some way to keep the pipe joint from pulling apart either internally or externally. The allowable leakage limit of 10.5 gallons per inch of diameter per mile per day for PVC pipe is set in AWWA C900. Thrust blocks or restraining systems explained later in this research project are necessary to resist the thrust force exerted by the fluid inside the pipe in pressure applications (Howard, 2015).

2.1.4.2 Heat Fused

PVC and Polyethylene pipe are available with fusible joints. Polyethylene pipe is better known for fusible joints and used extensively in trenchless applications. For standard PVC heat-fused joints are known as butt fusion joints. The ends of two straight pipes are aligned, heated, and

pressed together to form a solid connection as illustrated in Figure 2.5. A skilled and knowledgeable person is required to execute a heat fused joint. After allowing the manufacturer's recommended minimum time to cool down the joint, the heat-fused joint will achieve a joint generally regarded as stronger than the pipe itself. (Howard, 2015). Done incorrectly, it will fail.



Source: Underground Solutions, Inc. 2016.

Figure 2.5 Butt fusion of PVC joint

2.2 CURRENT STANDARDS FOR PVC

The American Water Works Association (AWWA) has established standards for manufacture, design, and installation of polyvinyl chloride pressure pipe, fittings and appurtenances for water and other liquids, including:

2.2.1 AWWA C605

Underground Installation of Polyvinyl Chloride (PVC) and Molecularly Oriented Polyvinyl Chloride (PVC-O) Pressure Pipe and Fittings. This standard covers underground installation and hydrostatic testing procedures for polyvinyl chloride (PVC) and molecularly oriented polyvinyl chloride (PVC-O) pressure pipe and fittings that comply with either ANSI/AWWA C900, ANSI/AWWA C905 (AWWA 2010), or ANSI/AWWA C907. This standard provides the minimum requirements for underground installation and hydrostatic testing procedures for polyvinyl chloride (PVC) and molecularly oriented polyvinyl chloride (PVC-O) pressure pipe and fittings used to transport potable water, reclaimed water, wastewater, irrigation water, or for the conveyance of any fluid compatible with PVC or PVC-O.

2.2.2 AWWA C900-16

Polyvinyl Chloride (PVC) Pressure Pipe and Fabricated Fittings, 4 inches through 60 inches (100 mm. through 1,500 mm.). AWWA has published a new C900 standard, superseding the standards C900-07 and C905-10. (The C905 standard is essentially no more.) The new standard covers 4 inches through 60 inches (100 mm. through 1,500 mm.) polyvinyl chloride (PVC) pressure pipe and fabricated fittings with ductile and cast iron pipe equivalent outside diameter (CIOD) or steel pipe (IPS) dimensions. The dimension ratios (DRs) includes 14, 17, 18, 21, 25, 26, 27.5, 32.5, 41 and 51 with corresponding pressure class (PCs) of 305, 250, 235, 200, 165, 160, 150, 125, 100 and 80 psi. The purpose of this standard is to provide direction and guidance for the PVC pressure pipe and fabricated fitting materials used for underground water distribution systems. Requirements are given for the following topics: permeation; material, dimension, pipe manufacturing requirements, an exercise to determine the physical pipe properties of the pipe, fabricated fittings; seamless joints (butt fusion and solvent cemented bond) and fittings (mechanical joints); pressure-rating designations; joint designs and, pressure class and pressure design recommendation. The standard dictates guidelines for the manufacturers for quality control and qualification tests requirements including marking, handling and, packaging of the pipe. Covered in an appendix is an example for designing for recurring and occasional surges in the pipe.

2.2.3 AWWA C907

Injection-Molded Polyvinyl Chloride (PVC) Pressure Fittings, 4 inches through 12 inches (100 mm. through 300 mm.), for Water, Wastewater, and Reclaimed Water Service. This standard covers pressure class 150 polyvinyl chloride (PVC) injection-molded fittings with push-on rubber gasketed joints in nominal sizes 4 -12-inch diameter. The fittings are for use with PVC water distribution pipe having an outside diameter conforming to the dimensions of cast-iron pipe, and with dimension ratios of 18 or 25 as described in ANSI/AWWA C900, Standard for Polyvinyl Chloride (PVC) Pressure Pipe, 4 inches through 12 inches, for Water Distribution. The standard also provides further design considerations when the fittings used with PVC pressure pipes other than Class 150 and Class 100.

2.2.4 AWWA C909

Molecularly Oriented Polyvinyl Chloride (PVC-O) Pressure Pipe, 4 inches through 24 inches (100 mm. through 600 mm.) for Water, Wastewater, and Reclaimed Water Service. This standard refers to molecularly oriented polyvinyl chloride (PVC-O) pressure pipe manufactured from starting stock pipe made from ASTM D1784 (ASTM 2011a) cell class 12454-B material. The manufacturer takes stock materials and extrude the material and the oriented circumferential expansion adds strength to provide a hydrostatic design basis (HDB) of 7,100 psi (49.0 MPa). The pipe has cast-iron-pipe-equivalent (CI) outside diameter (OD) dimensions and with thinner wall thickness sufficiently sized for pressure classes 100, 150, and 200 psi, in 4 inches through 24 inches (100 mm. through 600 mm.).

2.2.5 AWWA Manual M23 - PVC Pipe - Design and Installation

This manual provides guidance and data on designing, installing, and maintaining PVC pipe and fittings in drinking water distribution systems. Coverage includes manufacturing, hydraulics, chemical and abrasion resistance properties, external loads, pressure capacities, flexibility ratings, installation, fittings and appurtenances, joining, supports, transportation, storage, and maintenance.

2.2.6 Fusible PVC

The AWWA does not provide a separate standard for the fusible PVC; the C900 briefly describes the material. The pipe used for fusible PVC follows manufacturing and testing requirements outlined in the AWWA C900 and has NSF 61 certification.

2.3 INSTALLATION REQUIREMENTS FOR PVC

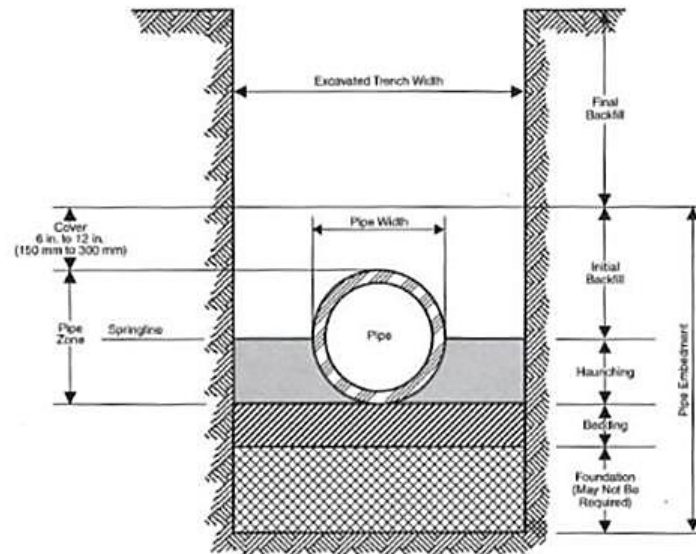
The water industry follows AWWA C605 as the standard guideline for the PVC pipe installation supported by the AWWA M23 manual (AWWA 2002). The PVC Pipe Association, Uni-Bell has developed guidelines in conjunction with AWWA C605 for the installation of the PVC pipe.

Figure 2.6 illustrates the various trench terms used during installation of pipe from bedding to backfill surface. It is imperative to place bedding materials properly to minimize trench settlement. A foundation might be necessary when the trench bottom is unstable. A bedding depth of 4 to 6 inches is recommended. The first layer of backfilling is prepared up to midpoint or springline of the pipe and is called haunching. The purpose of the haunching is to secure the pipe firmly in the trench and provide horizontal support to reduce the vertical deflection of the pipe. The initial backfill runs from springline over the pipe to a depth of 6 to 12 inches above the top of the pipe. Installers usually place tracer wire on top of the pipe within this backfill layer. Embedment is the term used to describe the materials placed from bedding (or foundation if applicable up through the initial backfill. Final backfilling to the surface in unimproved off-road areas may re-use the material that was excavated on top of the pipe. However, for most improved surfaces, either the design engineer or the local regulator (highway department) will require special backfill and restoration consistent with restoring the improved surface. To avoid the settlement of the soil in any case, the backfilling is placed in compacted layers using pneumatic compactors to the desired soil density. (AWWA 2002 and Uni-Bell, 2012).

The basic components involved in installation of PVC pipe are summarized as follows:

1. Receiving of pipe
2. Unloading and handling of pipe
3. Storage
4. Trenching
5. Dewatering trench
6. Field cutting of PVC pipe if necessary
7. Lowering of pipe into trench
8. Cleaning and inspection of pipe
9. Lubrication of spigot end
10. Joint assembly

11. Installation of fitting and valves
12. Tracer wire for locating pipe in future
13. Service line tapping



Source: Reprinted with permission from AWWA 2002 (2nd ed). Manual of Water Supply Practices, M23 (p.78). *PVC Pipe – Design and Installation*. Copyright © American Water Works Association.

Figure 2.6 Terms used in pipe installation

2.4 COMPARING PVC PIPE AND DI PIPE

PVC pipe is commonly compared to other options most notably polyethylene (PE) pipe and the long time major pipe product iron pipe. For distribution systems (pipes 12” and less), pipe manufacturers, their trade associations and utilities compare ductile iron pipe and PVC that have significant differences in pipe characteristics and performance.¹

2.4.1 Fabrication

For this review at the researchers reviewed conventional bell and spigot pipe for both ductile iron and PVC. Ductile iron manufacturers employ coatings to mitigate DI pipe corrosion. Exposing the unlined interior iron surface directly to potable water for a prolonged period, often creates issues as tuberculation may be formed. To avoid this, the pipe receives a cement lining and an asphaltic seal coat to assist the rapid curing of the cement liner and protect the cement liner from aggressive water (DIPRA, 2016). Ductile iron pipe has an exterior asphaltic coating to reduce oxidation as well. Ductile iron pipe with a zinc coating inside the asphaltic coating to inhibit corrosion has become available in the US recently. In aggressive soils, pipe manufacturers also recommend polywrapping. PVC pipe is neither lined nor coated.

¹ PE pipe has a trade association called the Plastics Pipe Institute (PPI). Fusible products are considered outside the scope of this project, as iPVC and PVC-O are not made in fusible form in North America.

2.4.1.1 Standards

AWWA C600–10 is the current AWWA standard for DI pipe for installation and C151–09 for DI pipe centrifugally cast. As noted previously C605–13 is the AWWA standard for PVC installation (PVC and PVC-O), C900–07 for PVC pressure pipe (4-inch–12-inch), and C907-12 is the standard for injection molded PVC fittings (4-inch–12-inch) and C909–09 for PVC–O (4-inch–24-inch). Note that iPVC pipe also would use the existing C900 as it follows the dimensions of that material.

2.4.1.2 Manufacturing

For ductile iron, the molten iron is casted centrifugally to form a pipe, followed by slow cooling (the process of annealing) of the pipe to attain the physical properties. The cooled pipes then receive cement mortar lining on the inside and then an asphaltic coating on inner and outer surface of the pipe. In the manufacture of DI pipe, a perishable bell-shaped sand core is attached to the DI pipe mold during the casting process. PVC pipe are casted continuously without the bell. The manufacturer reheats the plain end pipe to a pliable state and then connects a separate bell shape piece from the belling machine.

The manufacturing process of PVC pipe involves either extrusion process or injection molding. During injection, molding process the molten polymerized polymer is forced in to the pipe molds and then water-cooled. During the extrusion process (Figure 2.7), the molten polymerized polymer is extruded using single/multi screw extruders and water cooled to obtain the PVC pipe. No coatings or linings are added.



Source: PPII 2015.

Figure 2.7 PVC extrusion line

2.4.2 Structural Properties

2.4.2.1 Tensile Strength

Metals by nature are stronger and stiffer than plastics, at 73°F, DI pipe can take a tensile pull up to 60,000 psi while standard PVC pipe (C900) can be loaded up to 7000 – 8000 psi. Iron pipe evolved with ductile iron, a less brittle and stronger product than its cast iron pipe forerunners that allowed the industry to reduce pipe wall thickness.

2.4.2.2 Specific Gravity

The specific gravity of pipe can have advantages and limitations. The lower specific gravity of PVC can assist in handling the material but raises issues about buoyancy in wet locations. PVC pipe with its specific gravity of 1.4 g/cc at 73°F. The DI pipe has specific gravity of 7.1 g/cc, and clearly requires machinery to handle the pipes.

2.4.2.3 Field Demonstrations

Both PPII and manufacturers of PVC-O have videoed visually impressive field demonstrations to show pipe strength of extruded PVC pipe. While ductile iron material exhibits superior structural strength, Demonstrations such as those pictured in Figure 2.8 show field impact tests that a ductile iron pipe cannot execute without heavy damage.



Source: IPEX 2016.

Figure 2.8 IPEX field test of its C909 under pressure from YouTube

2.4.3 Environmental Considerations

2.4.3.1 Corrosion

PVC pipe is inert to the most chemicals found in a pipe environment. DI pipe oxidizes when in contact with oxygen to form ferrous oxides (rust) and long-term exposure causes corrosion that can jeopardize structural integrity. To overcome corrosion DI pipe, manufacturers apply asphaltic coatings to the external pipe surface and cement mortar lining to the inner surface of the pipe. The action of aggressive water may dissolve the mortar liner and expose the inner pipe surface to trigger the oxidation process internally. To deal with aggressive water, DIPRA cites the use of NSF approved non-volatile asphaltic coating on the surface of the finished mortar lining to protect the mortar. DIPRA recommends the use of polyethylene wrap in corrosive soil environments to protect the pipe externally.

2.4.3.2 Permeation

According to the WRF report, *Impact of Hydrocarbons on PE/PVC Pipe and Pipe Gaskets* (Ong et al, 2007), PVC pipe is impervious to gasoline and other compounds including benzene toluene and TCE at concentrations encountered in the environment. However, stagnant or high concentrations of some hydrocarbons can be problematic in what could be characterized as

hazardous areas. The wall of PVC pipe allows the hydrocarbons to permeate and contaminate the water though not the degree of polyethylene pipe. Ductile iron pipe is impervious to hydrocarbons and the preferred choice of material to place in organically contaminated soil condition.

2.4.4 Operational Considerations

2.4.4.1 Hydraulic Capacity

The design hydraulic factor typically employed is the C factor, the Hazen William coefficient. The flow through the pipe is essentially a function of the C factor and the interior pipe diameter. The higher the C factor is, the higher the hydraulic flow and the less the pressure head loss. According to Bonds (2016), for DI pipe the C factor is 140 (achieved after cement lining) and C=150 for PVC. The C value for cement lining applied in the field on unlined cast iron pipe is about 130 (Detroit Water & Sewerage Department, 2004). The pipe inside diameter directly affects hydraulic capacity. For products with the same outside diameter, the thinner walled ductile iron pipe can argue that they have increased capacity size for size.

2.4.4.2 Surge/Water Hammer Pressure

Surge in piping line occurs when the velocity of the flow in the pipe is abruptly changed. The sudden velocity changes can be caused by the operation of valves and pump (power loss for example) or by the expulsion of air from the piping system. With proper design and operation, the surge effect can be minimized.

The surge pressure for 8 inch, PC235 PVC (DR 18, t = 0.50 inch, Di = 8.55 inch) and CL350 DI (t = 0.25 inch, Di = 8.8 inch) pipe, with change in velocity of 2 feet/second can be calculated using following equations from AWWA M23 (2002):

$$Ps = \frac{aV}{(2.31)g} \quad \text{Eq. 2.1}$$

where: Ps = Surge pressure, a = wave velocity (feet/second)
V = flow velocity in the pipe and g = 32.17 feet/sec²

$$a = \frac{4660}{\sqrt{1 + \left(\frac{kDi}{Et}\right)}}$$

This can be further simplified to

$$a = \frac{4660}{\sqrt{1 + \left(\frac{k(DR-2)}{E}\right)}} \quad \text{Eq. 2.2}$$

where: k = fluid bulk modulus (300,000 psi for water), Di = Pipe inside diameter, in inches,
E = Modulus of elasticity (400,000 psi for PVC), (24,000,000 psi for DI pipe)
t = wall thickness, in inches,
DR = dimension ratio

For the 8-inch pipes specified, surge pressure in PVC pipe is 15.9 psi and DI pipe is 107.7 psi.

The example demonstrates that surge pressure is significantly greater in the pipes with high elasticity modulus (DI) compared to low elasticity modulus (PVC) with similar dimensions. The surge pressure is directly proportional to the modulus of elasticity. The material with higher modulus of tensile elasticity means higher the resultant surge pressure caused by a change in flow velocity also increases. Materials such as DI, steel and concrete pipe have high surge pressure due to their high modulus of elasticity ($DI = 24 \times 10^6$ psi) when compared to plastics with low modulus of elasticity ($PVC = 4 \times 10^5$ psi). This suggests that more flexible PVC pipe absorbs the surge rather than pass it along.

2.4.4.3 Installation

Both PVC and DI pipe are certified for installation using open cut and trenchless methods. The salient feature of PVC pipe being lighter makes it easier to handle compared to DI pipe that may require heavier equipment to handle. On the other hand, plastic pipes are non-conductive; buried plastic pipes so tracer wire applied at installation is recommended to facilitate locating the buried pipe. AWWA recommends installing PVC pipe with minimal joint deflection, while the DI pipe can deflect up to 5 degrees during installation of the pipe. Corrosive soil requires protecting the DI pipe; it is recommended that DI pipe be polywrapped during the installation. Both products are compatible with an array of fittings and restraining methods. Installer must check for compatibility of appurtenances with the pipe material.

2.4.4.4 Tapping

DI pipe can be directly tapped for service connections for most sizes, after the pipe is placed in service. Nevertheless, care must be taken with smaller sized pipe because corrosion may result in the reduction of the wall thickness. For PVC pipe, it is recommended to use saddles to make the main connection for services at all times. The installer must take care in using proper tapping saddles and tapping drills for any new service connection. An improper or dull cutting tool can generate heat, which causes localized weakness of the pipe.

2.4.4.5 Condition Assessment

There are several condition assessment technologies available to determine the condition of DI pipe, available wall thickness for DI pipes. Many techniques rely on the conductive and electromagnetic properties of iron. Limited condition assessment technologies are available for the PVC pipe, though failures are not as numerous as with the more established iron pipe. Acoustic leak detection with iron pipe is easier than plastic pipes though inroads have been made for detection leak noise on PVC by using subsonic frequencies per work performed by the National Research Council of Canada (Hunaidi and Chu, 1999).

2.4.4.6 Maintenance Costs

The installation of ductile iron pipe requires additional measures if corrosion or stray current is a concern. Several methods are available to inhibit corrosion. Utilities may employ cathodic protection using sacrificial anodes or induced current to protect the pipe. If used, cathodic

protection is continuous service to the pipe, and may require additional budget to maintain the DI pipe. Sacrificial anodes must be monitored as they are consumed over time.

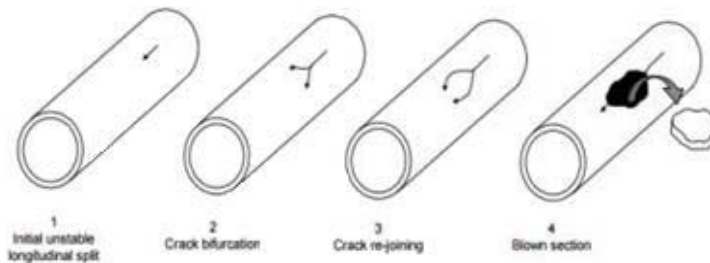
2.4.5 PVC Pipe Failure

When PVC water pipelines are within design parameters, manufactured correctly and properly installed, utilities can anticipate the pipeline to last 75–100 years (design life) without failures. Like any pipe, there are premature failures that have been reported. Many are associated with poor installation practice or surge and there have been manufacturing issues. According to Ekes et al. (2011), the average age of water pipelines in U.S. utilities is 50 years or older. Age is certainly not the sole factor in how long a pipe will last but pipe will eventually deteriorate and fail. The failure mechanism depends on, parameters such as operating pressure, environment, topography, pipe material, the temperature of water, soil conditions and others. A comprehensive report on “Long Term Performance Prediction of PVC Pipes” published by AWWA Water Research Foundation (now WRF) identified types, causes and modes of failure for PVC pipes (PVC –O, PVC – M and PVC-U). The field performance of PVC in the report was studied based on the survey responses from Australian, British, and American water utilities. A failure model was developed by conducting laboratory tests on the PVC pipes; the tests provided the inputs for the model and furthered understanding of PVC failure mechanisms under controlled action.

Folkman (2014) conducted a comprehensive study sponsored by Uni-Bell on PVC pipe longevity at Utah State University’s Buried Structures Laboratory. The test results in the U.S. and around the world suggest that PVC pipe can be expected to provide reliable service in excess of 100 years. PVC pipes excavated showed a high degree of resilience in freezing conditions, met all applicable standards, and had no change in mechanical properties and strength. The study cited the WRF report (Burn et al. 2005) on PVC Performance about 100 years as a conservative estimate for a properly designed and installed PVC pipe. The study concludes that if a pipe fails in less than 100 years, it would be attributed to a manufacturing defect, improper installation, poor designed, inadequate maintenance or simply not suited for the task (Folkman 2014).

2.4.5.1 Failure Modes

The most common PVC failure mode is longitudinal split. The failure mode corresponds to single crack initiation and propagating along the length of the pipe. This type of failure occurs when PVC pipes experience axial stress (Burn, et al, 2005; Deshmukh, 2012). By the way it is manufactured PVC (C900) pipe is not as strong in the axial direction as it is in the circumferential direction. Longitudinal splits will propagate from taps and pipe resting on irregular bedding. The consequences of a 20-foot-long pipe break can be far more severe than the typical circumferential break seen from iron pipe under stress. Longitudinal splits in PVC tend to branch as they propagate along the pipe that leads to blown out sections. Figure 2.9 illustrates how a longitudinal break tends to fork and then rejoins the original path of crack to cause a blowout.



Source: Adapted from Burn et al. 2005.

Figure 2.9 Illustration of blown section

2.4.5.2 Vulnerability to Pipe Failure

Unlike other pipe material, PVC fails for the same reasons, though the nature of failure modes differs. The PVC pipe failure may occur due to chemical attack, design, installation practice, manufacturing, pipe handling (Gramann et al., 2009) that are briefly summarized here.

Chemical Attack. PVC pipe offers resistance to most of the chemicals found in the water pipe environment. However, PVC is vulnerable to high concentrations of certain hydrocarbons such as acetone and alcohols. Chemical resistance tables for an array of chemicals are available. When in contact with hydrocarbons the PVC pipes, the hydrocarbon permeates through the pipe walls and contaminating water (Ong, et al., 2007). Fortunately, the environment does not generally contain organics with high enough concentrations of these materials to be vulnerable.

Failure Due to Poor Installation. The pipe undergoes premature failure when not installed per manufacturer direction, specifications, and standards (Gramann et al, 2009). PVC pipe should be handled carefully to prevent any breakage or minor damage that can grow worse with time. Installers can over-insert the spigot of the pipe into the bell as shown in Figure 2.10. The pipe typically has clear markings to insert the pipe the correct way. Gasket issues such as over or under lubrication and trapped debris are universal to bell and spigot pipes. Improper bedding preparation that fails to provide uniform support for the pipe is a significant problem found with PVC. Placing the pipe on sharp protruding materials stresses the pipe and can contribute to failure. Because unsupported but loaded PVC pipe tends to lose shape, proper backfill practice (including good material and proper tamping) is vital for conventional PVC pipe installation. The study of non-uniform bedding on PVC pipe conducted by Balkaya et al (2013), demonstrated that the PVC pipe experiences additional stresses in locations of non-uniform support than those with uniform bedding support.



Source: Courtesy of WSP Canada, Inc.

Figure 2.10 Bell split of PVC pipe

Tapping. A common problem found with early PVC pipe installations was making connections (taps) on the pipe. The AWWA M23, manual recommends the use of saddles for any size and class of pipe. There are instances of PVC pipe failure while performing tapping with saddles. This may be due to the stress induced into the pipe while tapping, the insufficient distance between service connection taps, the use of the wrong tap machine, drill bit or saddle. Over time and with experience, utilities have minimized PVC tapping issues. Figure 2.11 demonstrates recent PVC pipe failure due to tapping using inappropriate tapping tool by the contractor at the American Water in New Jersey.



Source: Courtesy of American Water.

Figure 2.11 Failure due from tapping

Manufacturing. The defects due to manufacturing have occurred with major impact on the PVC water pipe industry. A well-publicized, contentious but successful lawsuit (subject to appeal) filed against one manufacturer alleging substandard manufacturing may have serious implications. An array of tests can be employed to help confirm material quality when called into question, many of which are identified in subsequent pages. Figure 2.12 is an example of a manufacturing defect when foreign matter is trapped in the plastic during the pipe manufacturing.

Operational Failure. Operation failures of PVC are attributed to excessive induced stresses and strains on the pipe while in service. Operational factors such as excessive and surge pressure or external loading that are repetitive are the most obvious causes. The operational failure may be caused in conjunction with other factors such as poor installation (poor bedding/compaction, improper bell and spigot homing, insufficient depth of restrain joints etc.), soil movement and traffic loads in the PVC pipeline that magnify additional stress not anticipated during the pipe design.



Source: Beamer et al. 2009.

Figure 2.12 Damage from impurities in pipe

2.4.6 Aging or Degradation of PVC Pipe

2.4.6.1 Chemical Deterioration

Over extended time, PVC like other plastics experiences chemical change. PVC will experience breakdown of its long chained molecular structure producing change in its physical properties, most notably an increase in brittleness of the material and brittle failures would be the expected long-term outcome. Recent studies including one by the WRF project an expected life of 100 years or more for PVC pipe. The DIPRA analysis of life cycle costs comparing ductile iron and PVC employ a 75-year life estimate for PVC.

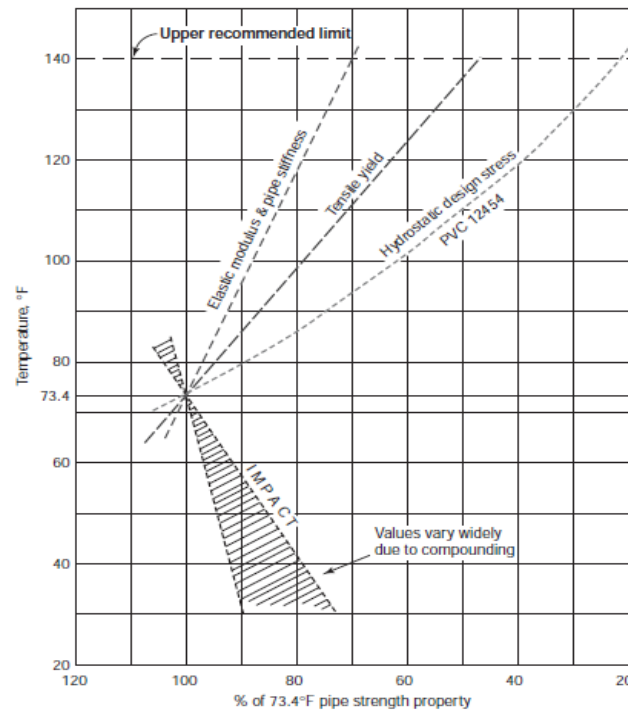
Several reports have been published on the performance, failure modes and annual failure rates of PVC and ductile iron pipe material. Rajani and McDonald (1995) submitted a report to the National Research Council of Canada that researched the annual water main break rate per 100 miles of pipe types in Canada, reporting the DI pipe rate of 15.2, and a 1.2 failure rate for PVC pipe. The annual failure rates per 100 miles from the Uni-Bell funded Folkman report for DI pipe was 4.9 and PVC was 2.6. There are limitations from both the studies such as scope of utilities surveyed, length of PVC pipes vs DI pipes, ages of installation and inclusion of pipe sizes (service lines through large diameter pipes). The EPCOR's study on Edmonton, Alberta compared PVC pipes against other pipes and found better performance from PVC pipe in their aggressive soils.

The researchers present these limited studies as background, conclusions cannot be drawn from these reports as they vary significantly and data gaps may exist. Utilities should examine local decisions in selecting the appropriate material. For example, DI pipe may perform best where there is high operating pressure but where soil is aggressive, the solution may not be the best choice. The selection of materials cannot rely only on the material physical properties, but must consider environmental and several operational parameters that provided the utility a long-lasting pipe. Here are some other factors to consider

2.4.6.2 Thermal Effects on PVC Pipe

Unlike the DI pipe, PVC pipe is subject to the material change with changing temperature. According to the AWWA M23 manual, the testing temperature for PVC pipe properties is at 73.4 °F (23 °C). However, depending upon the season the temperature of the pumped water in the distribution network, temperature can vary between near freezing temperature and above 90 °F (32 °C).

The operating temperature affects the engineering properties of the PVC pipe. As the operating temperature and surrounding soil of the pipe decreases the properties such as tensile and pipe stiffness increases this increases the pipe's pressure and increases the resistance for earth pressure. However, the properties such as impact strength and the flexibility decrease as temperature decreases. This could be a concern during installation in cold temperature. Conversely, the increase in temperature increases the impact and flexibility properties in the pipe, decreasing tensile and stiffness properties and reducing the pressure capacity. See Figure 2.13 as it applies to conventional PVC.



Source: Uni-Bell 2012.

Figure 2.13 PVC pipe strength vs temperature

2.4.6.3 UV Degradation

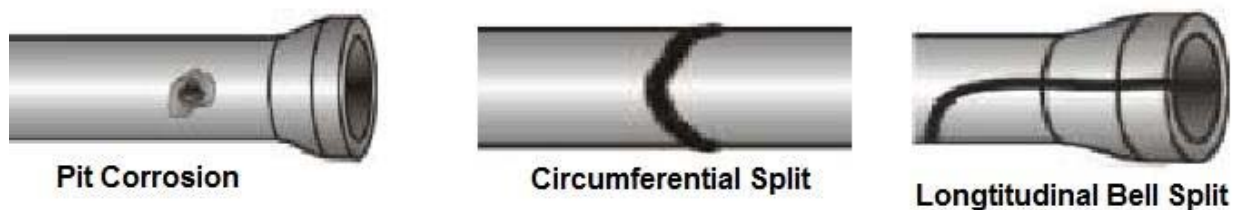
With prolonged exposure of PVC pipe to the sunlight, the free radicals in the polymer can react with the UV rays and may trigger the deterioration in the property of the pipes. The extended exposure to direct sunlight causes the PVC pipe to expand and shrink that can weaken the pipe structure. Uni-Bell (n.d.) studied the characteristics of the PVC pipe exposed to direct sunlight for two years concluded minimum or no changes with the tensile strength and modulus elasticity property of the pipe. However, the study reported a decrease in the impact strength of the pipe due to action of weathering and exposure to the direct sun. Manufacturers recommend that PVC users cover the pipe to avoided extended exposure to the sun. DI pipe does not degrade when exposed to sunlight, though prolonged exposure may cause tackiness of the asphaltic coating and residual of the coatings has been observed if the water is pumped before the coating is cooled.

2.4.7 Ductile Iron Pipe Failure

2.4.7.1 Failure Modes

Figure 2.14 shown below illustrates various failure modes.

Circumferential Split. Circumferential split failures are attributed primarily to the longitudinal stress on the pipe, a common type of failure in small pipe. The failure crack propagates around the circumferential direction of the pipe. Researchers cite soil movement, pipe bending, excessive load, inappropriate bedding, and rapid changes in water temperature as contributing factors (Deshmukh, 2012). The failure may occur in multi stages, the pipe may crack partially through the wall and then stop causing a leak. The cracked pipe may leak without completely splitting. Prolonged leaking along with water pressure typically will break the pipe all around.



Source: Makar et al. 2001.

Figure 2.14 Failure modes in ductile iron pipe

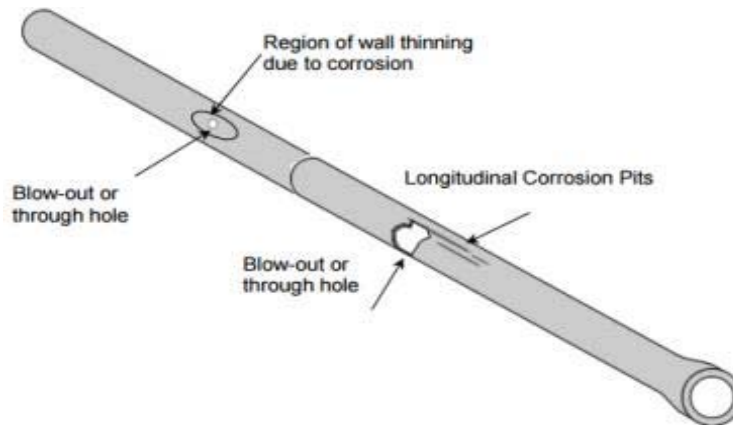
Pit Corrosion. Oxidation and bacteriological activity are the primary causes of corrosion. The reduced wall thickness due to corrosion can reach to a point where the internal pressure pushes away any remaining wall material. Depending upon the area of localized corrosion and pipe wall reduction the failure size can grow from pinhole to large size holes.

Longitudinal Break. This type of break is caused by transverse stress on large pipe due to hoop stress from internal pressure in the pipe, soil above the pipe and surface load. The longitudinal failure is more common during winter as the water and ground temperature drops and increases the hoop stress on the pipe (Deshmukh, 2012). A crack propagates down the length of the pipe and due to the internal pressure and weakened pipe wall cause the pipe to split or break.

Joint Leaks. While not typically found in ductile iron pipe with modern gaskets unless there is poor bedding support, cast iron pipes with a variety of joint materials experience leaks at bells that can result in the longitudinal type break shown on the far right of Figure 2.14.

Bell Split. A bell split occurs by a crack that propagates from the bell end of the pipe and travels a short way down its length and terminate before running into the entire pipe length. The bell split is attributed to the thermal expansion and contraction between the bell and immediate spigot connection or joint material.

Blowout. The blowout failure is associated with corrosion. When the pipe exposed to the aggressive soil or at the high water table, the oxidation process can cause localized pit corrosion. Figure 2.15 shows how a corrosion hole can grow to a crack, fork, and lead to a blowout. Monash University demonstrated this form of failure most recently in WRF funded project performed in Australia (Kodikara presentations on Advanced Condition Assessment & Failure Prediction Technologies for Optimal Management of Critical Water Supply Pipes – Water RF Project #4326).



Source: Makar et al. 2001.

Figure 2.15 Blowout hole mechanism in DI pipe

2.4.7.2 Causes of Failure

Ductile iron pipe has experienced failures owing to poor installation, manufacturing defects, third party damage and shifts in the soil due to changing moisture content. Ductile iron is vulnerable to a wider range of chemical degradation owing to corrosion, primarily oxidation. Though more flexible than the cast iron materials, they are considered more vulnerable to shifts in the ground than plastic materials.

Chemical Attack. The DI pipes have zero tolerance for the chemical attack caused due to the action of oxidations, sulfidation and acids. According to the study on the water main break rates in the USA and Canada by Folkman (2012) attributed, about 43% of the failure reported by the utilities was due to oxidation of the DI pipes. Unlike the PVC pipes, the DI pipes offer very good resistance for the hydrocarbons and have been popular choice of pipe for the utilities to install in hydrocarbon contaminated soil environment. (Vinyl Pipes, 2016; Vinyl Institute, 2016)

Corrosion. External corrosion can be due to the soil property (corrosive soil) and internal corrosion could be due to the action of water in contact with direct metal surface (Makar, et al, 2001). Ductile iron pipe is prone to external corrosion as the common coatings in the US are not particularly effective in corrosive environments. In Europe zinc and epoxy coated pipes are becoming increasingly popular and have recently been introduced in the US. Properly installed cathodic protection and polywrapping the pipe can mitigate corrosion. Corrosion inside the pipe usually takes the form of tuberculation on unlined pipe. Today's pipe has an effective sealed cement lining to eliminate this issue for the most part. The pattern of corrosion can dictate whether the failure that results is a pinhole or propagates into other forms of breaks including blowouts.

Thermal Stress. The temperature fluctuations in the pipe influence failures in the metallic pipes. The DI pipes are strong in nature and confidence in handling the temperature fluctuations. However, the DI pipe could be categorized as good conductor of heat and electricity. Due to the prolong exposures to the lower temperature of water and soil around the pipe during cold season may induce the stress in the DI pipe and influence the action of contraction in the pipes. The contraction of the fixed pipe develops tension at the joints and compression in the center of the pipe (similar to the fixed steel beam member structure). These small variations in the pipe dimensions along with the water pressure can increase the stress in the pipe walls and lead to failure. Similarly, when the temperature of water and pipe increases, the pipe tends to elongate in the longitudinal direction. This induces the compression stress at the joint and tension at the center

of the pipe. This fluctuation in the pipe dimensions and volumetric changes can influence the pipe failures. The circumferential split is the frequent mode of fracture due to the thermal variation.

Poor Installation. Proper pipe support plays a vital role in the performance of the pipe and its useful life. The DI pipes have often failed by lack of proper pipe support and poor installation. The DIPRA's installation manual cites that the DI pipe requires the trench bed to be well prepared to support the pipe before installation and recommends using crushed stone and compacted to support the bed in swampy conditions. Additionally, the DIPRA also recommends to poly-wrap the pipe before the installation. Improper wrapping may trigger localized corrosion and fail the pipe (Figure 2.16). There is also concern that when leaks do begin on polywrapped, the moisture will be trapped and accelerate further issues.



Source: Courtesy of American Water.

Figure 2.16 DI corrosion

Tapping. According to AWWA M41 manual, DI can receive the basic service tap directly on the pipe in most conditions (AWWA 2009a). The M41 manual indicates that a common $\frac{3}{4}$ -inch taps can be directly tapped on pipes less than 6 inches as well as one-inch direct tapping for pipes on 6 inch and larger pipes. However, if the pipes are in service for more than 50 percent of its useful life or the DI pipe installed without poly-wrap, the manual recommends tap service connections use saddle connections because the thickness of the wall may have been reduced and sufficient thread contact between the tap corporation and the ductile iron pipe wall is required.

Manufacturing Defects. With proper inspection at time of delivery, DI pipe defects due to manufacturing can be readily spotted. The most common defects are irregular roundness at the bell and spigot ends. This can happen at the manufacturing facility or while the pipe is in transit. Improper loading of the manufactured pipes for shipping can cause the deformation of the pipe roundness. The next most frequent defect in the DI pipe is the uneven thickness of the cement mortar lining that can reduce the hydraulic capacity of the pipe. These manufacturing defects are obvious and can be visually inspected prior to the pipe installation. Unnoticeable defects such as presence of foreign matter in the pipe, uneven thickness of the pipe and small cracks during the annealing process cannot be detected easily by visual inspection, as the finished pipes undergoes layer of mortar lining (inner side of the DI pipe) followed by asphaltic coatings (exterior and interior sides of pipe). The concealed defects may influence premature failure in the DI pipes.

2.4.7.3 Monitoring Pipe Performance

Condition Assessment. At some point, all pipe placed underground will deteriorate unseen and it will become important to assess their condition and detect failure (leaks) or eminent failure in some way. With aging infrastructure issues, developing asset management programs and improved condition assessment techniques, there has been an increased effort within the water industry to evaluate the condition of underground assets. Several condition assessment technologies are available to monitor the health of pipes, find leaks or estimate the remaining service life of the pipe. Notable technologies are available to assess metallic and other failing pipes, especially those with a high consequence of failure (like PCCP pipe). Because the oldest pipes are iron, technologies such as magnetic flux leakage, remote field eddy current, ultrasonic technologies are now available.

Leak Detection. Because condition assessment is expensive, most utilities perform a *de facto* assessment process by monitoring pipe failures and use the frequency or extent of those failures to make replacement decisions. This places value on finding leaks from failing pipes more rapidly. Leak detection methods have evolved in recent times. The focus of methods began with metallic pipes that are simply older and more leak prone. Condition assessment techniques really do not appear to be abundant for PVC that reflects the limited need for assessment at this time as much as the potential challenge to devise a sound methodology. Leak detection for PVC pipes is more challenging due to its structural properties; leak noise does not travel as well in PVC pipe and is largely subsonic. For larger pipe, sophisticated methods for other pipe types that travel inside the pipe will be appropriate for PVC and other nonmetallic pipe.

Pipe Locating. As noted earlier, PVC being a nonconductive material requires some form of markers to help locate their underground location. Tracer wire, magnetic tape and marker balls have been employed to make this an easier process but wire and tape are vulnerable to disruption. (The use of witching sticks has a disputed reputation.) Ductile iron as a conductive material is readily located.

Pipe Storage. The storage of PVC pipe inventory for a significant length of time requires attention to controlling exposure to sunlight. Ductile iron does not require covering for extended outdoor storage but as a heavier material requires more care and attention to handle safely.

Pipe Linings and Coatings. PVC pipe is uncomplicated and has neither exterior coatings nor interior linings. Ductile iron lining typically receives a cement lining covered with a seal coat. For locations with soft aggressive waters, the seal coat is the only true protection and there have been no studies identified to analyze the durability of the seal coats. In the US, the exterior coating provides some protection from the soil environment. Polyethylene wrap is prescribed to add protection in corrosive soils; this can be effective but does increase time of installation.

2.5 PRE-PROJECT TESTS ON iPVC PIPE

The product studied for this research project is the innovative iPVC pipe. The manufacturer of iPVC pipe, PPII conducted several tests on iPVC pipe well before the research work in the US began. The iPVC pipe has the same thickness as standard PVC (see Figure 2.17).



Source: Courtesy of PPII.

Figure 2.17 8” DR-18 iPVC wall thickness

Table 2.3 summarizes the test results for iPVC pipe performed by PPII.

Table 2.3
Preliminary iPVC pipe test results by PPII, Korea

Test Description	iPVC Pipe DR-18	AWWA Standards Requirements
Tensile Strength (psi)	7,780	7,000
Impact Strength (ft-lb/inch)	1.26	0.65
Modulus of Elasticity (psi)	428,000	400,000
Vice Flattening Test	No Cracks	-
Long Term Pressure Test (1000 hrs.) 73 °F at 500 psi	No Failure	-
Short Term Burst Test (5 sec)	Pass	-
Acetone Immersion Test	Pass	-
Hydrostatic Burst Test	Pass	-
Elongation at Break (%)	574	>400
Compression Set Test (%)	14	20 (Max)
Short Term Burst Pressure Test (psi)	899	>755
Pressure at 6,090 psi	18 hrs.	1 hr.
Deflection Temperature Test	76 °F	70 °F
Flammability Test (ASTM D635-14)	<10 mm	<25 mm

Source: Data from AWWA 2016 and PPII 2015

The earlier test results as per Table 2.3 show that iPVC pipe exceeds AWWA C900 and C909² criteria. The impact load, hydrostatic burst pressure, tensile strength, and weight for iPVC pipe is higher than the recommended AWWA requirements for standard PVC. PVC and iPVC pipe have been tested under low temperature (–4 °F) for impact resistance. PVC pipe failed from a drop height of 4.9 feet. The iPVC pipe only showed a scratch on the surface with the load dropped from

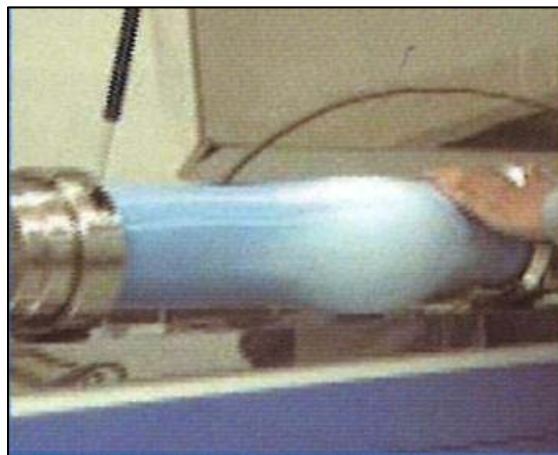
² C909 AWWA criteria essentially mirrors C900 except for the Hydraulic Design Basis and pipe dimensions (thickness). It is clear that C909 exceeds some the criteria listed above but this is not presented to utilities.

a height of 16.4 ft. Figure 2.18 displays the contrasting results of the impact of the dropped load on a common PVC pipe and the iPVC.



Source: Courtesy of PPII.

Figure 2.18 Impact testing on PVC pipe on the left and iPVC on the right



Source: Courtesy of PPII.

Figure 2.19 iPVC pipe pressurized, frozen

PPII has also performed practical demonstrations to display the strength and flexibility of the iPVC pipe. PPII tested an iPVC pipe sample by freezing the water contained in the pressurized iPVC pipe. The freezing water expanded the pipe material but without any failure in the pipe as seen in Figure 2.19. In a field demonstration, a full-size excavator passed over the pipe (Figure 2.20). The bucket end of the excavator pinched the pipe with maximum load (Figure 2.21). Under load, the pipe was squeezed (by 80% for crawl test and 90% for bucket test) but returned to its original dimensions, without damage, after the loading was removed. Observers noted only a few superficial scratches on the external surface of the pipe.



Source: Courtesy of PPII.

Figure 2.20 Crawl demonstration



Source: Courtesy of PPII.

Figure 2.21 Bucket demonstration

CHAPTER 3

TESTING METHODOLOGIES

The testing of the iPVC pipe is one of the key objectives of this research project. The purposes of testing were to provide better information about the engineering properties of the product by conducting selective destructive and nondestructive tests on the pipe and gain confidence before performing a pilot installation of the pipe. The results of the lab tests are discussed in Chapter 4. The objectives include studying the performance of the pipe at its ultimate loading capacity and correlate to the field installation requirements. The results of the bedding test and pilot installations of the pipe are described in Chapter 5.

Chapter 2 discussed the available literature on the tests used in PVC testing, specifically those performed in this research project. This chapter discusses the testing methodology conducted on iPVC pipe in this research. AW developed a testing protocol for the iPVC research project after assessing available standard tests that could be performed. The researchers employed labs at UTA and Microbac to perform the tests. The parties worked together to follow procedures for hydrostatic short-term burst pressure, impact, stiffness, and tensile testing based on relevant ASTM standards. Owing to the strength of the iPVC material and the need to examine possible changes in installation methods, the researchers modified testing, adding the fatigue test and the bedding test to provide a better understanding of how the iPVC would perform in the field.

3.1 INTRODUCTION

PPII performed extensive testing on the iPVC pipe prior approaching the American Water to help certify its use in other countries. The testing conducted on the pipe, were in compliance per the standards recognized in the water industry (AWWA/ASTM/ISO standards). PPII has done much of the testing with NSF, mindful of the need to employ an internationally recognized testing organization. The American Water has examined the results including those listed previously in the Table 2.3 that offered an early indication of the pipe performance. Some tests slated in the project confirm prior PPII testing but most looked to identify any potential weakness in the pipe or explore installation requirements.

AW worked with Center for Underground Research and Education (CUIRE) at the University of Texas at Arlington (UTA) to select of tests at the beginning of the project. After the series of discussions, the project team shortlisted six tests to evaluate the pipe and its performance under the controlled laboratory and field conditions. The selected laboratory tests include hydraulic burst test, tensile test, impact test, stiffness test and field tests included fatigue tests and bedding test. The results from these tests will provide pipe installers with confidence in carrying out their work. PPII is exploring the potential for the product if made available to the water utilities in North America.

Four of the six laboratory tests on the iPVC for the project could be conducted in accordance with ASTM standards recognized in the AWWA C900/C909 and cited in AWWA M23 Manual. ASTM does not define the bedding or fatigue tests. Owing to the need to perform testing rapidly and hold schedule, American Water divided the material testing for the research project between UTA and Microbac Laboratories, Boulder, Colorado. UTA conducted the tests including tensile, hydraulic burst, fatigue, and bedding tests and Microbac laboratory tested the pipe for tests tensile, hydraulic burst, stiffness, and impact tests. The goal was to perform a

significant amount of the testing in advance of a second phase of the project to install about 1,500 feet of 8-inch DR 18 iPVC pipe in the St. Louis County, MO.

3.1.1 Testing Logistics and Mobilization

The iPVC manufacturer shipped pipe from their factory in South Korea by ship so the iPVC testing required careful planning and long lead times to get pipe samples to the labs. Shipping took at least 30 days just to get to the west coast of the US. Hence, prior to the testing of the pipes, PPII worked with American Water and UTA to discuss the quantities of pipe, cut dimensions and shapes required for the selected tests and installation. UTA generated the list of quantities along with the dimensions and American Water reviewed and submitted to PPII to initiate the pipe cut desired pipe dimensions for testing. The desired cut test specimens for the material testing arrived at the UTA on July 30, 2015 (Figure 3.1). In addition to material supply mobilization, UTA engaged students, mobilized and ordered test equipment, labelled and prepared specimen for the testing.



Source: Courtesy of UTA.

Figure 3.1 Stockpiled sample material to UTA

3.1.2 Engagement of Microbac Lab, CO

Unexpected delays in the start of the project moved the testing from summer to fall, and UTA delays in providing equipment threatened to push the pilot field installation to the spring of 2016. Additionally, it was becoming clear that testing equipment would have to be top of the line, capable of operating at very high levels. The principal investigator decided to split the work between UTA and a well-equipped, certified plastics testing laboratory. American Water identified specific tests required and engaged Microbac Laboratories, Inc. Microbac's testing facility for plastic pipe is located in Boulder, Colorado; they are an accredited ASTM laboratory. The lab confirmed that they could perform any of the lab tests. Remaining samples were divided between

the labs. For the tensile testing and hydrostatic burst test, the researchers felt it beneficial to secure test results from both laboratories. The team reviewed the materials that had been sent to UTA and made arrangements to ship additional materials from Korea to the Microbac lab.

3.1.3 Pipe Testing Summary

PPII performed tests on the iPVC pipe well before the project began. PPII authorized standard tests, primarily by NSF, in order to gain certification worldwide. These earlier tests demonstrated the material complied with the AWWA, ISO and ASTM requirements. The tests on the pipe adhered to the AWWA and ASTM requirements as outlined in the AWWA C900 standard and the AWWA M 23 PVC Pipe Design and Installation Manual. The section below discusses the tests conducted by the UTA and Microbac Lab on the iPVC pipe. The iPVC pipe research project testing consists of six different tests based on the acceptable testing protocols reviewed by American Water:

1. Hydrostatic Short-term Burst Pressure Test
2. Impact Test
3. Stiffness Test
4. Tensile Test
5. Fatigue Test
6. Bedding Test

UTA executed the hydrostatic short-term burst pressure test, tensile test, fatigue test and bedding test. Microbac performed the hydrostatic short-term burst pressure test, tensile test, impact test and stiffness test.

3.2 HYDROSTATIC SHORT-TERM BURST PRESSURE TEST

3.2.1 Purpose

The burst test method is used to determine the resistance of pipe material to hydraulic pressure in a very short time. The standard used for this testing was the ASTM D1599-14 “Standard Test Method for Resistance to Short-Time Hydraulic Pressure of Plastic Pipe, Tubing, and Fittings.” This test method could be employed in the industry for quality control purposes or as part of specifications in future iPVC projects. This test determined the burst pressure of iPVC pipe and subsequently used to calculate the hoop stress. Researchers were vitally interested to know how the pipe would fail.

Hoop stress is defined as the stress in the circumferential (tangential) direction in cylindrical and non-cylindrical vessels, when loaded by the hydrostatic head of a liquid in a fully- or partially-filled container or by internal or external pressure in a closed vessel. The hoop stress is exerted perpendicular both to the axis and to the radius of the pipe (Figure 3.2). The hoop stress of the pipe can be calculated using Equation 3.1:

$$S = \frac{P(d)}{2t} \quad \text{Eq. 3.1}$$

where: S = hoop stress (psi),
P = internal pressure (psi),

D = average outside diameter (inch),
d = average mean diameter (inch), (D-t) and
t = minimum wall thickness (inch)

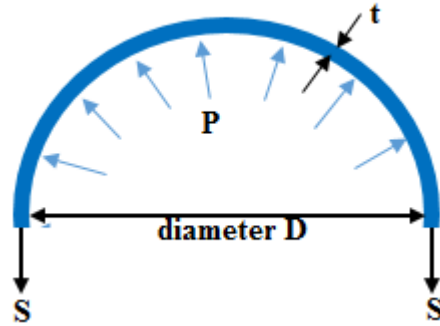


Figure 3.2 Hoop stress due to internal pressure

3.2.2 Related Research

The burst test is a common testing procedure employed by the manufacturer to qualify the pipe material under the defined pressure class of the PVC pipe. According to AWWA C900-16 standard, the DR 18 PVC pipe should be able to resist a minimum of 755-psi internal water pressure. This test is often used to investigate the in-service PVC pipe performance to understand the deviation of the property changes in the material with the original specs of the pipe. The test may also be used during the pipe failure forensic analysis. Table 3.1 provides the minimum burst pressure test required for PVC pipe per ASTM F1674-11 (ASTM 2010b).

Table 3.1
Burst pressure requirement for PVC 1120 pipe, 73 °F water

Dimension Ratio	AWWA Pressure Class, psi (kPa)	Sustained Test Pressure, psi (kPa)	Hydrostatic Test Pressure, psi (kPa)
13.5	--	670 (4,619)	1000 (6,895)
14	305 (2,100)	650 (4,482)	985 (6,791)
17	250 (1,720)	530 (3,654)	800 (5,516)
18	235 (1,620)	500 (3,447)	755 (5,205)
21	200 (1,380)	420 (2,896)	630 (4,344)
25	165 (1,140)	350 (2,413)	535 (3,689)
26	160 (1,100)	340 (2,344)	500 (3,447)
32.5	125 (860)	270 (1,862)	400 (2,758)
35	--	250 (1,724)	380 (2,620)
41	100 (690)	210 (1,448)	315 (2,172)
51	80 (550)	168 (1,158)	260 (1,793)

Source: Reprinted, with permission, from ASTM 2010b, copyright ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA 19428.

EPCOR Water Services Inc. conducted its own study in 1994 to evaluate the performance of PVC pipes in the City of Edmonton, Alberta, Canada. EPCOR conducted the study on 8-inch and 10-inch DR 18 PVC pipe installed in 1977. EPCOR confirmed tested sections exceeded minimum test requirements after years of service. The pipe ultimately failed at 1,000-psi burst pressure. Other unspecified classes of PVC pipes in service tested in the study did not fail until pressure exceeded 1,000 psi (Sergeant, 2014).

3.2.3 Procedure

In simple terms, the burst test is a process in which the test specimen is subjected to an increasing level of internal pressure until failure occurs. Failure is defined as the first weep or leaking of fluid. The minimum allowable time to failure is 60 seconds; however, the failure time may be extended beyond 60 seconds for a more conservative result. ASTM D1599 outlines procedures A and B. Procedure A of ASTM D1599-14 is used to determine burst pressure of a specimen if the mode of failure is to be determined. Procedure B of ASTM D1599-14 is used to determine that a specimen complies with a minimum burst requirement.

iPVC testing was conducted on two different samples lengths. The length of the samples tested at UTA was 30 inches Microbac conducted the burst test on 42-inch samples. The testing duration for iPVC samples was slightly longer than the ASTM standards procedure. The researchers decided to vary the rate of application of the burst pressure in part to more closely simulate longer-term stress. Three samples tested at UTA had failure time as 56 seconds, 59.7 seconds, and 80 seconds and the fourth sample had a failure time of 139 seconds. All the samples tested at Microbac had failure time of more than 100 seconds with the maximum failure time of 150 seconds.

3.2.4 Expected Outcome

Data obtained by this test method are expected to predict the behavior of pipe under conditions of temperature, time, method of loading, and hoop stress similar to those used in the actual test. For iPVC pipe project, the test will determine the burst pressure of iPVC pipe and lead to calculating the hoop stress and evaluating the performance of iPVC pipe as compared to the AWWA standards minimum requirement of 755 psi for a PVC pipe. Researchers are looking for evidence that the pipe will not simply fail longitudinally but in random directions.

3.2.5 Benefit to the Industry

Satisfactory test results will provide the maximum pressure capacity and maximum hoop stress induced in the iPVC pipe when subjected to uniform internal pressure and allow users to compare the material more directly to conventional PVC. The burst test will also show how the pipe fails. If the pipe does not simply fail in a longitudinal direction, it suggests that iPVC pipe failures may be less catastrophic.

3.3 IMPACT TEST

3.3.1 Purpose

The purpose of this test is to evaluate the impact resistance of thermoplastic pipe and fittings under specified conditions of impact. The impact resistance of thermoplastic pipe relates

to the suitability for service and handling during installation and the quality of manufacture. Impact resistance may also provide a relative measure of a material's resilience during handling and installation and, for non-buried applications, to in-service breakage. The standard used for this testing is the ASTM D2444-99 “Standard Test Method for Determination of the Impact Resistance of Thermoplastic Pipe and Fittings by Means of a Tup (Falling Weight)” (ASTM 2011b).

3.3.2 Related Research

The WRF project *Long Term Performance of PVC Pipe* (Burn et al, 2005) identified the drop impact test as a commonly used indicator for PVC pipe outside the US and listed the following standards and the range of requirements in Table 3.2. The Table 5 of ASTM D2241-15 dictates the minimum impact energy for different PVC pipe sizes and dimension ratios. According to this table, for 8 inch and above PVC pipe must display resistance to impact energy of 160 foot-pounds when impacted with 20-pound tup B (meaning a drop from 8 feet). The standards for PVC-O pipe is higher. However, neither AWWA standard C900 nor C909 contain any requirement for impact resistance.

Table 3.2
Required impact resistance (falling weight)

Standard	Minimum Criteria (Size)	Maximum Criteria (Size)
ASTM D2241 (PVC)	10 foot pound (0.25 inch)	160 foot-pounds (>8 inch)
ASTM F1483 (PVC-O)	100 foot-pounds (4 inch)	200 foot-pounds (12 inch)
AS/NZS 1477 (PVC)	7 foot-pounds (0.5 inch)	108 foot-pounds (>6 inch)
AS/NZS 4765 (PVC-M)	1,441 foot-pounds (4 inch)	3,603 foot-pounds (>12 inch)
AS/NZS 4441 (PVC-O)	43 foot-pounds (2 inch)	230 foot-pounds (>12 inch)
ISO 4422 (PVC)	1.5 foot-pounds (0.5 inch)	92 foot-pounds (>12 inch)

Source: Adapted from Burn et al. 2005

Note AS= Standards Australia, NZS = Standards New Zealand

Bauer (1994) discussed the performance comparison of oriented PVC (PVC-O) and PVC-U (PVC) pipe by conducting several tests on the pipe samples. One of the tests discussed in the Bauer paper is the impact test, the author predicts that the PVC-O, if made at the same wall thickness as PVC would withstand much larger impacts by a factor of 3 to 5. Such testing was not possible as PVC-O pipes are much thinner than PVC pipe. The reference does not provide complete information on the pressure class and thickness of pipes used or the shape and weight of tup employed.

3.3.3 Procedure

The standard test procedure by ASTM requires testing 125 specimens, out of which 25 specimens are reserved for preliminary testing to pinpoint the approximate drop height and weight of the tup to cause failure. The preliminary test uses trial and error, or judgment, to estimate the drop height at which 85% of the specimens will pass. During the testing, the 100 samples were divided into two sets of 50. The first set of 50 specimens use the height obtained during the preliminary test to pass at least 85% of the specimens. The second set of 50 is tested on samples by increasing height of the drop or weight of the tup to achieve 85% specimen failure. The value

of the mass is recorded at tup, the drop height, and the number of passes. The test continues until failure in the test specimens through shattering or any crack or split created by the impact can be seen by the naked eye (ASTM 2011b).

PPII already tested and qualified the iPVC pipe per ASTM D2444-10. The sole objective of retesting the impact study was to estimate the maximum impact energy of the iPVC pipe. Hence, the current impact test was modified, to align with the research objective by AW. Although the standard test procedure requires testing 100 specimens, in the current research study 70 specimens were tested, largely because there was little question that the units would pass. To eliminate the preliminary testing, previously studied impact results were provided to the lab that indicated the impact result was above the capacity of the equipment. This reoccurred at Microbac and samples that passed the test without any failure were re-tested again. Initially, the samples were tested at the standard 73°F and several remaining test samples were tested under lower temperature (32 °F).

3.3.4 Expected Outcome

The researchers expect the ultimate impact resistance of the DR 18 8-inch iPVC pipe to be determined. Considering the demonstrations of iPVC pipe resilience by PPII, the breaking of iPVC pipe samples would be a challenge to the limits of the equipment.

3.3.5 Benefit to the Industry

The impact resistance of thermoplastic pipe and fittings relates to suitability for service and to the quality of processing. Impact resistance provides a relative measure of a material's resistance to breakage during handling and installation. The iPVC pipe impact testing may be used by the industry to compare other plastic pipes as a performance evaluation parameter.

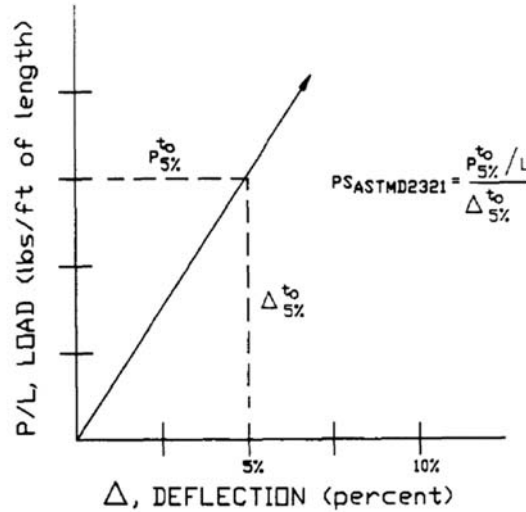
3.4 STIFFNESS TEST

3.4.1 Purpose

The purpose of this test as per ASTM D2412-11 is to determine the load-deflection characteristics of stressed pipe. The test targets specific deflections of plastic pipe that are achieved by direct application of parallel-plate loading.

Plastic pipe stiffness is the measurement of the load capacity of the pipe subjected to vertical loading conditions. Pipe stiffness is a function of the material type and the geometry of the pipe wall. Plastic pipe stiffness can be determined using the ASTM D2412-11 “Standard Test Method for Determination of External Loading Characteristics of Plastic Pipe by Parallel-Plate Loading” test shown in Figure 3.3. The pipe stiffness (PS) is defined as the ratio of applied force (F) in pounds per linear inch over the measured change of pipe inside diameter (Δy). The pipe stiffness can be calculated by Equation 3.2. Equation 3.3 is useful to calculate PS when the force acting vertically on the pipe per unit length and the deflection of the pipe available.

$$PS = \frac{F}{\Delta Y} \quad \text{Eq. 3.2}$$



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Figure 3.3 Load-PVC deflection curve

Pipe stiffness equates to the slope of the load-deflection diagram as shown in Figure 3.3. The stiffness of the pipe can be calculated with respect to the dimension ratio (DR) of the pipe. However, the value of the pipe stiffness obtained by the DR based Equation 3.3 is more conservative, always less than or equal to the pipe stiffness obtained from Equation 3.2 (AWWA 2002).

$$PS = 4.47 \frac{E}{(DR-1)^3} \quad \text{Eq. 3.3}$$

The stiffness factor (SF) is defined by the Equation 3.4 (ASTM D2412-11). The allowable AWWA deflection pipe stiffness permitted in design is 5% vertical deflection. In other words, the maximum change permitted in the vertical plane is 5% of the original pipe inside diameter (with application of load). ASTM D2412-11 states that creep due to the time taken to reach the 5% deflection may affect the stiffness of larger size pipe made from relatively low modulus material. Therefore, PVC pipe stiffness is strain and time dependent. In order to calculate the pipe stiffness, the Equation 3.3 can be further simplified to Equation 3.4.

$$SF = 0.149 r^3 (PS) \quad \text{Eq. 3.4}$$

where: E = Flexural modulus of elasticity (psi)

I = Moment of inertia

D = Mean diameter of pipe (inch), (Outside diameter – thickness/2)

r = Mean radius of the pipe = D/2

F = Force applied per unit length (pounds/inch)

Δy = vertical deflection (ID) in inch

3.4.2 Related Research

Bishop (1990) conducted an experimental study on the non-pressure PVC pipe to evaluate the long-term stiffness on the pipe when exposed to various environments under constant strain and the influence of the pipe environment on the stress relaxation of the PVC pipe. Three effect types of non-pressure PVC pipe manufactured per different ASTM 1784 cell class (12454B, 12154A, 13364B) PVC compounds were selected in this experimental study. Environments employed included air and water mixed with low concentrations (5%) of sulfuric acid and sodium hydroxide). The impact on PVC pipe was measured by change in the pipe mass and change in the strength on unstressed samples exposed to the various environments. The experiment monitored the instantaneous slope of the load deflection curve as a function of time.

To understand the deviation in stiffness strength, six-inch long samples were tested to determine the initial stiffness strength per ASTM D-2412- 87. The researchers exposed the experimental samples in the environmental medium for one-week and then clamped in a position of fixed deflection ranging from 5% to 10 %. The samples were evaluated at time interval of 1 day, 1 week, 2 weeks, 4 weeks, and every 4 weeks thereafter up to one year. The load increment was subsequently increased to produce an added deflection increment to a total deflection of 7.5% or 10%. The slope of the load-deflection curve for this new load increment was calculated for each new time interval. Figure 3.3 provides the relationship of load-deflection curve. The pipe stiffness results for this research are provided in Table 3.3.

The researchers concluded that the long-term stiffness and stress relaxation of the pipe can be influenced by exposing the pipe to different environments. Samples prepared from three resin showed consistent variations in performance between cell classes.

Table 3.3
Pipe stiffness for non-pressure PVC pipe

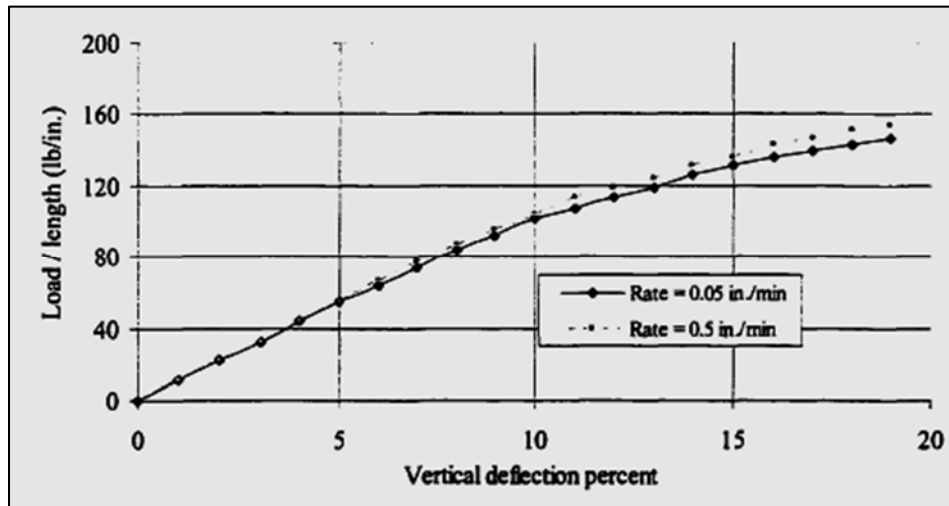
Description	Pipe A	Pipe B	Pipe C
SDR	35	--	35
ASTM Cell Class	12454 B	12154 A	13364 B
Specific gravity	1.14-1.42	1.64-1.66	1.53-1.54
Pipe Stiffness (psi)	54.1-60.95	65.70-70.79	44.91-48.34

Source: Reprinted, with permission, from Bishop 1990, copyright ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA 19428.

Schluter and Shade (1999) reported the parallel plate tests performed at three different loading rates using PVC and HDPE pipes. These rates were 0.05 inches/minute, 0.5 inches/minute, and 5 inches/minute. Changing the loading rate by a factor of 100 resulted in a 6.5% stiffness change in PVC pipes and 56% in HDPE pipes. The study also stated that the ASTM D2412-11 deflection rate of 0.5 inches/minute does not relate to the real-world deflection rate and that a deflection rate of 0.05 inches/minute is more realistic. It was concluded that both laboratory measurements and theoretical calculations of ASTM D2412-11 are too simplistic and that the deflection rate effect on PVC pipes is minor but has a great influence on HDPE stiffness.

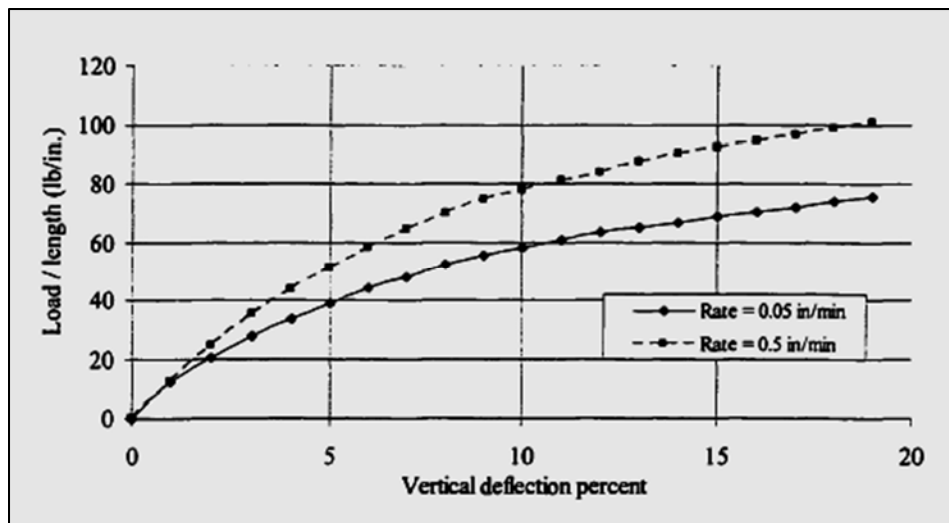
Another study by Sargand et al. (1998) evaluated PVC and HDPE pipes using variable rate parallel plate test equipment applied at two different rates of deflection: 0.5 inches/minute and 0.05 inches/minute on 18-inch pipes. Figures 3.4 and 3.5 show the load per unit length (pound/inch) versus the vertical deflection percent results of variable loading rate parallel plate

tests performed on PVC and HDPE pipes, respectively. Pipe stiffness calculated using Equation 3.3 is summarized in Table 3.4. The reduction of pipe stiffness calculated at higher deflection rates was 3% to 6% for PVC and up to 25% for HDPE pipes. These results show that the deflection or loading rate has little effect on the PVC pipe stiffness while HDPE material is more sensitive to the rate of load application.



Source: Sargand et al. 1998.

Figure 3.4 Parallel plate test for 18-inch PVC pipe



Source: Sargand et al. 1998.

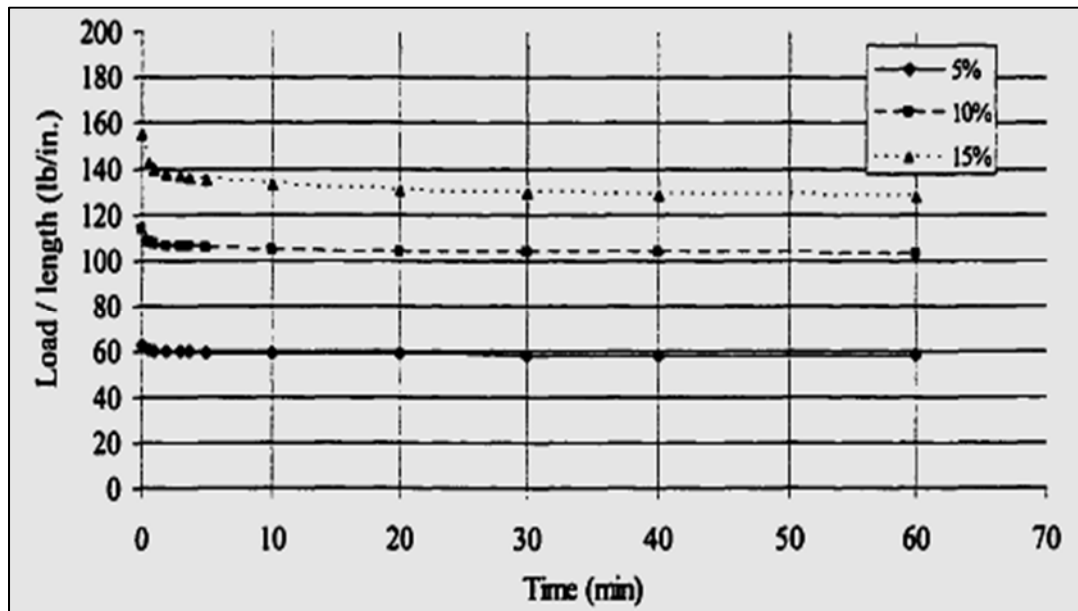
Figure 3.5 Parallel plate test for 18-inch HDPE pipe

Table 3.4
Pipe stiffness of parallel plate test at two different loading rates

Pipe Material	Loading Rate (inch/min)	Pipe Stiffness (lb./inch) at Percent Deflection			
		5%	10%	15%	19%
PVC	0.5	62	57.9	50.8	45
	0.05	60.5	55.6	48.4	42.5
HDPE	0.5	56.2	44.8	34.7	23.9
	0.05	42.5	33.2	25.9	22.3

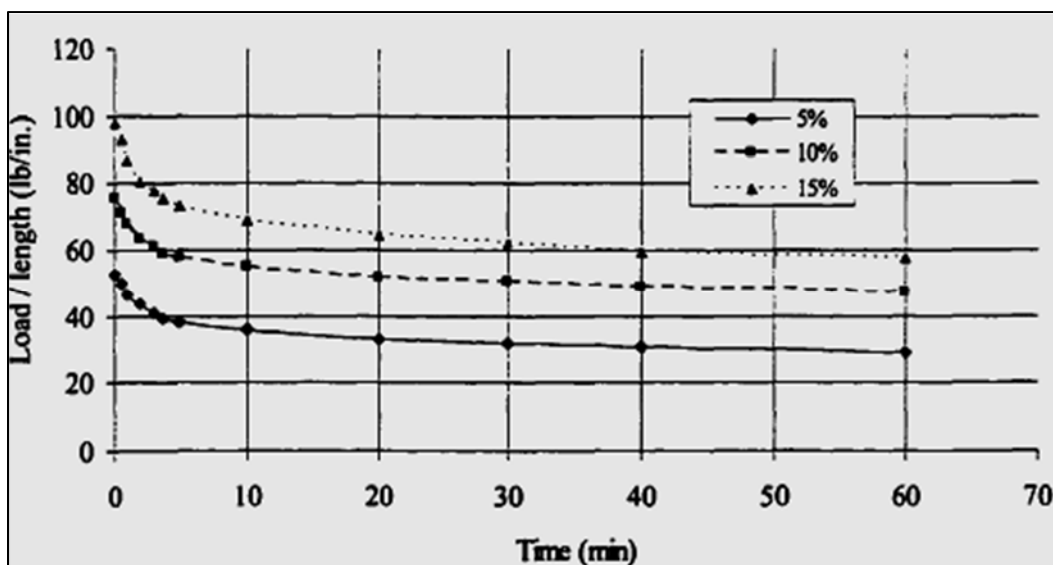
Source: Sargand et al. 1998

Related research later studied the stress relaxation of PVC and HDPE pipes using the parallel plate test. A variable load was applied over a period of one hour in order to maintain at fixed vertical deflection. Researchers performed separate tests to maintain percentages of 5%, 10%, and 15%. Figure 3.6 illustrates the stress relaxation results for PVC pipes, while Figure 3.7 illustrates the stress relaxation of HDPE pipes. The time was extrapolated to estimate the pipe stiffness at 50 years. The percent reduction in stiffness was dependent on the percent deflection for PVC pipes and showed a range of percent reduction between 12% and 32%. The percent reduction in stiffness for HDPE pipes was between 75% and 82%. While the percent reduction in pipe stiffness is greater for HDPE pipes, it is less dependent upon the degree of vertical deflection.



Source: Sargand et al. 1998.

Figure 3.6 Stress relaxation of PVC pipe



Source: Sargand et al. 1998.

Figure 3.7 Stress relaxation for HDPE pipe

Sargand et al performed these tests to understand the effect pipe behavior with time and results are presented below. Per Table 3.5, the loss of pipe stiffness over time is significantly higher in HDPE pipe as compared to PVC pipe material. The loss in stiffness relates to the loss in the ability of the pipe wall to withstand the vertical load exerted on it by loading. Significant loss in pipe stiffness over time could result in significant deformation of pipe under loading over time, ultimately leading to failure of the pipe. It is interesting to note that during this study, the author does not report any failure of HDPE or PVC pipe due to the loss in the pipe stiffness.

Table 3.5
Pipe stiffness results of stress relaxation tests

Pipe Material	Time	Pipe Stiffness (lb./inch) at Percent Deflection		
		5%	10%	15%
PVC	1 minute	60.3	107.7	140.6
	50 years	52.6	88.7	95.7
HDPE	1 minute	46.8	67	88.1
	50 years	8.4	16.3	16.2

Source: Sargand et al. 1998

3.4.3 Procedure

Researchers at Microbac employed the ASTM D2412-11 test procedure for the stiffness test. The process starts by measuring the specimen sample average inside diameter and pipe perimeter to the nearest millimeter (1/32 inch) or less. The average pipe wall thickness and average pipe outside diameter were measured from the top as well as the outside diameter to the nearest 0.2 mm. (0.01 inches). After the initial measurements are recorded, the researchers place the pipe sample with its longitudinal axis parallel to the bearing plates and center it laterally in the testing machine. The upper plate makes contact with the specimen with no more load than what is

necessary to hold it in place to establish the beginning point for subsequent deflection measurements.

The technician compresses the pipe at a constant rate of 0.50 ± 0.02 inches (12.5 ± 0.5 mm)/minute. The load-deflection measurements are recorded continuously or intermittently to the relative movement of the bearing plates. The test is complete when the pipe specimen fails, defined as cracking, breaking or if the load on the specimen fails to increase with increasing deflection. The specimen passes if it reaches 60% of the average inside diameter or the required maximum deflection.

3.4.4 Expected Outcome

Researchers expected excellent pipe stiffness and pipe deflection values for iPVC pipe. Data will be collected at every 5% reduction in the ID of the iPVC pipe (95%, 90%, 85%, 80%...20%), the pipe stiffness, pipe deflection and the load applied. The iPVC should far exceed values for PVC pipes; the minimum requirement for PVC pipe stiffness is 364 psi per AWWA M23 Manual. The expected outcome was that the test might reach maximum reduction and continue until the top of the pipe made contact with the bottom of the pipe.

3.4.5 Benefit to the Industry

Pipe stiffness relates to handling and installation characteristics of a pipe during the early stages of soil consolidation around the pipe and the extent of deflection under load. The Spangler equation based on the pipe stiffness will provide the theoretical percent deflection experienced by iPVC pipe under loading. This value can be compared to the AWWA maximum allowable limit of 5% for flexible pipes. Pipe engineers use the deflection of pipe under load to evaluate the pipe material, trench and backfill requirements. The more resilient the pipe to vertical stress, the better able it will support itself in the trench under load.

3.5 TENSILE TEST

3.5.1 Purpose

The primary purpose of the tensile test per ASTM D638 (ASTM 2010a) is to determine the tensile properties of unreinforced and reinforced plastics in the form of standard dumbbell-shaped test specimens under defined conditions of pretreatment, temperature, humidity, and application of tensile stress.

For iPVC pipe project, the tensile testing was employed to evaluate the iPVC pipe behavior under loading. The test will help to understand the ultimate tensile strength the material can handle and to calculate its modulus of elasticity.

This test method aims to produce tensile property data for the control and specification of plastic materials. The test allows for computation of the modulus of elasticity and dimension ratio (OD/t) of iPVC pipe. The modulus of elasticity is a parameter used to predict the expected deflection in the pipe under earth and other loading conditions and calculate pipe stiffness. The results obtained from this test can be used for qualitative characterization of material and for future research and product development. The deflection in flexible pipe can be calculated using modified Iowa (Eq. 3.5). The deflection in flexible pipe can be calculated using modified Iowa (Eq. 3.5). The modified Iowa can be further simplified per Eq. 3.6:

$$\% \frac{\Delta Y}{D} = \frac{(D_L K P + K W') 100}{0.0149 P S + 0.061 E'} \quad \text{Eq. 3.5 (Uni-Bell, 2012)}$$

where: PS = Pipe Stiffness, psi
K = Bedding constant
W'= Live load, psi

$$\% \frac{\Delta Y}{D} = \frac{(D_L W_p + W_L) K_x 100}{\{2E/[3(DR-1)^3]\} + 0.061 E'} \quad \text{Eq. 3.6 (Uni-Bell, 2012)}$$

where: E = Modulus of elasticity of pipe (psi)
DR = dimension ratio (OD/t)
W_L = Live Load on the pipe, psi
W_p = Prism Load (soil pressure), psi
ΔY/D = Percentage deflection
K_x = Bedding constant
D_L Deflection lag factor
E' = Modulus of soil reaction, psi

3.5.2 Related Research

Neelam and Kalaga (2002) studied the elastic properties of PVC pipes using tensile tests per ASTM D638-14. They studied material properties used to describe the physical nature of PVC: yield strength (σ_y), yield strain (ε_y), percentage elongation, initial modulus of elasticity (E_i), and increase in axial strain (Poisson's ratio [ν]). The study describes the results of the tensile tests conducted on dogbone shaped PVC pipe specimens 8-inch diameter with a wall thickness of 3.5 and 5.5 mm. (0.138 to 0.217 inches). The dogbone specimens were extracted with the length oriented along the pipe longitude. An extensometer measured the axial strain during the test. Strain gauges measured strain. The test was performed at a deflection rate of five millimeters (0.197 inches) per minute. Each test stopped when the specimen fractured; the fracture load, ultimate load and final gauge length were recorded. The elastic parameters determined from the testing are summarized in Table 3.6. The modulus of elasticity and tensile strength results of PVC in this study were higher than those identified in the 'Handbook of PVC Pipe Design and Construction' standard by Uni-Bell of 400,000 psi and 7,000 psi respectively, suggesting that the factors listed in Pipe design may be conservative.

Table 3.6
Elastic parameters for PVC pipe

Parameter	Results
Tensile Strength (σ _y)	7,520 psi
Modulus of Elasticity (E)	507,000 psi
Shear Modulus (G)	195,200 psi
Poisson's Ratio (ν)	0.31

3.5.3 Procedure

The sample specimens for this research were prepared by trimming the pipe section in the standard dumbbell shape. The size and the dimensions of the dumbbell shapes are defined by the Type as provided under ASTM D638 (ASTM 2010a). The ASTM D638-14 recognizes five Type specimens (Type I, Type II, Type III, Type IV and Type V), and the selection of Type are based on the plastic resin (Sheet, Plate, Molded plastic, or rigid tubes), and thickness of the plastic. The thickness T for the DR18 class 235 iPVC pipe is 0.55 inches (14 mm), which complies with the Type III dimensions (full wall) of the ASTM table.

The tensile test was conducted by both UTA and Microbac. Tensile test specimens were prepared per Type III by the PPII and tested at UTA. When Microbac lab received samples, they advised that for PVC compounds with cell classification 12454-B and higher, the specimens for tensile test must be prepared per Type I (mid-wall) dimensions. American Water decided to pursue both the tests for both Type I and Type III samples to study the tensile properties. Microbac subsequently prepared and tested the Type I samples.

The tensile test is conducted by securing the conditioned dumbbell shaped specimen and pulled at a constant machine testing speed. Specimens are secured in the grips of the testing machine, taking care to align the long axis of the specimen and the grips with an imaginary line joining the points of attachment of the grips to the machine. According to ASTM D638-14, the machine speed for Types I, II and III can vary between 0.1 inch/inch min to 1 inch/inch min (see Figure 3.8). For this study, the samples were pulled at a constant speed of 0.5 inch/inch min. The testing instrument is equipped with the suitable extensometer to measure the deformation, Modulus of Elasticity, and the material extensions. The load extension curve of the specimen, load at the extension, yield and at the break are recorded. The results are discussed in the next chapter.

TYPES I, II, III & V

TYPE IV

Specimen Dimensions for Thickness, T, mm (in.)⁴

Dimensions (see drawings)	7 (0.28) or under		Over 7 to 14 (0.28 to 0.55), <u>incl</u>	4 (0.16) or under		Tolerances
	Type I	Type II		Type IV	Type V	
W - Width of narrow section	13 (0.50)	6 (0.25)	19 (0.75)	6 (0.25)	3.18 (0.125)	±0.5 (±0.02)
L - Length of narrow sections	57 (2.25)	57 (2.25)	57 (2.25)	33 (1.30)	9.53 (0.375)	±0.5 (±0.02)
WO - Width overall, min	19 (0.75)	19 (0.75)	29 (1.13)	19 (0.75)	-	+ 6.4 (+ 0.25)
WO - Width overall, min	-	-	-	-	9.53 (0.375)	+ 3.18 (+ 0.125)
LO - Length overall, min	165 (6.5)	183 (7.2)	246 (9.7)	115 (4.5)	63.5 (2.5)	no max (no max)
G - Gage length	50 (2.00)	50 (2.00)	50 (2.00)	-	7.62 (0.300)	±0.25 (±0.010)
G - Gage length	-	-	-	25 (1.00)	-	±0.13 (±0.005)
D - Distance between grips	115 (4.5)	135 (5.3)	115 (4.5)	65 (2.5)	25.4 (1.0)	±5 (±0.2)
R - Radius of fillet	76 (3.00)	76 (3.00)	76 (3.00)	14 (0.56)	12.7 (0.5)	±1 (±0.04)
RO - Outer radius (Type IV)	-	-	-	25 (1.00)	-	±1 (±0.04)

Source: Reprinted, with permission, from ASTM 2010a, copyright ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA 19428.

Figure 3.8 Tensile test specimen dimensions

3.5.4 Expected Outcome

Researchers expect testing to provide the tensile strength and modulus of elasticity of iPVC greater than conventional PVC values. AWWA C900 pipe requirements specify a minimum tensile strength of 7,000 psi and a minimum modulus of elasticity of 400,000 psi.

3.5.5 Benefit to the Industry

The modulus of elasticity is the primary input for the designers for calculation of pipe deflection due to different loading scenarios and assist the designers in selection of trench details including the depth of cover. The industry uses the modulus for the calculation of the stiffness of the pipe.

3.6 FATIGUE TEST

3.6.1 Purpose

The objective of the fatigue test task was to evaluate iPVC behavior under cyclic surge conditions by putting oscillating high pressure loading on a 10-foot section of iPVC pipe. The test will determine whether the iPVC pipe can withstand cyclic surge loading that are 1.5 times higher

than the maximum American Water operating pressure rating (225 psi) of the pipe for an extended time. There is evidence that PVC pipe subjected to cyclic stresses weakens more rapidly than pipe operating under steady pressure. Extreme surge testing is associated with aging PVC pipe and may suggest iPVC pipe longevity.

Pressure surges are the result of a rapid change in liquid velocity within a pipeline that causes the stored energy in the flowing fluid to be converted to pressure energy. Events like rapid valve closure or a pump tripping from power outages are common examples. The resulting pressure changes, commonly referred to as transients, hydraulic surges, hydraulic transients, or water hammer, are an important consideration in the design of water transmission and distribution systems.

Occasional pressure surges and recurring pressure surges are the two types of transient surges considered while designing. Transient surges are impulse events that occur with very rapid rates of pressurization. Occasional pressure surges can be defined as the peak pressure surges caused by events outside normal operations of a pipeline (e.g., power outage causing tripping of all system pumps). Recurring pressure surges are peak pressure surges caused by normal pipeline operation (e.g., pumps turned off and on, valves opening and closing) occurring at a frequency of more than once per day (Oliphant et al. 2012). Changes in pressure can be in excess of 100 psi/sec (Petroff 2013).

Metallic pipes have a much higher modulus of elasticity (more rigid and less flexible) than plastic pipe. According to AWWA C150/C151, the nominal surge allowance for ductile iron pipe is 100 psi, 3 times more than the AWWA standard for PVC pipes. This means that the PVC is essentially absorbing the energy of the surge and suggests PVC material may lose strength as it absorbs the surge energy. According to Burn et al, (2005), the plastic nature of the PVC pipes will tend to promote crack growth when subjected to erratic pressure variations. The higher the fatigue resistance is, the lower the risk of crack initiation.

3.6.2 Related Research

Several studies have described PVC's ability to handle desired surges generated from the operating and surge pressures. Burn et al. (2005) studied PVC fatigue resistance by conducting rotational bending tests on the pipe. From the test results, Burn found that conventional PVC used in North America offers slightly more resistance to fatigue than the rough equivalent PVC-U used in European and Australian markets. PVC-O used in North America exhibits highest resistance to all the material tested for fatigue (suggesting iPVC will also perform well).

Petroff (2013) conducted an experimental study to determine the effect of flow velocity on surge pressure. Petroff suggested that as the flow velocity increases, lower dimension ratio (thicker wall) pipes would have greater need to handle the surge pressure. A reasonable flow velocity recommended for design is 5 feet per second per the American Water Works Association Research Foundation (AwwaRF) report, 'Guidance Manual for Maintaining Distribution System Water Quality (2000). Utilities use this velocity in system maintenance for flushing, removal of biofilm and deposits. Petroff (2013) predicted the number of cycles that would result in HDPE pipe failure based on the Equations 3.9 and 3.10:

$$Number\ of\ Cycles = 10^{\frac{1.708 - \log\left(\frac{Peak\ Stress}{145}\right)}{0.101}} \quad Eq. 3.7 \text{ (Petroff, 2013)}$$

$$Peak\ Stress = (P_{Pumping} + P_{Surge}) \times \frac{(DR-1)}{2} \quad \text{Eq. 3.8 (Petroff, 2013)}$$

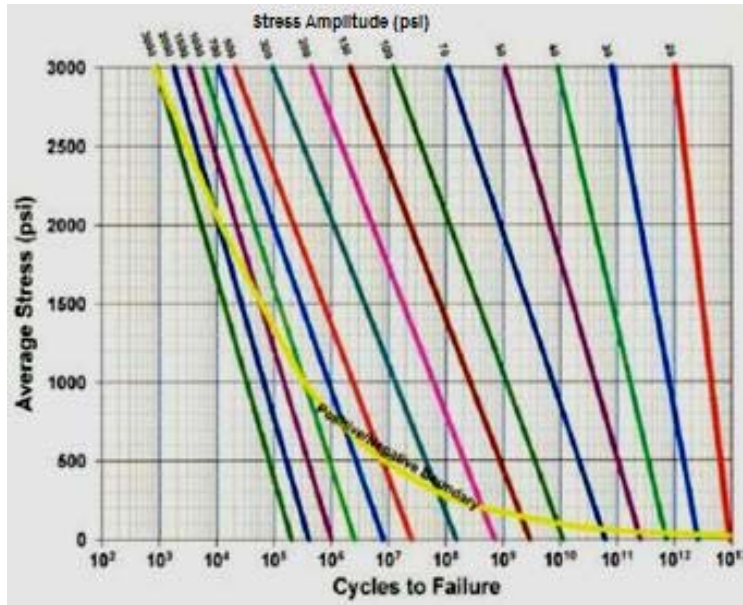
Herbert W. Vinson (1981) conducted a policy to predict failure in PVC pipes. He studied the response of 6-inch diameter PVC pipes to repeated large pressure surges to various peak hoop stresses. The approach developed by Vinson was used to predict the fatigue failure in PVC pipes. Vinson cycled the pipe from a base hoop stress between 400 and 500 psi to increasing peak hoop stresses. Based on his experiments, he developed an equation for predicting cycles to failure from a peak hoop stress:

$$C = (5.05 \times 10^{21}) \times S^{-4.906} \quad \text{Eq. 3.9 (Vinson, 1981)}$$

where: C = number of surges to failure
S = peak hoop stress, psi

Shigley and Mischke (1989) explained that fatigue is a function of stress amplitude and mean stress. Although the study was conducted for steel, a similar study was applied for PVC to predict crack initiation due to fatigue. Shigley and Mischke believed fatigue in a member is due to the number of times that stress occurs (i.e., stress cycles). If the Burn study conclusion is correct, and the plastic nature of PVC pipes will tend to promote crack growth when it is subjected to erratic pressure variations, conducting fatigue tests can predict the pipe resistance to crack initiation. The higher the fatigue resistance (and lower the stress) is, the lower the risk of crack initiation.

Similar studies to predict the fatigue life of PVC pipes were conducted by Hucks (1972), Bowman (1990) and Marshall et al. (1998). Moser (2001) examined these previous studies and conducted his own tests. He determined that the previous tests were inadequate and concluded that the way to predict failure of PVC would be to use two independent variables, stress amplitude and mean stress together. Figure 3.9 presents the S-N plot (Stress-Number of Cycles to Failure) developed by Moser.



Source: Jeffrey et al. 2004.

Figure 3.9 Moser's stress/cycles plot

Utah State University (Jeffrey 2002) conducted a fatigue study (cyclic test) on 6-inch C900 PVC pipe for Uni-Bell to validate failure models described in the prior paragraph. The cyclic study was performed in two phases: Phase I was conducted on ten pipe sections where Vinson's equation predicted the pipe to fail after 322,000 cycles; Phase II was conducted for 10 million cycles on five pipe samples that to test Moser's methodology for predicting failure time.

Jeffrey discusses the three important parameters while studying fatigue per Figure 3.10. These parameters are as follows:

Stress Range (σ_{range}): $\sigma_{range} = \sigma_{max} - \sigma_{min}$ Eq. 3.10 (Jeffrey et al. 2004)

Stress Amplitude (σ_{amp}): $\sigma_{amp} = \frac{(\sigma_{max} - \sigma_{min})}{2}$ Eq. 3.11 (Jeffrey, 2002)

Mean Stress (σ_{mean}): $\sigma_{mean} = \frac{(\sigma_{max} + \sigma_{min})}{2}$ Eq. 3.12 (Jeffrey, 2002)

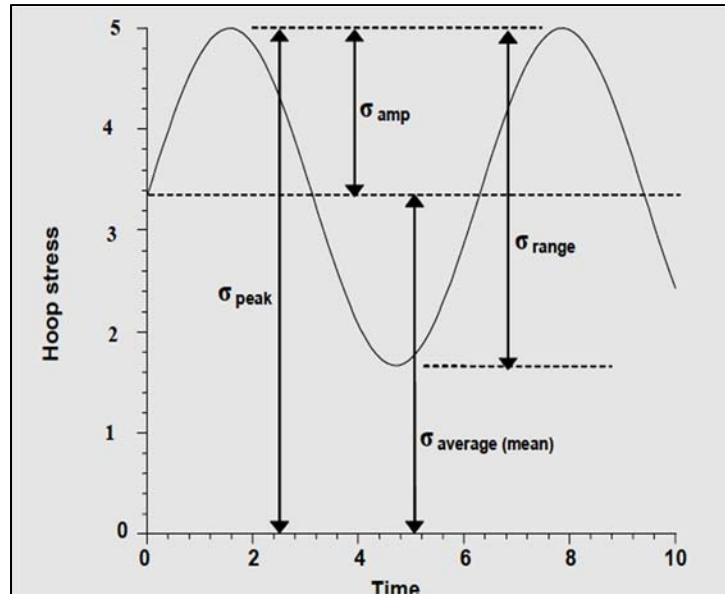
The stress is calculated based on the water pressure the pipes are subjected to using thin wall theory (Gere and Timoshenko, 1997). Figure 3.10 shows the parameters.

$$\sigma = \frac{Pr_{mean}}{t} \quad \text{Eq. 3.13 (Jeffrey, 2002)}$$

where: σ = circumferential or hoop stress

r_{mean} = mean radius and

t = minimum wall thickness



Source: Jeffrey et al. 2004.

Figure 3.10 Illustration of stress terminology

The testing continued to 10 million cycles without any failure. Jeffrey (2002) predicted the number of cycles for failure would be at around 20 million cycles. He also verified and confirmed that the mean stress and mean amplitude have direct influence on the fatigue of the PVC pipe. The testing by Jeffrey et al. (2004) to validate Moser's idea that mean stress and stress amplitude together influence PVC fatigue determined that stress amplitude primarily influences the fatigue in PVC and mean stress plays a lesser role. As the amount of fatigue failure data was very limited in the testing, Jeffrey recommends the use of Moser's plot only as a guide (Jeffrey et al. 2004).

3.6.3 Procedure

The UTA experimental setup consists of a 450-gallon water reservoir tank, a multi-stage centrifugal pump (15 HP), a data acquisition system, a control board, several pressure transducers, a DC power supply, one specimen (8-inch pipe 10-feet-long), and control valves including one back-flow pressure valve, two solenoid/pressure ball valves, and two butterfly valves. A galvanized steel pipe system with pipe diameters of one inch and two inches connects the equipment.

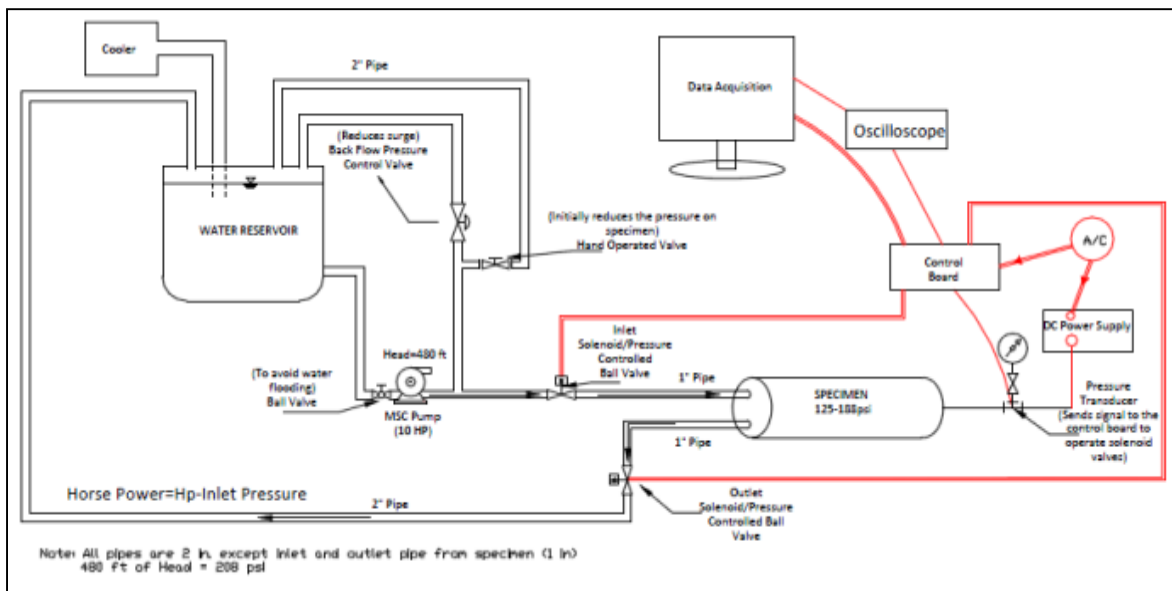
Backflow pressure control valves in the test setup protects the pump from excessive water pressure due to water hammer. Backflow pressure control valves reduced the pressure by assimilating the water head from the multi-stage pump and reduced the surge on the inlet valve. When the pump is operating and the control board is connected to the valves, the inlet valves open and let water run into the pressurized sample. The inlet solenoid valve opens and induces pressure inside the specimen to the desired 225 psi, while the outlet solenoid valve reduces the pressure inside the specimen to 150 psi when the pump switches off. The control board signalizes both inlet and outlet solenoid valves to open and close. The pressures employed were intentionally higher than the ASTM F1674-11 (ASTM 2010b) specified levels for DR18 pipe per Table 3.7.

Table 3.7
Cyclic pressure requirements 12454 PVC compound

Dimension Ratio (DR)	Peak Pressure, psi (kPa)	Base Pressure, psi (kPa)
13.5	254 (1751)	127 (876)
14	244 (1682)	122 (841)
17	198 (1365)	99 (683)
18	188 (1296)	94 (648)
21	159 (1096)	79 (545)
25	132 (910)	66 (455)
26	127 (876)	63 (434)
32.5	101 (696)	50 (345)
35	93 (641)	47 (324)
41	79 (545)	40 (276)
51	63 (434)	32 (221)

Source: Reprinted, with permission, from ASTM 2010b, copyright ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA 19428.

Data is conveyed through a pressure transducer used in the test setup to convert water pressure in the pipe into an analog electrical signal. The transducer is connected to the oscilloscope, which converts the output signal of pressure transducer to a waveform pattern in terms of voltage. The oscilloscope receives a signal from the pressure transducer and demonstrates the pressure waves on a desktop monitor screen. Figure 3.11 and Figure 3.12 present the schematic diagram and the actual fatigue test setup at UTA.



Source: Divyashree 2014.

Figure 3.11 UTA CUIRE fatigue test equipment schematic



Source: Courtesy of UTA.

Figure 3.12 UTA CUIRE fatigue testing set up

3.6.4 Expected Outcome

The fatigue test will help in evaluating the reliability and durability of the pipe under surge pressures and may predict the approximate service life of the iPVC pipe. If the pipe does not fail in the defined cycles, the expected life of the pipe may be estimated from the rate of expansion of the pipe and its dimensional changes over the life of the test. If little change is observed, provisions will be made to extend the test.

3.6.5 Benefit to the Industry

Observations for the dimensional changes of iPVC under cyclic loading will act as a performance indicator of iPVC pipe. The controlled surge pressure results may serve to predict the performance of the pipe for the surge events in service. The manufacturer will sponsor testing beyond 2 million cycles to add further confidence if the pipe continues to perform. The test specimen will be returned to the manufacturer for analysis when the test is completed.

3.7 BEDDING TEST

3.7.1 Purpose

The bedding test was designed to understand pipe deformation pipe under native soil and live loading conditions, outside the AWWA C605 backfilling requirements. Bedding tests do not have a defined standard test. The researchers developed an informal process to study the deflection behavior of the pipe under dead and live load. The procedure developed included the use of displacement sensors to measure the deflection of pipe and strain gauges to measure the stress experienced by the pipe.

3.7.2 Related Research

Alam and Allouche (2010) conducted an experimental investigation of pipe and soil friction coefficients for direct buried PVC pipes. They concluded that structural performance of flexible buried pipes is greatly influenced by the interaction between pipe and the soil envelope surrounding it. Figure 3.13 is a schematic diagram of a buried pipe. The pipe is subjected to thrust forces due to changes in flow direction, cross-sectional area, pipeline terminations, and/or thermal expansion/contraction. The researchers observed that the use of concrete reaction blocks as a way to restrain the pipe systems is on a rise, which helps reduce the amount of thrust experienced by the pipe.

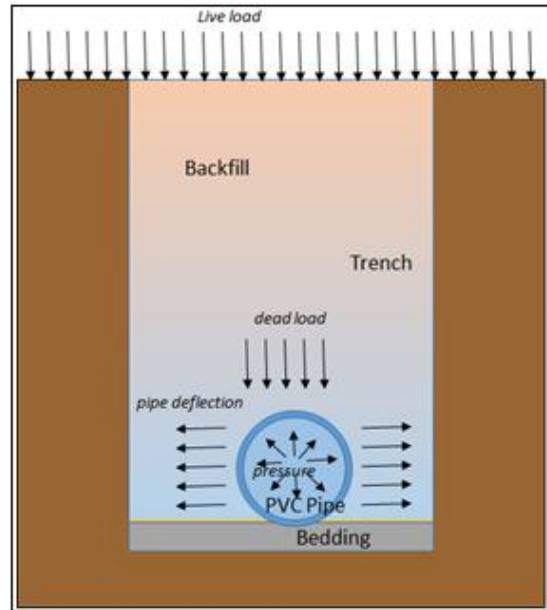


Figure 3.13 Schematic diagram of buried pipe and forces in trench

The experimental field test program used an 8-inch diameter, 14-foot long PVC pipe placed in silty sand, moist silty sand, graded gravel, silty clay, and moist silty clay as bedding materials. The experimental work on the buried pipe covered a wide-range of soil types, pressures, and moisture contents. The experiment investigated the soil-pipe friction coefficients of a direct buried, restrained, PVC pipe under controlled laboratory conditions. The force needed to overcome friction between pipe and its surrounding bedding, total pipe movement along its longitudinal axis, rigid body movement, and elongation of pipe under applied axial force were measured during the testing.

The PVC pipe was installed in a soil chamber and a circular opening to the end of the soil chamber was used to bolt the front-end of the pipe with a control actuator. The actuator was used to apply an axial tensile load to the pipe. A linear variable differential transformer (LVDT) was placed on the rear-end cap of the pipe to measure the rigid body movement of the pipe. Strain gauges were mounted on the top of the crown to measure the elongation of the pipe under the applied axial load. Four earth pressure cells were used to measure the soil pressure during the test.

Designers employ friction force calculations for calculating the minimum embedment support around the pipe length for any given project. The experimental results of the friction forces from the test were compared with the calculated results using three different approaches. The approach that best matched field results utilized Coulomb's equation along with modifiers suggested by Potyondy (1961) for the cohesion and soil friction angle coefficients. The approach assumes that the behavior at the pipe-soil interface is similar to that of soil-to-soil interface in making calculations. The approach slightly over-predicted the friction force for fine grain soils and under-predicted the force for gravelly soils.

A study by Zhan and Rajani (1997) evaluated the benefits of use of controlled low strength materials (CLSM) as trench backfill in contrast to traditional backfill materials such as sand and clay for a PVC pipe under traffic loading. It also studied the influence of CLSM on the behavior of buried pipes. The study sought to determine the sensitivity of load transfer from truckloads to buried pipes with different trench backfill materials, pipe burial depths and pipe materials and used finite element modeling that compared the finite element results favorably with the field results.

The National Research Council of Canada (NRCC) along with city of Edmonton, Alberta have undertaken field studies since 1993 to study the behavior of PVC water mains in different trench backfills and to examine the pipe-soil interaction. These studies have also evaluated the thermal performance of the backfill materials to study the risk of freezing water in the mains. As a part of this initiative by NRCC, two PVC 8-inch (200 mm) water mains were installed in parallel at different depths (8.2 feet and 3.3 feet) and monitored with different soils. The trench was divided into seven sections 66 feet (20 meter) in length. Each section was backfilled with different backfill materials such as native clay, sand (with and without insulation layers), CLSM, expanded shale lightweight aggregate, thermal Crete (biomass), and bottom ash. The mains installed at a depth of 3.3 feet (1.0 m) were studied under truck loading.

Strain gauges were installed in three of the seven sections of backfill materials with native clay, clean sand and CLSM. The strain gauges were installed to measure the circumferential (hoop) as well as longitudinal strains (axial). Three earth pressure cells were used to measure the earth pressures on the pipe.

In the 1995 study, the three sections of backfill with the strain gauges and earth pressure cells were subjected to truckloads of 45,000 pounds (200 kN) truck weight, 5,620 pounds (25 kN) for each front tire and 8,430 pounds (37.5 kN) in each of the four rear tires. Each section was subjected to loading and the truck remained stationary at each location for 5 minutes while the data for strain and pressure was collected. While the field-testing was performed, analysis with the help of finite element modeling was done to validate the field results and conduct sensitivity analyses to understand the importance of burial depth on the water pipes in the three different backfills.

The hoop strains estimated from a finite element analysis and observed in field tests were significantly less on pipes in the section of the trench with CLSM when compared to sand and clay backfill. The sensitivity analyses on an 8-inch (200 mm) PVC and ductile iron pipe were performed with variables of depths and these different backfills. The value of hoop strain or stress in the pipe wall illustrated the effectiveness of the backfill material. The lower the value, the more the backfill material must offer lateral support in the trench.

Test results determined the external hoop stresses for clay and sand backfills were 68% and 127% higher, respectively, at springline as compared to external hoop stress in CLSM backfill. The external hoop strain at springline in sand backfill is 92% higher than in clay backfill, while it is negligible in CLSM backfill. The study concludes that the CLSM backfill is a better alternative to sand and clay backfills for PVC pipes. CLSM protects the buried pipe from traffic loads better than sand and clay.

Balkaya et al. (2012) evaluated the stresses and the deformations in a buried PVC water pipe with bell-and spigot joints. The study aims to focus on non-uniform bedding conditions while considering future pipe products and pipe joints, and emphasizes the potential effects of joint leakage and soil erosion. Pipe joints greatly affect the performance of the pipe, and defects at the joint could lead to pipe failure. Leakage at joints could lead to erosion of the soil materials around the pipe creating voids under the pipe. The creation of voids leads to a non-uniform bedding at the joints. The pipe considered in this study is unsupported at the invert and haunches as voids are created to simulate non-uniform bedding while performing the finite element analysis. The changes in the stresses and deformations were determined based on the geometry of the voids.

While pipe design is based on its ability to withstand the amount of internal fluid pressure, it is also partially determined by pipe joint systems. If the pipe joint systems are installed incorrectly or become damaged, then water can leak out of the pipe. Joint leakage can lead to undermining of the bell joint and catastrophic failure. In order for the pipe to function efficiently,

the soil bedding level must be uniform around the joint. If the bedding is not uniform, it can cause pipe bending that can alter the joint tightness and lead to pipe failure.

The finite element modeling in this study strongly suggests that an increase in voids under the pipe leads to an increase in vertical displacements with the lowest increase at the crown and maximum at the invert of the pipe. If the void angle (width of invert without soil support) is small, the factor of safety drops significantly. If the voids under the invert have a larger angle and the pipe is unsupported from the haunches, more soil load is distributed through the soil resulting in less stress on the pipe. Highest stresses were observed when the voids were directly under the joints. The vertical displacement observed for PVC pipes was more in loose silty sand as compared to medium-dense sand.

Balkaya et al. (2013) studied the non-uniform bedding support conditions under continuous PVC water distribution pipes. The purpose of this study was to understand the effect of non-uniform bedding support on the stability of buried PVC pressure pipes and study the longitudinal soil-pipe interaction. The study aims were to develop a better understanding of longitudinal bending because of voids under the invert of buried PVC pipes. The performance of the buried pipe depends on the relative stiffness of the soil and the pipe and the structural performance depends on the structural characteristics of the soil and the pipe. ASTM D2321-14e1 (2005) lists various factors such as method and extent of compaction of embedment materials, types of embedment, water conditions in the trench, pipe stiffness, uniformity on embedment support, and installation practice that affect the deflection of the pipe. Ideally, a uniform bedding is important to provide a uniform support along and around the pipe.

Due to factors such as unstable foundation materials, uneven settlement due to angular distortion between individual lengths of the pipe, over-excavation and non-uniform compaction of the bedding soil, a pipe will have a non-uniform bedding support. The non-uniform bedding could result in longitudinal and circumferential cracks and joint openings, which will lead to leakage and ultimately failure of the pipe. Hence, it is imperative to understand the effects of non-uniform bedding on longitudinal bending in buried PVC pipes.

A PVC water pipe with a 6-inch (150 mm) outside diameter and thickness of 0.19 inches (5 mm) was studied for both uniform and non-uniform bedding conditions. The pipe was installed on a soil layer of 3.3 feet (1 meter) depth and a bedding depth of 9 inches (0.225 meters). It was covered with overburden soil to a depth of 8.2 feet (2.5 meters). Voids of varying sizes were created to make the bedding non-uniform with the effect of voids located under the invert and around the haunches of PVC pipe studied for this paper.

The finite element analyses indicate that the increase in voids will increase the stresses on the pipe walls. The results from the study illustrate that the pipes with non-uniform bedding conditions experience peak tensile wall stresses from 37% to 69% higher than those pipes with uniform bedding for medium dense sand and 45% to 95 % higher than dense sand.

For the installation of flexible pipe, backfilling procedure of soil is very important to help distribute loads through the bedding. If soil is poorly backfilled, it results in additional load on the pipe and increased deflection of the flexible pipe walls. Deflection is defined as the change inside the diameter that results when a load is applied to a flexible pipe. In pipe design, the vertical dimension is the greatest concern. Vertical deflection is usually limited to 7.5% of the base inside diameter; the inside diameter of the base is the nominal diameter less manufacturing and out-of-roundness tolerances inherent to the manufacturing process (Uni-Bell, 2012).

Beamer et al. (2009) at the Calleguas Municipal Water District in Southern California performed laboratory tests to find out the cause of the 16-inch PVC transmission main failures

experienced by the water district. The results showed that the pipe material did not comply with the minimum requirements. It was concluded that the central part of the PVC pipe wall was incompletely fused during manufacturing (Beamer et al. 2009).

3.7.3 Procedure

UTA conducted the bedding test outside the UTA CUIRE laboratory facility in Arlington, Texas. Figure 3.14 shows the location of the UTA CUIRE lab and the nearby bedding test location. AW advised UTA to conduct a bedding test similar to the University of Kansas study on the steel reinforced HDPE (Khatri, 2014).



Source: Courtesy of UTA.

Figure 3.14 Bedding test location, Arlington, Texas

Two test pits were excavated for the bedding test. The trenches were 30 feet long, 32 inches wide and 5 feet deep in natural soil. Figure 3.15 presents the test pit for the two tests. Figure 3.16 illustrates the installation details for a second bedding test with additional monitors installed. To understand the characteristics of native soil used as backfilling material, UTA analyzed the soil. The native soil was characterized as silty soil with mixture of sand and clay. Table 3.5 summarizes the native soil investigation at the bedding test locations.



Source: Courtesy of UTA.

Figure 3.15 Trench 1 and Trench 2

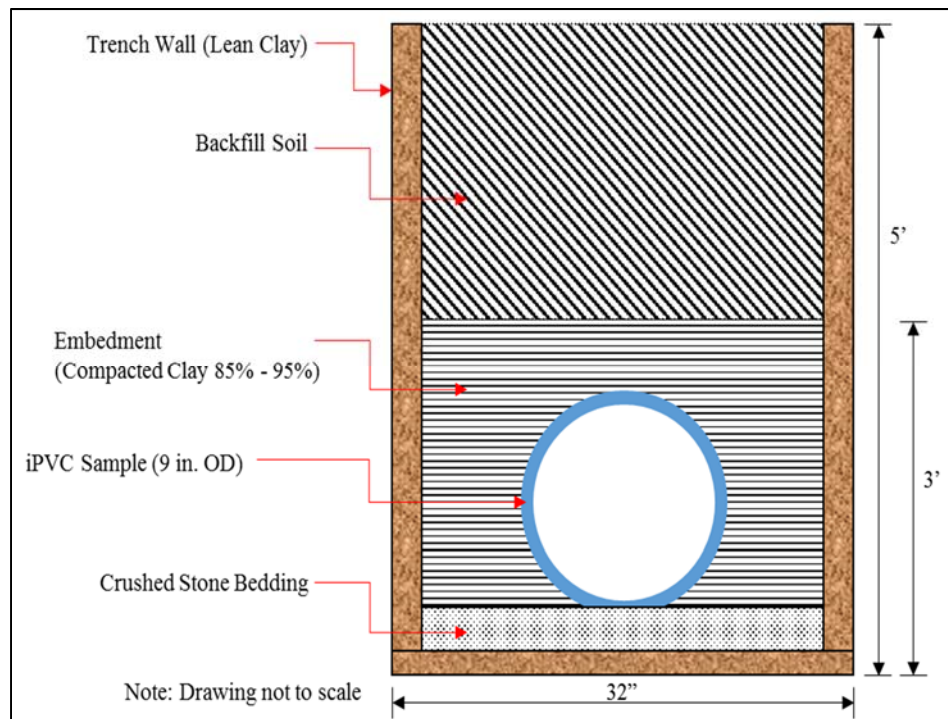


Figure 3.16 Cross section of bedding test 2

Crushed stone bedding was employed to stabilize the bed. The type of soil used for backfill and embedment was lean clay, a silty soil with low plasticity clay based upon the Unified Soil Classification (see Table 3.8).

Table 3.8
Native soil investigation report at bedding test locations

Grain Sizes	Atterberg's Limit
19% sand	Liquid limit = 33%
63% silt	Plastic limit = 12%
18% clay	Plasticity index = 21%

3.7.3.1 Test Pipe

The initial 8-inch iPVC pipe installed measured 20 feet with a bell and spigot joint in the middle (at 10 feet). The joints were pre-assembled in Korea and shipped to UTA for the field study.

UTA initiated two bedding tests. The first test (round 1) was piloted in the trench with single joint with two ten-foot sections connected by PPII. Due to the pre-assembled joints and smaller pipe diameter, the installation of sensors near the joint was not achievable. To provide additional data, a second bedding test (Round 2) with more pipe and an additional joint was added. UTA assembled the new joint after installing sensors near the connection. (The additional pipe came from Missouri American who were preparing to install pipe as part of a field test.) The second pipe sample was cut to into a 10-foot and 2-foot sections. The ten-foot section of the 12-foot pipe became the new spigot end for the Round 2 pipe. The sensors were installed near the new bell and new spigot, and the end of the pipe. The new pipe length for Round 2 measured, 22 feet long with a joint at 10 feet and 20 feet.

3.7.3.2 Instrumentation

Several instruments were deployed to measure the deformation and stress caused due to the movement of soil and simulated load on the test pipes. Instruments such as earth pressure cells, displacement sensors (deflectometers) and strain gauges were deployed to acquire stress, strain and deflection experienced by the test pipes due to the movement of the soil and simulated loads. These instruments were connected to the data loggers and the data loggers were connected to the computer for data recording. Network cables were used to connect the sensors to the data loggers and a total of about 3,000 feet of network cables were required for the experiment.

3.7.3.3 Earth Pressure Cells

Geokon™ Model 4810 vibrating wire earth pressure cells illustrated in Figure 3.17 were used for measurement of horizontal and vertical earth pressures in the second test. These sensors consist of two stainless steel plates welded together around their periphery with a narrow gap in between filled with hydraulic fluid. The external pressures experienced by the two plates squeezes them together creating equal pressure in the internal fluid. A length of stainless steel tubing connects the fluid filled cavity to a pressure transducer that converts the fluid pressure into an electrical signal transmitted by a cable to the data logger. The range of the pressure cells used was 51 psi with an accuracy of 0.1%. The details and specifications for the sensor are presented in Appendix B.

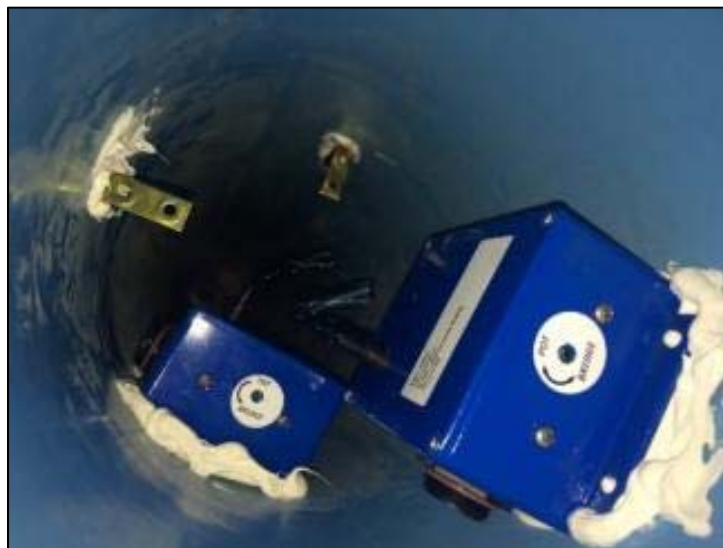


Source: Courtesy of UTA.

Figure 3.17 Earth pressure cells used in test

3.7.3.4 Displacement Sensors

Vishay micro-measurements cable-extension displacement sensors (Model CDS-05) were used to measure the horizontal and vertical pipe deflections. The sensor delivers a voltage signal linearly proportional to the extension of a retractable stainless steel cable. The base of the sensors is attached to the pipe surface and the string cables are attached to a hook to the opposite end on the pipe surface. The sensors connect to a data logger that is further connected to the computer for data collection. Two sensors were used for Test 1, and four sensors were used for Test 2 to measure the deflections. Figure 3.18 presents the displacement sensors (CDS) used for the tests. The details and specifications for the sensor are provided in Appendix B.



Source: Courtesy of UTA.

Figure 3.18 Displacement sensors used in second test

3.7.3.5 Strain Gauges

The strain gauges were deployed in the second test to measure the strain on the pipes due to external loads. The experiment uses the gauges manufactured by Tokyo Sokki Kenkyujo Co., Ltd. (Model FLA-6-11) uniaxial strain gauges for the measurement of strains. The installed strain gauge on the pipe is illustrated in Figure 3.19. The details and specifications for the sensor are presented in Appendix B. Installation of strain gauges is a very delicate process. In addition, it is imperative that the surface is properly prepared to secure the gauge. The following steps summarize the installation procedure:

- The surface of the iPVC pipe sample was cleaned where the gauge was supposed to be placed. Sandpaper was used to increase the surface area for contact of strain gauge with iPVC pipe.
- The conditioner provided by Vishay Micro-measurements was applied to the iPVC pipe sample to clean the surface thoroughly.
- UTA applied a neutralizer to the iPVC pipe sample to remove any remaining dust particles on the surface.
- Catalyst provided by Vishay Micro-measurements was applied to the surface of the iPVC pipe sample. This helps in reducing the time required for the strain gauge to bond with the sample.
- UTA technicians applied an M-Coat-A adhesive on the strain gauge and then attached the strain gauge to the iPVC pipe sample. Pressure was applied for two minutes on top of the strain gauge to develop a proper bond between the gauge and iPVC pipe.
- The UTA technicians applied M-Coat JA-1 on top of the strain gauge for extra protection for the gauges.
- The wire from the strain gauge was connected to the Vishay™ System 7000 data logger similar to the displacement sensors, and the data was collected on a computer.



Source: Courtesy of UTA.

Figure 3.19 Strain gauge attached to iPVC pipe

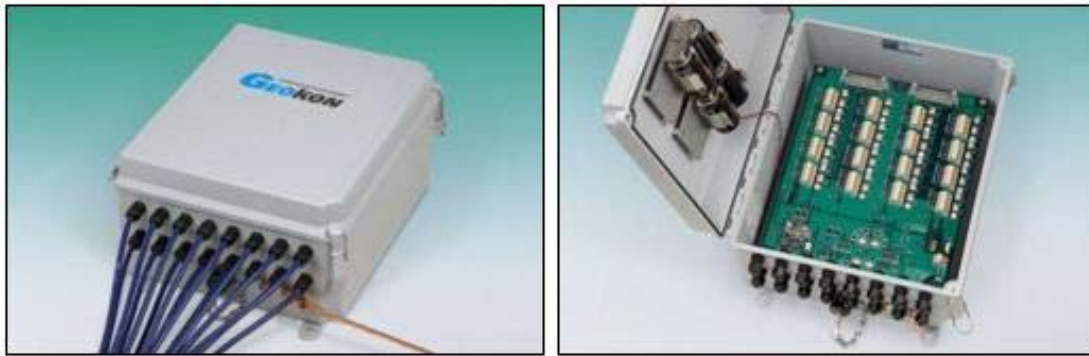
3.7.3.6 Data Loggers

Separate data loggers were used to accrue data from the attached pipe.

- The data loggers for the earth pressure cells were Geokon™ 8002-16 (LC-2 x 16). The

data logger consists of 16 channels out of which eight channels are used for eight earth pressure cells. Figure 3.20 illustrates the data logger used in the second round test. The data logger was connected to a desktop computer and data was retrieved by using Geokon™ Logview software. The details and specifications for the data loggers are presented in Appendix B.

- The data loggers for displacement sensors in Test 1 employed a four-channel P3 model from Vishay™ from the two sensors used for the test with the help of a software specific for this data logger. Figure 3.21 illustrates the P3 data logger.
- A Vishay™ System 7000 32-channel scanner was used to collect and record data from displacement sensors and strain gauges in Test 2. The scanner connects to a desktop computer for data logging. Strain Smart™ software was used to collect and report the data recorded by the scanner. Figure 3.21 presents the scanner used in the Test 2. The details and specifications for the sensor are presented in Appendix B.



Source: Geokon 2016.

Figure 3.20 Geokon™ 8002-16 (LC-2 x 16) data logger used in Test 2

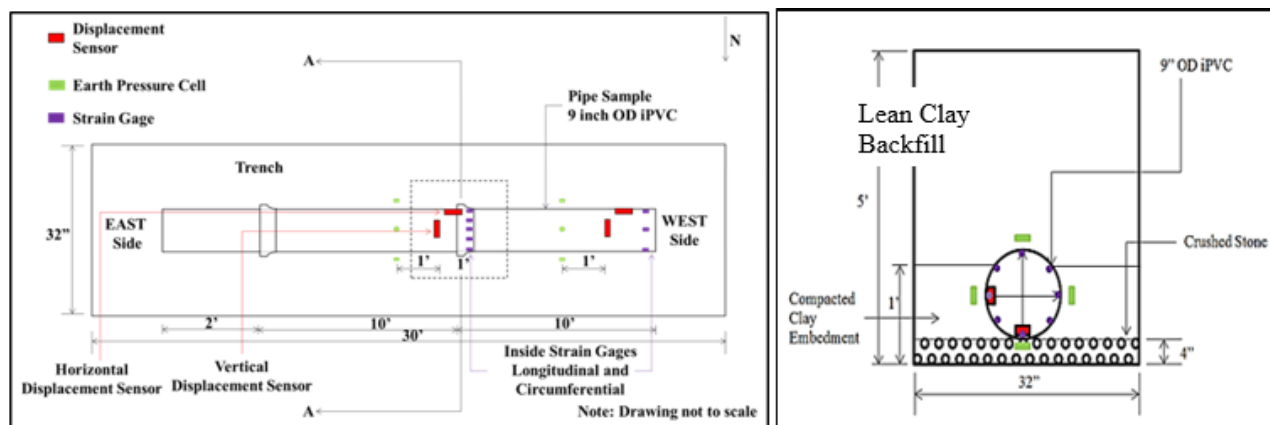
The Round 1 test utilized two displacement sensors located at each at the end of the test pipe to measure the vertical deflection. The second test setup pursued an approach studied at the University of Kansas, to test steel reinforced high-density polyethylene (SRHDPE) pipe (Khatri, 2014). The second pipe sample was instrumented with four displacement sensors, twenty strain gauges, and eight earth pressure cells. Two displacement sensors, eighteen strain gauges and four earth pressure cells were placed at the joint of the pipe and the remaining two displacement sensors, four strain gauges and four pressure cells were placed two feet from the end of the pipe. The displacement sensors will provide the deformation in the horizontal and vertical directions, in the pipe wall at the joint and at the end of pipe due to the load experienced by the pipe.



Source: Vishay Precision Group 2016.

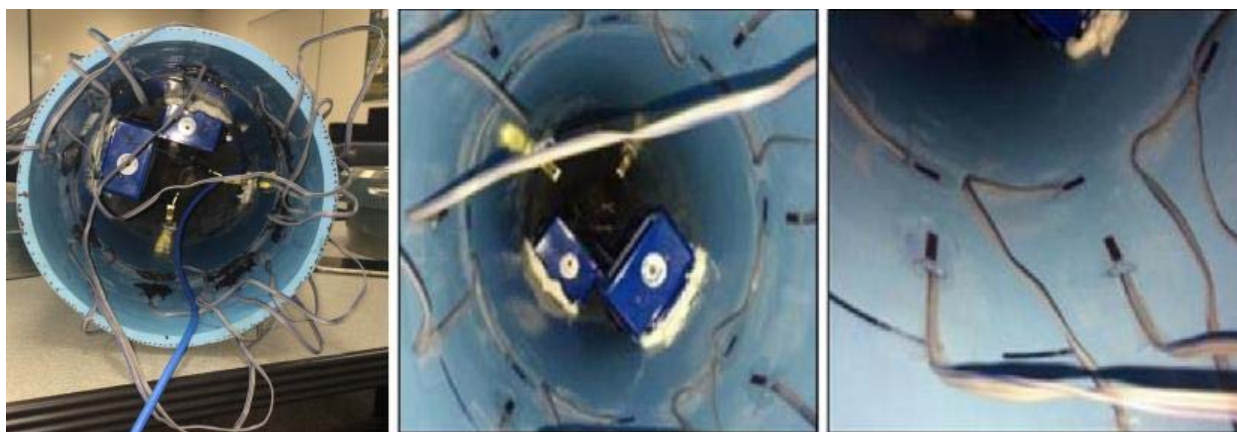
Figure 3.21 (a) P3 data logger for Test 1, (b) System 7000 data logger for Test 2

The strain gauges will provide the strain experienced by the pipe walls longitudinally and circumferentially at the gauge mounted locations. The use of earth pressure cells facilitates measuring the load experienced by the pipe walls due to the soil as well as any external loads exerted on the pipe. The location of sensors is of great significance in this test. Figure 3.22 presents the locations of the pressure cells, displacement sensors and strain gauges schematically. Figure 3.23 shows photographs of these installed monitors.



Source: Courtesy of UTA.

Figure 3.22 Schematic of pipe showing instrument layout

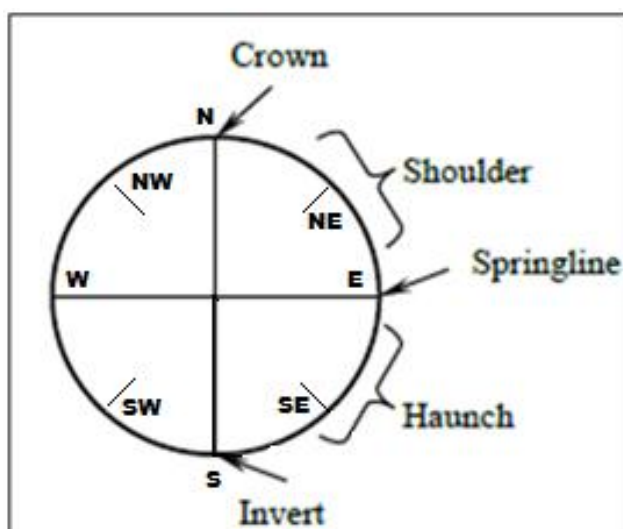


Source: Courtesy of UTA.

Figure 3.23 Photograph of pipe interior showing displacement sensors and strain gauge

3.7.3.7 Nomenclature

It was very important to mark the location of sensors on the pipe as well as use proper nomenclature to collect data. The pipe locations used common pipe terms as identified in Figure 3.24.



Source: Courtesy of UTA.

Figure 3.24 Terminology employed for pipe

The sensors were abbreviated as SG for strain gauges, CDS for displacement sensor and EPC for earth pressure cells. The direction of measurements used were circumferential (C), longitudinal (L), vertical (V), and horizontal (H). The load measured from the EPC was either a vertical load (VL) or side load (SL). UTA employed a nomenclature system as illustrated in Figure 3.25 to show orientation on the pipe cross section. Table 3.9 presents the sensor details as per location, direction of measurement, and the code used in this test.

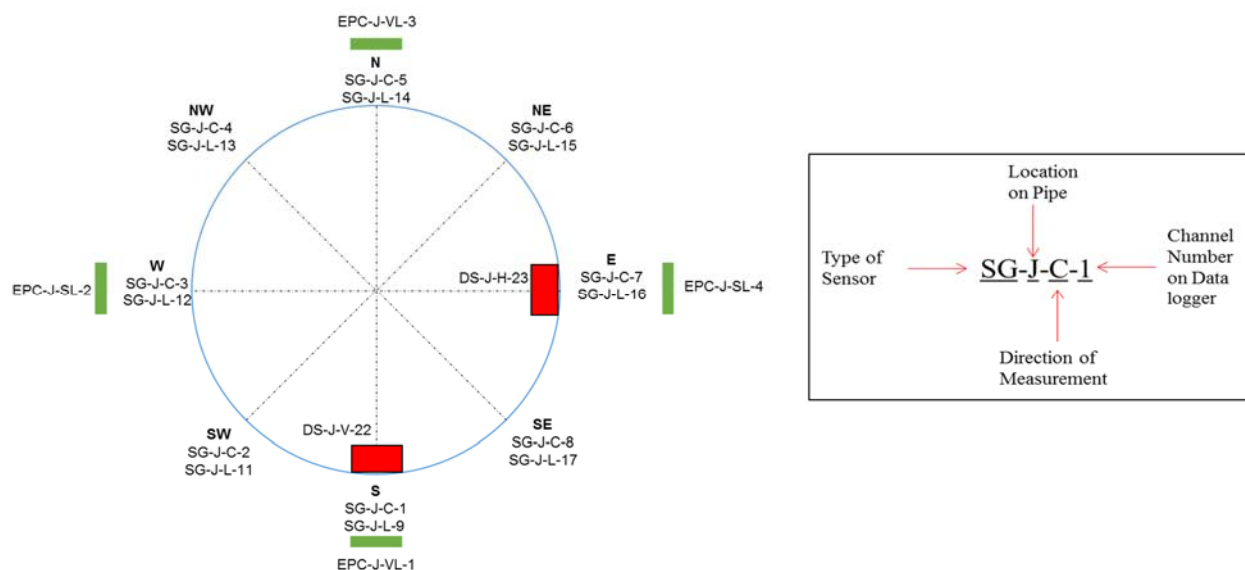
Table 3.9
Details of sensors used for bedding test 2

Sr. No.	Code	Location	Sr. No.	Code	Location	Abbreviations
1	SG-J-C-1	S	19	EPC-J-VL-1	S	SG - Strain Gauge
2	SG-J-C-2	SW	20	EPC-J-SL-2	W	DS - Displacement Sensor
3	SG-J-C-3	W	21	EPC-J-VL-3	N	EPC - Earth Pressure Cell
4	SG-J-C-4	NW	22	EPC-J-SL-4	E	J - Joint
5	SG-J-C-5	N	23	EPC-J-VL-5	S	E - End of Pipe
6	SG-J-C-6	NE	24	SG-E-C-18	S	V – Vertical
7	SG-J-C-7	E	25	SG-E-C-19	W	H – Horizontal
8	SG-J-C-8	SE	26	SG-E-C-20	N	C – Circumferential
9	SG-J-L-9	S	27	SG-E-C-21	E	L - Longitudinal
10	SG-J-L-11	SW	28	SG-E-L-27	S	VL - Vertical Load
11	SG-J-L-12	W	29	SG-E-L-28	W	SL - Side Load
12	SG-J-L-13	NW	30	SG-E-L-29	N	–S – South
13	SG-J-L-14	N	31	DS-E-V-24	N-S	SW – South-west
14	SG-J-L-15	NE	32	DS-E-H-25	W-E	W - West
15	SG-J-L-16	E	33	EPC-E-VL-6	S	NW – North-west
16	SG-J-L-17	SE	34	EPC-E-SL-7	W	N - North
17	DS-J-V-22	N-S	35	EPC-E-VL-8	N	NE – North-east
18	DS-J-H-23	W-E	36	EPC-E-SL-9	E	E – East; SE – South-east

3.7.3.8 Sign Conventions

Measurement of pipe deflections (changes in horizontal and vertical diameters), and pipe wall strains require establishment of a sign convention for collecting the results. Any decrease in diameter is reported as negative deflection and any increase in diameter is reported as positive

deflection. So, under load pipe would tend to have a negative in the vertical direction and an increase in the horizontal direction. Likewise, when pipe wall strains are reported, compressive strains will be reported as negative (−) and tensile strains (+) will be reported as positive.



Source: Courtesy of UTA.

Figure 3.25 Nomenclature used for sensors in bedding test 2

3.7.3.9 Data Collection and Monitoring

UTA collected data from the first test in the P3 model data logger from Vishay™. The two sensors from the test pipe were connected to the P3 with the help of two Ethernet cables. The P3 for the test pipe is periodically connected to a computer that records the daily deflection data; the data is displayed on the computer with software specific to the P3 data logger.

The data collection for the second test was more complicated and involved the use of two different software programs. The earth pressure cell readings were collected with the Geokon™ 8002-16 (LC-2 x 16) data logger and Geokon™ Logview software. The deflection readings and the strain gauge readings were collected using Vishay™ System 7000 32-channel data logger and Strain Smart™ software. The data was collected every day and the whole setup of data collection was monitored once or twice a week to ensure that the data was being recorded and the sensors were working correctly. The data collected from the sensors was exported to Microsoft Excel and stored in a compiled data file for all the readings.

3.7.3.10 Pipe Installation

UTA's contractor prepared a trench bottom four inches deep using crushed stone before round two of the bedding test. The round two installation of iPVC pipe was carried out on February 12 and 13, 2016. Figure 3.26 shows the trench at various stages of installation work. Prior to installation, the trench was marked for locations of pressure cells around the pipe. The pressure cells were protected with a thermo-ply sheet to avoid any damage as well as it helps in locating the pressure cells after completion of the testing. The backfilled soil was compacted to a reported 85% - 95% compaction level around the pipe for a depth of two-feet from the bottom of the trench.

The remaining two feet of trench to the surface was backfilled with the lean clay. Extra soil and gravel was added on the surface of the trench after backfilling to stabilize the trench for truck traffic and added more load on the pipe.



Source: Courtesy of UTA.

Figure 3.26 Pipe and sensor installation (Test 2)

3.7.4 Live Load Test Scenarios

For test two, a twenty-ton truck was used to create a live load highway simulation over the trench on two occasions: June 30 and August 8, 2016. The weight of the empty truck was approximately 28,000 lbs. The truck was loaded with gravel with a total combined weight of truck and gravel of 50,000 lbs. The truck was driven on the top of the trench along the length of the pipe to exert load across the full length of the iPVC pipe. The tires of one side passed directly over the pipe. Two runs one using an empty dump truck and the other a truck filled with gravel were planned.

Weather influenced the scheduling of tests especially heavy periods of rain that occurred in the Dallas area prior to the first test and a lack of rain for thirty days prior to the second test. Only two scenarios were executed on June 30 (run gravel loaded truck throughout the length of the trench for 2 hours, and park gravel loaded truck on top of the trench). Other scenarios were performed on August 8, 2016.

3.7.5 Expected Outcome

Based upon results of the stiffness test, it is expected that even with poor soils in the backfill that pipe deflection under load will fall below the 5% deflection limit.

3.7.6 Benefit to the Industry

If the expected outcome were realized, most requirements for special backfill specified for iPVC pipe associated with PVC pipe would not be required. This would reduce costs of PVC pipe

installation in some circumstances. The reduced stress also suggests that the pipe can be deflected at the joints, a result already reported with the thinner walled PVC-O pipe.

CHAPTER 4

LABORATORY TESTING RESULTS

This chapter presents the laboratory testing results from UTA and Microbac performed under the supervision of AW and conducted on DR 18 iPVC pipe.

4.1 HYDROSTATIC SHORT-TERM BURST PRESSURE TEST

The hydraulic burst test was executed to determine the level of resistance of the iPVC pipe to severe hydraulic pressure within a short time interval. The purpose of the test was to predict the behavior of the iPVC pipe under controlled temperature, time, and pressure, calculate the maximum hoop stress based on the pressure attained at the failure, and determine the mode of failure and failure pattern. Both the UTA and Microbac facilities prepared and conditioned the specimens per ASTM D1599–14 guidelines.

The hydraulic burst test begins by securing and restraining the end caps to the conditioned PVC pipe and then rapidly pressurizing with water. Pressure in the pipe is increased uniformly and continuously until the specimen fails. The result for this test is defined as the pressure maximum preceding any instantaneous loss of the pressure or visible leaks or rupture of the pipe. The failure pressure, hoop stress at failure and time to fail is recorded.

All the samples tested at the UTA experienced catastrophic failure of iPVC pipe. Figure 4.1 captures the typical catastrophic failure observed during testing of iPVC pipe at UTA. The Microbac lab reported ductile and catastrophic modes of failures during the iPVC pipe testing. A catastrophic failure in which the pipe shattered into pieces implying some response to pipe brittleness and a ductile failure where the pipe responds more elastically and physically changes shape before ultimately splitting to a far less extent. (Failure caused by pressure loss, ballooning of pipe and pin hole leak observed in pipe samples.) Figure 4.2 illustrates both the ductile failure and catastrophic failures observed at Microbac. Table 4.1 presents test results, samples 1 through 10 presents the sample tested at the Microbac lab and samples 11 through 14 presents the outcome of burst test at the UTA.



Source: Courtesy of UTA.

Figure 4.1 Hydrostatic burst test failures (catastrophic) at UTA



Source: Courtesy of Microbac.

Figure 4.2 Hydrostatic burst test failure (ductile and catastrophic) at Microbac Lab

Table 4.1
Short-term burst pressure test results from Microbac and UTA

Sample # - Lab	Failure Pressure	Failure Time	Failure Mode
1 - Microbac	1,070	127	Catastrophic
2 - Microbac	1,050	112	Catastrophic
3 - Microbac	1,020	122	Catastrophic
4 - Microbac	1,050	101	Catastrophic
5 - Microbac	1,010	113	Catastrophic
6 - Microbac	1,030	116	Catastrophic
7 - Microbac	1,030	150	Ductile
8 - Microbac	1,010	145	Ductile
9 - Microbac	1,035	126	Ductile
10 - Microbac	1,020	121	Ductile
11 - UTA	1,065	56	Catastrophic
12 - UTA	1,060	60	Catastrophic
13 - UTA	1,060	139	Catastrophic
14 - UTA	1,075	80	Catastrophic
Average	1,042	112	-
Std. Dev.	21	27	-

Graphical representation of the hydrostatic burst test results from UTA and Microbac is presented in Figure 4.3. The solid yellow dots in the graph presents the results from UTA and blue dots presents the results from Microbac. The solid line in the graph presents the AWWA minimum requirements and the dotted lines in the black represent the average iPVC pipe test results. Regardless of the speed to reach failure, the pressure result was consistently over 1,000 psi. It appears that the different end cap systems and the different pipe lengths used made little difference in the result.

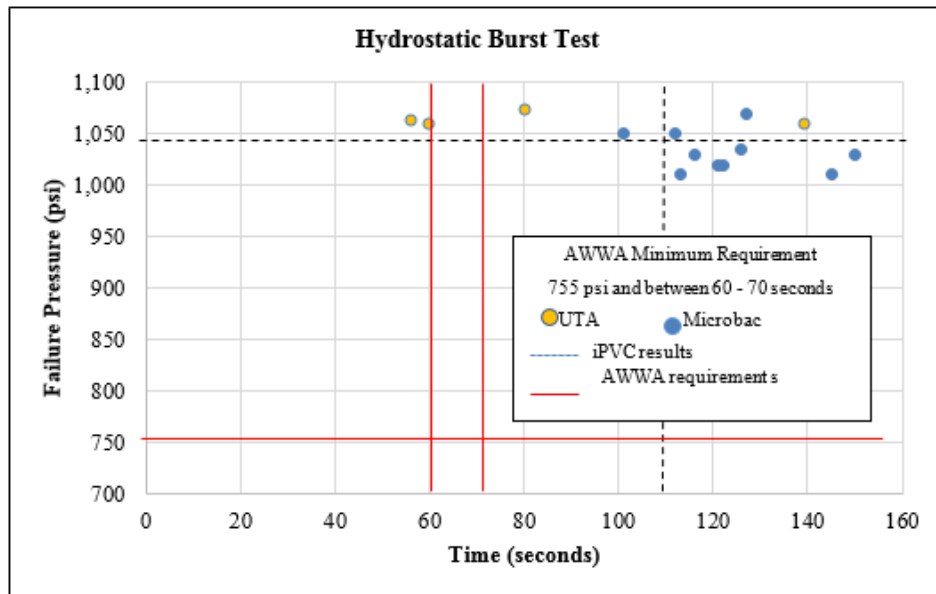
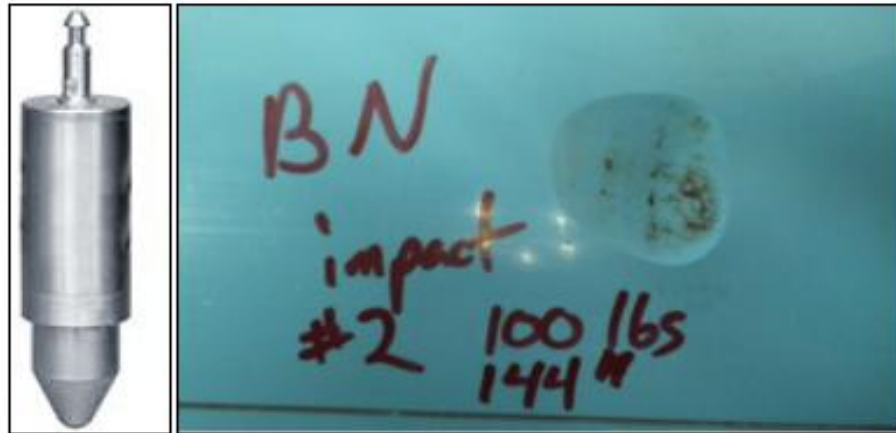


Figure 4.3 Hydrostatic burst test results

4.2 IMPACT TEST

The impact test was performed by Microbac in accordance with ASTM D2444-99 (reapproved 2010) standard initially with samples at 73 °F with standard tup A (cone-shaped, Figure 4.4) weighing 100 pounds. With equipment having a maximum drop height of 12 feet, the tup was able to generate impact energy of 1,200 foot-pounds. The test was performed on 35 pipe samples with this configuration, and the maximum impact of the apparatus did not break, but only dented the surface of the pipe samples at 73 °F per Figure 4.4.



Source: Courtesy of Microbac.

Figure 4.4 Falling weight style A tup and impact test result

In order to test the material to failure in some way, AW decided to test the remaining pipe samples at a colder temperature (32 °F) that could be readily achieved at the Boulder, Colorado laboratory in January. The samples were conditioned at 32 °F for 16 hours and impacted within 1 minute of removal from sub-ambient temperature. This test resulted in the breaking of the pipe samples at 1,050 foot-pounds (dropping the 100-pound tup from a drop height of 10.5 feet). Table 4.2 summarizes the test results for the impact test at 73°F and the test results from 32°F can be found in the Appendix A.

Table 4.2
Impact test results at 73 °F at Microbac for partial number of test samples

Specimen	Weight of Tup (pounds)	Height of Drop (feet)	Impact Energy (foot-pounds)	Results
AV	30	10.0	300	Pass
AB	30	10.0	300	Pass
Z	35	10.0	350	Pass
N	40	10.0	400	Pass
T	40	11.8	470	Pass
BP	50	12.3	613	Fail
Q	60	12.3	737	Pass
K	60	12.3	737	Pass
BS	65	12.3	799	Pass
L	65	12.3	799	Pass
AJ	70	12.3	860	Pass
AB	100	12.0	1200	Pass
BN	100	12.0	1200	Pass

4.3 STIFFNESS TEST

The stiffness test was conducted at the Microbac lab facility to determine the potential for deflection and note the general behavior of the pipe under vertical load. The stiffness test results presented in Table 4.3 were useful for the iPVC pilot installation at the Missouri American Water. The test studied the behavior of pipe at 5% decrements in the mean diameter (D) from 100% of the pipe before load applications to 60% D. At 60%, the experiment was stopped and evaluated for any visual cracks or fracture and none were identified. The experiment continued until the pipe inner walls from the top met the pipe at the bottom (see Figure 4.5). The pipe deformation went beyond a reduction to 20% D without fracture, cracks, or failure. The average pressure recorded beyond 20% D deflection was about 7,500 psi and the average maximum load was about 10,500 psi. Figure 4.6 shows the typical load as a function of the reduction in the mean diameter and Figure 4.7 shows the load as a function of percentage D. For the first 5 inches of reduction, the pipe required a decreasing increment in load to reduce each inch. This trend was reversed in the last two inches of reduction until the limit of reduction was reached when the top and bottom of the pipe were touching and offered additional support. The performance of the all samples tested was consistent as suggested by Figure 4.7.



Source: Courtesy of Microbac.

Figure 4.5 Full deflection of iPVC pipe between plates

Table 4.3
Partial stiffness test results for iPVC pipe at Microbac

Specimen	Load @ 95 % D	Force per unit length @ 95% D	Pipe Stiffness @ 95% D	Load @ 90% ID	Force per unit length @ 90% D	Pipe Stiffness @ 90% D
	Lbs.	Lbs./inch	psi	Lbs.	Lbs./inch	psi
R	1,508	191.6	451	2,647	336.34	396
Y	1,468	184.8	439	2,534	321.98	379
W	1,540	193.6	460	2,651	336.85	396
U	1,490	190.8	445	2,571	326.68	384
V	1,521	192.8	455	2,614	332.15	391
AS	1,509	192.4	451	2,595	329.73	388
AP	1,553	195.6	464	2,689	341.68	402
AQ	1,448	186.4	433	2,489	316.26	372
AU	1,548	196.4	463	2,651	336.85	396
Average	1,509	191.6	451	2,605	331	389
Std. Dev.	36	4	11	64	8	10

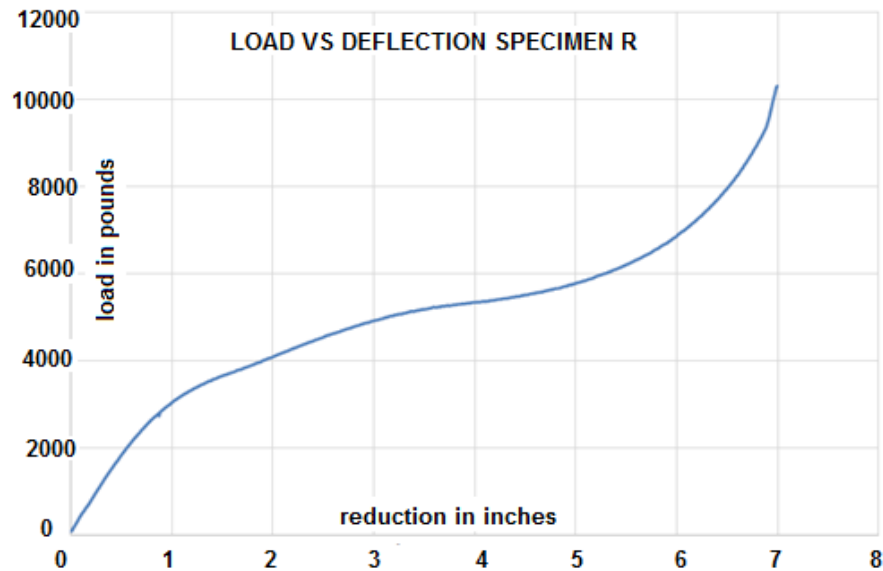


Figure 4.6 Typical load versus deflection plot for stiffness test

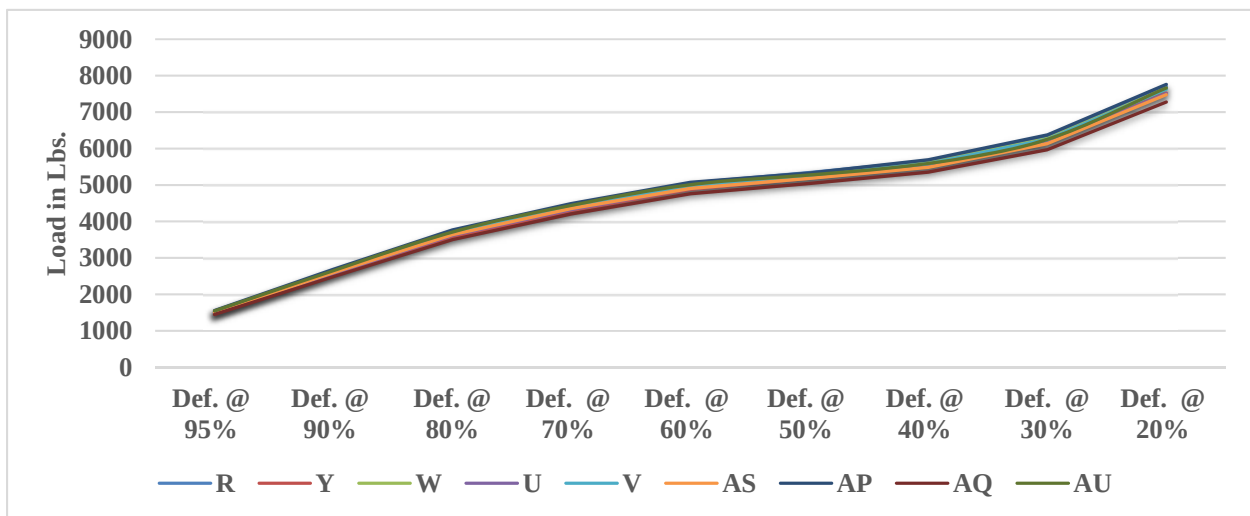


Figure 4.7 Load versus deflection for all stiffness test samples

4.4 TENSILE TEST

Both Microbac and UTA labs conducted tensile tests. The Microbac lab conducted the test with the type I and type III tensile samples and UTA conducted test with the type III samples. The initial tensile test conducted by UTA used full walled samples (coincides the wall thickness of DR 18 PVC pipe = 0.5 inches). To validate the UTA results, 10 type III “dogbone” samples were provided to Microbac. After receiving the tensile test samples, Microbac lab recommended that the tensile test specimen for ASTM 1784 cell class 12454 PVC compound must be prepared per type I (thinner wall) and not type III (thicker wall). The research team decided to pursue testing both the specimens to understand the anomalies in the material configuration. Figure 4.8 presents the tensile test in action at the Microbac Lab and Tables 4.4 and 4.5 present the results of tensile test at the Microbac and UTA (see Table 4.4 for A1-A10 and Table 4.5 for DG through DU).



Source: Courtesy of Microbac.

Figure 4.8 Type I tensile testing at Microbac lab

For the type I test, the average tensile strength observed was 7,930 psi with a modulus of elasticity of 461,000 psi. Table 4.4 summarizes the test results from the Microbac for type I pipe samples. Figure 4.9 and Figure 4.10 present a graphical summary of tensile strength and modulus of elasticity values of the type I iPVC pipe samples. Figure 4.11 shows how the samples performed as they were tested.

Table 4.4
Type I mid-wall pipe sample tensile test results at Microbac

Specimen	Width (inch)	Thickness (inch)	Tensile Strength (psi)	Modulus of Elasticity (psi)
A-1	0.498	0.130	8,030	459,000
A-2	0.499	0.130	8,010	424,000
A-3	0.498	0.130	7,880	455,000
A-4	0.498	0.129	7,890	499,000
A-5	0.498	0.130	7,970	448,000
A-6	0.498	0.130	7,920	501,000
A-7	0.499	0.130	7,880	559,000
A-8	0.499	0.131	7,800	401,000
A-9	0.499	0.129	7,900	420,000
A-10	0.501	0.131	8,020	448,000
Average	-	-	7,930	461,400
Std. Dev.	-	-	75	46,755

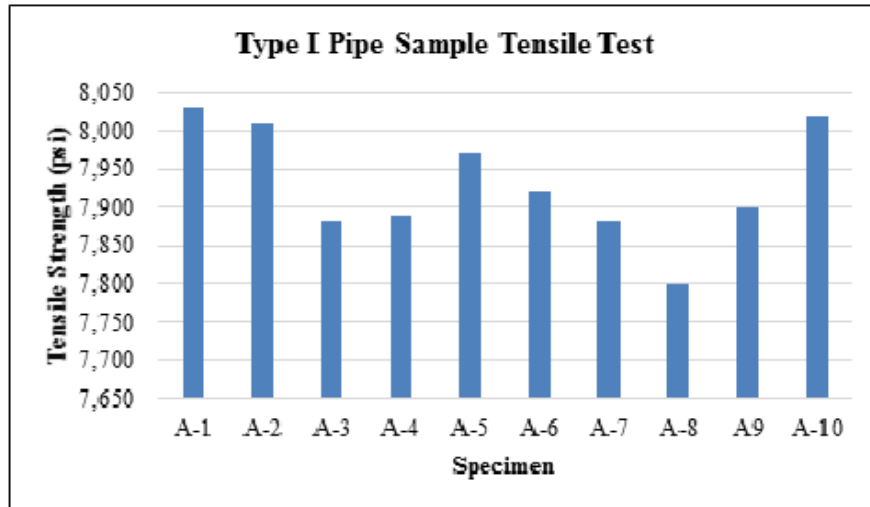


Figure 4.9 Tensile strength test results (type I)

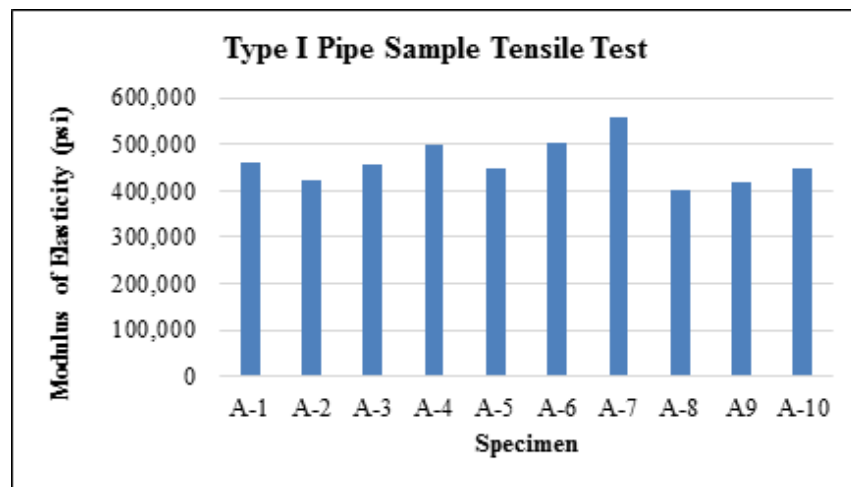


Figure 4.10 Calculated modulus of elasticity from tensile test I results



Source: Courtesy of UTA.

Figure 4.11 Type III tensile testing at UTA

Microbac performed tensile tests ten Type III samples (full-wall) per ASTM D638-14 (first ten values Table 4.5, DB through DN) and UTA labs performed tensile tests on six specimens (last six values Table 4.5 DG through DU). Figure 4.9 presents the tensile test specimen fracture at the UTA. The average tensile strength reported for these test samples was 7,920 psi with modulus of elasticity of 395,000 psi. UTA did not report a modulus of elasticity throughout the tensile test experiment. UTA lacked the proper extensometer component in their tensile test apparatus that is attached to the specimen sample. Microbac explained the lower modulus results of the iPVC pipe was due to the selection of the Type III samples used in the tensile testing. For PVC pipe extruded from ASTM D1784 (ASTM 2011a), Cell Class 12454B PVC compound, the tensile sample is recommended to be prepared per Type I dimensions specified under ASTM D638. The available results are summarized in Table 4.5. Figure 4.12 and Figure 4.13 present graphical summary of tensile strength and modulus of elasticity values of the Type III iPVC pipe samples.

Table 4.5
Type III full-wall pipe sample tensile test results

Specimen-Lab	Sample Width	Sample Thickness	Tensile Strength	Modulus of Elasticity
	inch	inch	Psi	psi
DB - Microbac	0.749	0.540	7,840	396,000
DC - Microbac	0.750	0.528	7,870	382,000
DD - Microbac	0.747	0.528	7,820	394,000
DE - Microbac	0.747	0.536	7,820	389,000
DF - Microbac	0.751	0.535	7,810	383,000
DQ - Microbac	0.749	0.536	7,790	389,000
DH - Microbac	0.749	0.524	7,830	400,000
DI - Microbac	0.751	0.536	7,770	404,000
DK - Microbac	0.749	0.541	7,810	396,000
DN - Microbac	0.753	0.530	7,810	420,000
DG - UTA	0.748	0.531	8,322	Not available
DJ - UTA	0.749	0.531	8,385	- Not available
DL - UTA	0.748	0.531	9,149	- Not available
DM - UTA	0.75	0.541	6,825	- Not available
DP - UTA	0.747	0.531	7,518	- Not available
DU - UTA	0.748	0.541	8,328	- Not available
Average	-	-	7,920	395,300
Std. Dev.	-	-	470	10,570

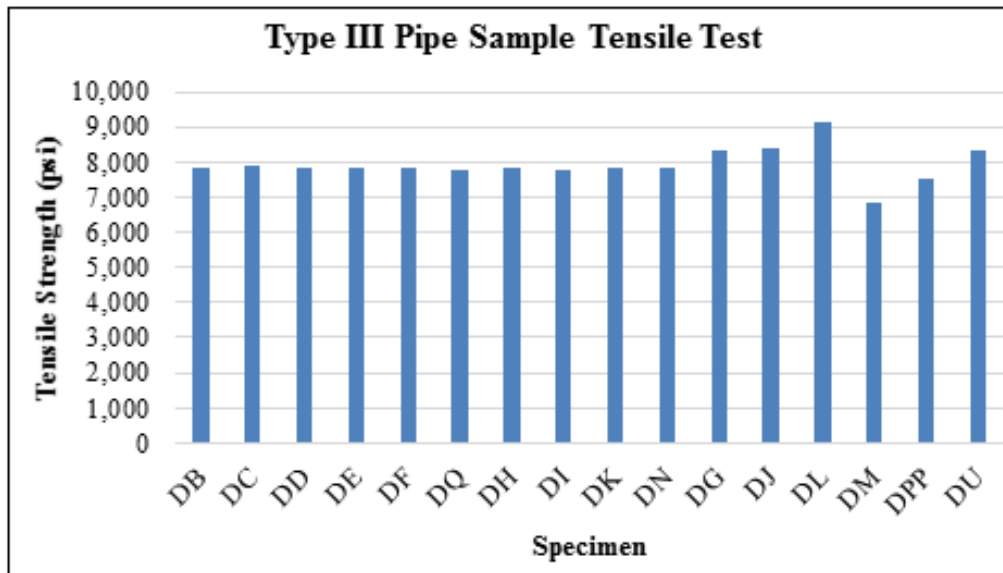


Figure 4.12 Tensile strength test results (type III)

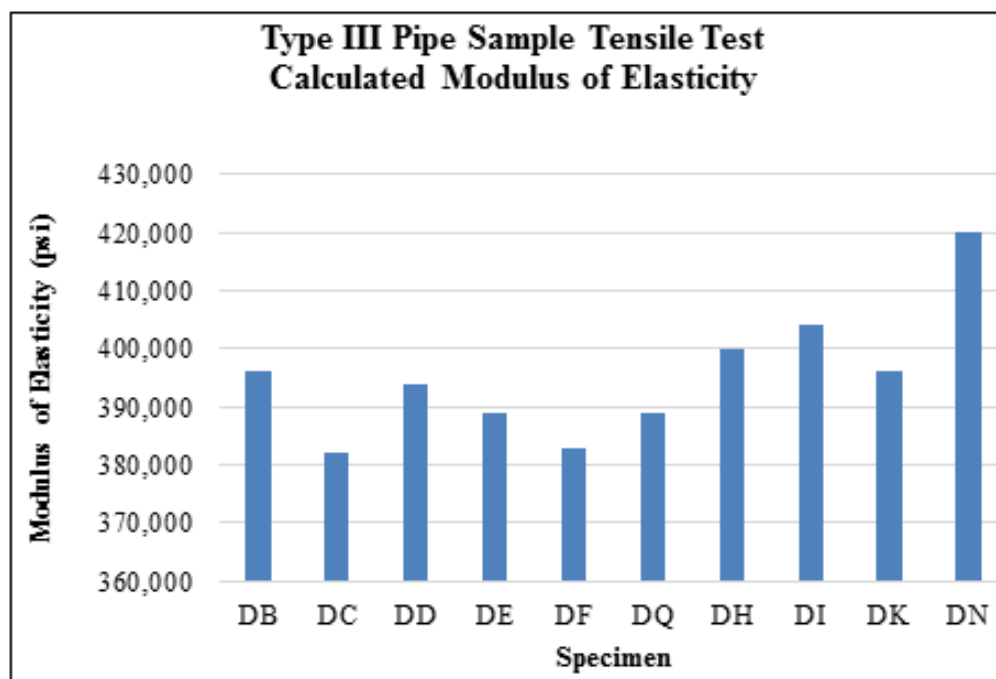


Figure 4.13 Calculated modulus of elasticity from tensile test III results

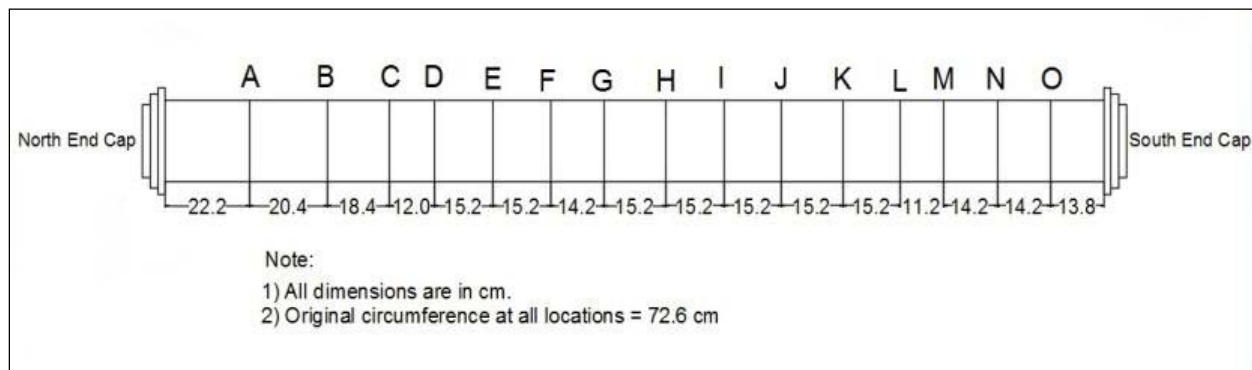
UTA reported a few anomalies in their testing results while testing at UTA-CUIRE. The researchers believe these anomalies are the result of one or more of the following: improper conditioning of pipe samples before the testing, inaccurate placement of samples on the testing machine or improper grips to secure the samples. This helped lead to a decision to supplement tensile testing at the Microbac Lab.

4.5 FATIGUE TEST

The objective of this test was to determine whether the 8-inch DR 18 iPVC pipe could withstand the induced cyclic loads of 1.5 times higher than the expected maximum operating pressure rating of the pipe (150 psi) for 2 million cycles. The test was set up and operated by UTA. The water pressure inside the pipe sample oscillated between 150 psi to 225 psi in 10–12 second cycles. The project team decided to measure the pipe at as many locations as possible. The ten-foot pipe was marked longitudinally at fifteen locations (A through O) and the increment in the circumference was measured at regular intervals as the test progressed (see Figure 4.14). The temperature of water was maintained at 60 °F throughout the test using coolers attached to the reservoir.

The first set of readings were reported after the completion of 40,000 cycles. There was marginal increase of two millimeters. (0.08 inches) in circumference of pipe at six locations. The research team suspected that the incremental change in the circumference of the pipe was caused by initial pressurization of the pipe, as the circumference remained constant after a small number of cycles. To validate this assumption, the test was stopped after completion of a half million cycles and readings were obtained after a 24-hour period. The pipe sample regained its original dimensions at all the 15 points, validating the cause of circumferential changes was due to the internal pressure exerting hoop stress in the pipe. Fourteen locations out of fifteen marked on the pipe witnessed some change between two and three millimeters (0.08 and 0.12 inches) in the circumferential variations. The test ended for the project after passing the required 2 million cycles on June 8, 2016. At the request of PPII, the fatigue test continued beyond a goal of reaching four million cycles without significant further change.

After stopping the test at 2 million cycles, the maximum circumferential change observed was three millimeters. (0.12 inches) at 14 locations: point E being the exception. One week after stopping the test, the circumference regained its original dimensions at 14 out of the 15 locations. It is very likely that the results would vary for iPVC pipe based on the diameter size as well as the DR. The change in circumference as the test progressed is illustrated in Figure 4.15. It should be noted the test was continued to over 4 million cycles. The results of the additional testing and PPII proposed analysis of the 10 foot thereafter are outside the scope of the project. When reported the additional test will help in evaluating the reliability and durability of the iPVC pipe.



Source: Courtesy of UTA.

Figure 4.14 Pipe circumference monitoring locations

Table 4.6
Circumference measurements as a function of number of cycles

Number of Cycles	Circumference (cm)														
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
0	72.6	72.6	72.6	72.6	72.6	72.6	72.6	72.6	72.6	72.6	72.6	72.6	72.6	72.6	72.6
39,653	72.8	72.8	72.8	72.7	72.7	72.7	72.7	72.7	72.7	72.7	72.8	72.8	72.7	72.7	72.6
284,035	72.8	72.8	72.8	72.8	72.8	72.7	72.7	72.7	72.7	72.7	72.8	72.8	72.7	72.7	72.6
Test stopped for 24 hours to evaluate change in circumference reverses if test interrupted															
284,035	72.6	72.6	72.6	72.6	72.6	72.6	72.6	72.6	72.5	72.6	72.6	72.6	72.6	72.5	72.4
586,618	72.8	72.8	72.7	72.7	72.7	72.6	72.6	72.6	72.7	72.7	72.8	72.6	72.6	72.6	72.6
696,835	72.8	72.8	72.7	72.7	72.7	72.6	72.6	72.7	72.7	72.7	72.7	72.6	72.6	72.6	72.6
1,133,076	72.8	72.8	72.8	72.7	72.7	72.7	72.6	72.8	72.7	72.7	72.7	72.6	72.6	72.7	72.7
1,348,007	72.8	72.8	72.7	72.7	72.7	72.6	72.6	72.7	72.7	72.7	72.7	72.5	72.6	72.6	72.7
1,542,838	72.8	72.8	72.8	72.8	72.8	72.8	72.8	72.9	72.9	72.9	72.9	72.9	72.9	72.9	72.9
1,673,193	72.8	72.8	72.8	72.8	72.8	72.8	72.8	72.8	72.8	72.8	72.8	72.8	72.8	72.8	72.8
1,831,019	72.9	72.9	72.9	72.9	72.8	72.9	72.9	72.9	72.9	72.9	72.8	72.9	72.9	72.9	72.8
1,886,382	72.9	72.9	72.9	72.9	72.8	72.9	72.9	72.9	72.9	72.9	72.8	72.8	72.8	72.8	72.8
1,941,541	72.9	72.9	72.9	72.9	72.8	72.9	72.8	72.8	72.8	72.8	72.8	72.9	72.9	72.9	72.8
1,988,986	72.8	72.8	72.8	72.8	72.8	72.8	72.8	72.8	72.8	72.8	72.8	72.7	72.7	72.7	72.7
1,995,783	72.8	72.8	72.8	72.8	72.8	72.8	72.8	72.8	72.8	72.8	72.8	72.7	72.7	72.7	72.7
2,005,081	72.8	72.8	72.8	72.8	72.8	72.8	72.8	72.8	72.8	72.8	72.8	72.7	72.7	72.7	72.7
2,093,509	72.9	72.9	72.9	72.9	72.8	72.8	72.9	72.8	72.8	72.8	72.8	72.8	72.8	72.7	72.7
2,139,469	72.9	72.9	72.9	72.9	72.9	72.9	72.9	72.9	72.9	72.8	72.8	72.8	72.8	72.7	72.7
2,238,451	72.9	72.9	72.9	72.9	72.9	72.9	72.9	72.9	72.9	72.9	72.8	72.9	72.8	72.8	72.8
Test stopped for 24 hours to evaluate change in circumference reverses if test interrupted															
2,238,451	72.8	72.8	72.7	72.7	72.7	72.7	72.7	72.7	72.7	72.7	72.7	72.7	72.6	72.6	72.6
Test continued as directed by PPII with intent to run to 4 million cycles															
2,238,451	72.7	72.7	72.7	72.7	72.7	72.6	72.6	72.6	72.6	72.6	72.6	72.6	72.6	72.6	72.6
2,243,301	72.8	72.8	72.7	72.7	72.7	72.7	72.7	72.7	72.6	72.6	72.6	72.6	72.6	72.6	72.6

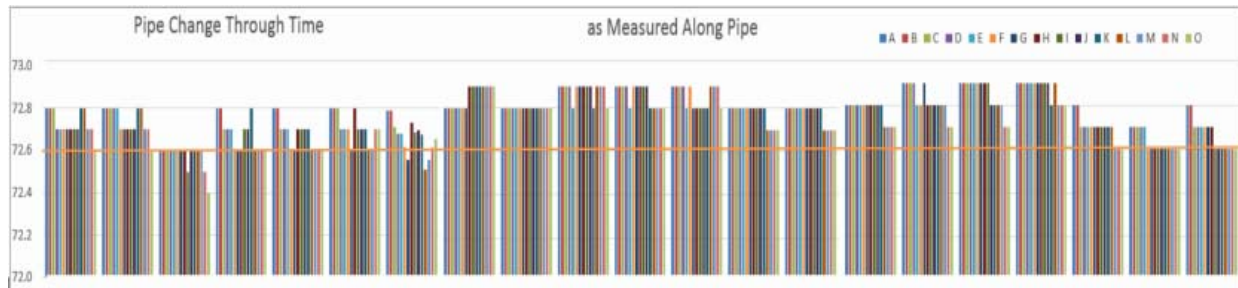


Figure 4.15 Circumference of pipe through 2.3 million cycles

CHAPTER 5

FIELD TESTING AND EVALUATION OF IPVC PIPE

This chapter shifts the evaluation methodologies from the lab to the pipe trench. This two-part evaluation includes installing the pipe in the field at two American Water sites and evaluating the pipe and stresses on it in a monitored bed at the University of Texas.

5.1 FIELD TESTING ST. LOUIS COUNTY, MO

Missouri American Water (MOAW) accepted the task of installing 1,500 feet of 8-inch DR 18 iPVC pipe in February 2016 at a St. Louis County location with aggressive silty clay soils. The pipe material was provided by PPII from Korea; shipped on October 24 and received at the MOAW yard on November 16. The researchers provided iPVC test results to the Missouri American Water (MOAW) at the St. Louis County periodically prior to the field installation.

5.1.1 Test Location

MOAW engineering staff requested 1400 feet of 8" iPVC along with 100 feet of 6" iPVC for hydrant and pipe connections. MOAW selected a pipe replacement project in the southerly portion of their service territory where an 8-inch cast iron pipe needed to be retired due to frequent pipe failure. The MOAW team proceeded with the pipe designing and securing the permits to execute the job. The project site located along Meramec Bottom Road at the southern extreme of St. Louis County is not far from the Meramec River. The pipe would be placed in a flood plain area with highly corrosive soils and operate under higher operating pressures. Figure 5.1 shows the location of pilot installation and the proximity of the Meramec River that flooded the site in early January 2016. The location of the pipe to be installed was primarily off the road. The pipe required connections to existing PVC and cast iron pipe, a hydrant, and connections to be made to a few existing customers



Figure 5.1 St. Louis County pipe location site

5.1.2 Soil Investigation

MOAW with the help of local geotechnical laboratory (SCI Engineering Inc.) conducted soil investigation near the pilot installation to determine the condition of the existing soil. From the test results, the soil contained 9% sand, 68% silt and 23% clay with liquid limit, plastic limit, and plasticity index of 40, 25 and 15. From the plasticity chart, the soil can be classified as a combination CL/ML. CL is inorganic clays of low to medium plasticity, gravely clays, silt clays or lean clays; ML is inorganic silts and very fine sand, rock flour, silty or clayey fine sands or

clayey silts with slight plasticity. A high silt content was expected given the location in the flood plain. From the soil triangle chart, the soil can be classified as silt loam. These soils are not recommended for backfilling of plastic pipe.

To verify the corrosive index of soil near the pilot installation, American Water checked the United States Department of Agriculture (USDA) web soil survey (Figure 5.2). The area of web survey for corrosivity is represented under the polygon (labelled area of interest (AOI)). The AOI includes the area of the iPVC installation. The pipeline was constructed in the areas designated 66024 and 66014 per Figure 5.3. From the web survey confirmed the area as silty loam. The corrosion rating for the area highlighted 66024 is high and the area highlighted 66014 is low. The web survey also confirmed the highlighted area within the flood zone. There were some delays for securing a regulatory permit to install pipe in a flood zone.



Source: Data from USDA n.d.

Figure 5.2 USDA web soil survey at the pilot installation

Corrosion of Steel— Summary by Map Unit — St. Louis County and St. Louis City, Missouri (MO189)				
Map unit symbol	Map unit name	Rating	Acres in AOI	Percent of AOI
60003	Menfro silt loam, 9 to 14 percent slopes, eroded	Low	2.0	3.6%
60234	Weller silt loam, 2 to 5 percent slopes	High	2.7	4.9%
64018	Freeburg silt loam, 2 to 5 percent slopes, occasionally flooded	High	3.2	5.8%
66014	Haymond silt loam, 0 to 3 percent slopes, frequently flooded	Low	24.8	45.2%
66024	Wilbur silt loam, 0 to 2 percent slopes, frequently flooded	High	16.8	30.7%
66092	Fishpot-Urban land complex, 0 to 5 percent slopes, rarely flooded	High	5.3	9.7%
Totals for Area of Interest			54.9	100.0%

Source: Data from USDA n.d.

Figure 5.3 Corrosion results from USDA soil web survey

5.1.3 Field Installation St. Louis County, Missouri

Armed with much of the test data, MOAW moved forward with what became a typical PVC pipe installation (open cut). The Missouri American crew installed the pipe in compliance with AWWA C605, PVC installation procedure. Although the original plan called for a warm weather installation, work began in late January. The MOAW construction crews install pipe year-round.



Source: Courtesy of American Water.

Figure 5.4 iPVC delivered to the trench

The installation process included handling, cutting, trimming, tapping, and connecting to various fittings and other pipe materials (Figure 5.4). The crew completed the installation in a few

weeks and connected the line to an existing cast iron main. About 200 feet pipe was backfilled using native soil to verify the performance of the iPVC pipe in poor soil. The iPVC pipe was flushed, pressure tested (200 psi), disinfected per AWWA C605 guidelines and placed in service on February 24, 2016.

Five customer services were relocated to the iPVC main. The service connections were executed by hot tapping the pipe using appropriate tapping and saddle materials. MOAW confirmed that the installation of the iPVC pipe was no different from the conventional PVC pipe installation (Figure 5.5).



Source: Courtesy of American Water.

Figure 5.5 Tapping the iPVC pipe per AWWA guidelines

The field installation significantly aided the researchers and PPII in assessing actual execution of installation of iPVC pipe. PPII sent several representatives to the site and they learned about improved ways to package the pipe for shipment. A camera crew from Korea was also present, filming for a television show describing the project for broadcast back in Korea. Figure 5.6 shows the Korean contingent examining a portion of the off-road pipe installation.



Source: Courtesy of American Water.

Figure 5.6 iPVC installation with manufacturer representatives on hand

5.1.4 Economic Analysis

The pilot installation of iPVC pipe was placed outside the paved area of Meramec River Bottom Road. With less traffic, two street crossings and no sidewalks to restore, the project location was ideal for utility to install the new pipe for the first time but installations outside paving areas is uncommon. A check for similar projects during 2015 did not identify a project close enough in conditions to perform a direct comparison on a cost basis largely attributed to significant paving present in other projects. The limited paving restoration was performed by a contractor and the costs can be significant.

5.1.4.1 Comparing with PVC Pipe

The MOAW staff confirmed that the handling and installing (size of the crew, equipment used and backfilling) the new iPVC pipe is similar to that of conventional PVC pipe. Consequently, the cost associated with the labor and equipment is same for the PVC and iPVC pipe regardless of the size or location of project except for cost of pipe itself. American Water specifies DR 14 PVC pipe (up to 12-inch diameter) for any new installation or replacement pipe project in their distribution network. The MOAW engineers prefer the additional thickness of the DR14 PVC pipe and expect a longer life from the material. It is expected that the iPVC pipe will cost more across than conventional PVC at equivalent DR sizes. The researchers believe that the DR18 iPVC pipe exhibits strength and performance greater than DR 14 conventional PVC. For MOAW who prescribes DR14 conventional pipe there would be partially offsetting savings in the material cost.

5.1.4.2 Comparing with DI Pipe

With significant experience installing polywrapped ductile iron pipe, the MOAW staff agreed that the plastic pipes will function more reliably in the corrosive soil and is easier to install when compared to DI pipe. When comparing backfill materials and bedding preparation between

DI and PVC pipes, the utility installers confirmed there is no difference in their practice in the trench. However, additional step of poly-wrapping of replacement DI pipe is considered to be time consuming. There may be a small savings from equipment and labor cost, but the significant cost savings may occur in the material cost difference and long run maintenance cost (corrosion protection) of the DI pipe.

5.2 FIELD TESTING – MANVILLE, NJ

5.2.1 Site Location

NJ American (NJAW) identified a site near Garry Street and Haran Avenue in Manville, NJ located adjacent to the Central New Jersey Regional Airport and Millstone River for its trial of iPVC pipe (Figure 5.7). NJ American employs contractors to install pipe. PPII shipped 2,000 feet of pipe in 18-foot-lengths that consisted of 1,500 feet of 8-inch pipe and 500 feet of 6-inch pipe. The new iPVC pipe was replacing a problematic 6-inch asbestos cement main installed during 1950's. Unlike the few rural service taps in the St. Louis County pilot, the pilot Manville, NJ project included numerous (47) service connections.

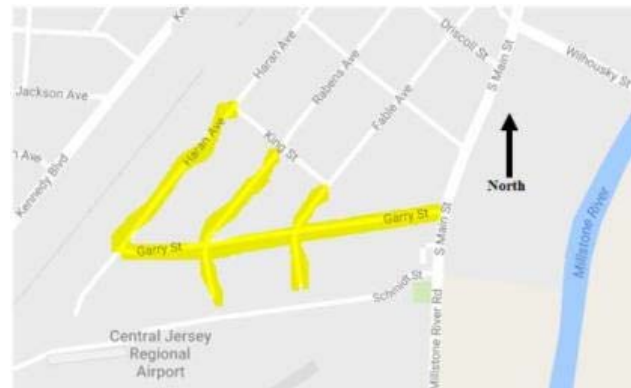


Figure 5.7 Project location at Manville, NJ

Unlike the few rural service taps in the St. Louis County pilot, the pilot Manville, NJ project included numerous (47) service connections.

5.2.2 Soil Investigation

Soil investigations were not conducted at the Manville, NJ site. Requirements for pipe installation in the road called for special backfill. This is quite often the case for installations regardless of the pipe selected under roadways. Consequently, there is no advantage for one pipe material over another if special backfill is required in all cases. The primary consideration is the traffic loading that will follow the pipe installation and providing a stable subsurface.

5.2.3 Installation

The New Jersey American contractor followed open cut procedures to install the iPVC pipe in compliance with AWWA C605, PVC installation procedure. The installation began during the first week of September 2016 and completed in October 2016. The installation processes included handling, cutting, trimming, numerous tappings, valve connection and connecting to the existing system. The contractor flushed, pressure tested (150 psi), and disinfected the iPVC pipe per AWWA C605. Figure 5.8 shows the installation of iPVC pipe at Gary Street, Manville, NJ.



Source: Courtesy of American Water.

Figure 5.8 Contractor installing new iPVC pipe at Manville, NJ

5.2.4 Flexible Gasket

The Manville, NJ received iPVC pipe that included a new gasket design. The gasket is for manufactured by Trelleborg, a German manufacturer specifically for PVC-O pipe joints. The gaskets behave quite differently from convention PVC gaskets. The gaskets allow the pipe to deflect at the joint in horizontal and vertical direction and joined pipes can be easily separated without any use of power tool/equipment. This is contrary to the typical PVC pipes manufactured in the US that restrict deflection and do not allow pipes to be separated after joints are made. The easy separation of the pipe concerned New Jersey American Water and the researcher on-site during the first Friday of installation. The researchers, unaware of the gasket change from those used in St. Louis County, requested the manufacture (PPII) to verify the gaskets were appropriate. Over the weekend, PPII provided additional information on these gaskets and conducted tests in Korea. New Jersey American directed the contractor to conduct a pressure test on the partial installation before proceeding with the installation.

The Trelleborg Company manufactures the gaskets in Germany that are used with European PVC-O pipe. PPII conducted successful leak and burst tests on their iPVC pipes with the Trelleborg gaskets before changing to this more flexible design but did not realize there would be installer's concern about the flexibility provided by the gaskets.

The flexibility of gaskets has suggested additional opportunity for the iPVC that are currently under study. PPII had previously advised that they do not allow deflection at pipe joints but the use of the gaskets and some testing by PPII at their Korean facility and studies at Cornell University for earthquake resistance may lead to flexibility for deflection in the near future. The new iPVC pipe installed with minimum deflection passed the pressure testing without any leaks. Figures 5.9 and 5.10 provide the information on the new iPVC pipe gasket. A change in the criteria for the iPVC pipe relevant to deflection is under discussion but not formerly changed at this time.



Source: Courtesy of American Water.

Figure 5.9 Separation at the joint from the new Trelleborg gasket



Source: Courtesy of American Water.

Figure 5.10 Trelleborg gasket versus conventional PVC gasket

5.2.5 Economic Assessment

There was a work stoppage when the gaskets employed were called into question but essentially the installation took the same time with similar costs as conventional PVC. The gaskets and their flexibility to cause some minor concern as a conscientious effort was made to minimize deflection at the joints throughout the installation though this may not have been necessary.

5.3 FIELD TESTING – BEDDING TEST

AW elected to study iPVC deformation behavior under controlled live and dead load conditions in native clay soil found at the University of Texas- Arlington. There was no specific ASTM standard available for a bedding test and hence UTA decided to install the pipe based on its previous testing experience. Contractors initially installed pipe in October 2016. The initial bedding test results were not considered in this research report, as the sensors installed on the first iPVC pipe sample were insufficient to provide enough data for analysis. Only two displacement sensors were installed in the first attempted test and no strain gages or pressure cells were provided. AW stepped in to outline a more formal test of iPVC pipe. Based on an approach described in a report by Khatri (2014), a second bedding test was conducted with sufficient sensors for data collection and analysis. Since the pipe joint is more critical in terms of deflection, emphasis was

placed upon the pipe joint as well as the end of the pipe. The data collection for second round bedding test began in February 2016.

The use of multiple sensors proved prudent as a number of sensors failed during the testing. The earth pressure monitors reported data from four pressure cells at the joint of the pipe. One pressure cell (EPC-J-VL-5) stopped working after the trench was backfilled. As the test progressed, another pressure cell EPC-J-SL-4 (at south springline of the pipe) also stopped functioning. The circumferential strain data loggers collected data at the joint of the pipe using eight strain gauges, longitudinal strain data at the joint of the pipe was collected using seven strain gauges. One strain gauge (SG-J-L-12) apparently disabled during the installation of the joint of the pipe and provided no data.

Similarly, four earth pressure cells were collecting data at the end of the pipe. During the testing, one pressure cell EPC-E-SL-7 (at the north springline of the pipe), and pressure cell EPC-E-SL-9 (at south springline of the pipe) stopped functioning. Three circumferential strain gauges (SG-E-C-18, SG-E-C-20, SG-E-C21) stopped functioning and, hence, data from only four strain gauges (one circumferential and three longitudinal) were collected. The displacement sensors were collecting the vertical and horizontal deflections of iPVC pipe at the pipe joint as well as at end of the pipe.

5.3.1 Effect of Only Earth Load on iPVC Pipe

Pipe deflections observed at the joint and end of the pipe are presented respectively in Tables 5.1 and 5.2. Only a few points of data are included in the table for simplicity purpose. Figure 5.11 and Figure 5.12 illustrate the graphical presentation of deflection of iPVC pipe under earth load at the joint and end of the pipe, respectively. Horizontal and vertical deflections were relatively closer in absolute values throughout the testing. (Any decrease in diameter is reported as negative deflection and any increase in diameter is reported as positive deflection.) The expected negatives value of vertical deflection indicate that the pipe diameter decreased in the vertical direction due to the load applied and the expected positive value of horizontal deflection indicates that the iPVC pipe expanded horizontally when the load was applied. A deflection of one millimeter represents 0.44% deflection of the outside pipe diameter. An allowable (5%) deflection of C900 PVC pipe would be 11.35 mm.

Table 5.1
Pipe deflection at joint of pipe due to earth load

Date	Deflection (mm)	
	Vertical	Horizontal
February 16, 2016	-0.114	0.144
February 23, 2016	-0.084	0.134
March 1, 2016	-0.292	0.298
March 8, 2016	-0.228	0.222
March 15, 2016	-0.186	0.201
March 22, 2016	-0.288	0.276
March 29, 2016	-0.266	0.254
April 5, 2016	-0.273	0.250
April 12, 2016	-0.426	0.396
April 19, 2016	-0.392	0.472
April 26, 2016	-0.110	0.200
May 3, 2016	-0.253	0.241
May 10, 2016	-0.184	0.164
May 17, 2016	-0.485	0.515
May 24, 2016	-0.100	0.111
May 31, 2016	-0.283	0.307
June 7, 2016	-0.554	0.580
June 14, 2016	-0.659	0.639
June 21, 2016	-0.698	0.713
June 28, 2016	-0.680	0.659

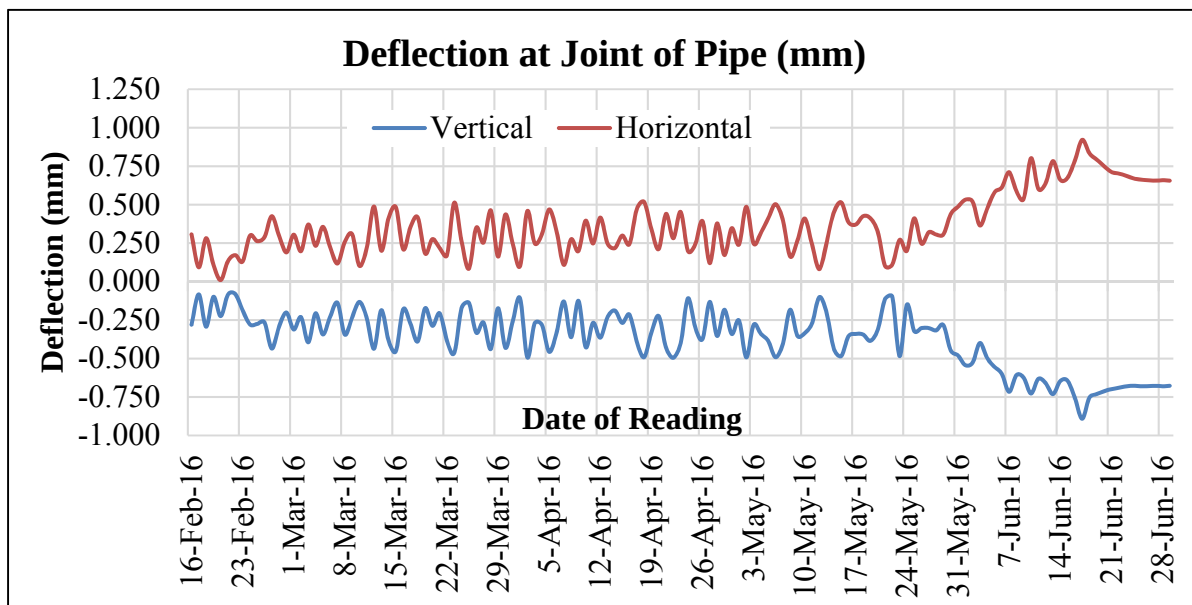


Figure 5.11 Pipe deflection at joint due to earth load

Table 5.2
Pipe deflection at end of pipe due to earth load

Date	Deflection (mm)	
	Vertical	Horizontal
February 16, 2016	-0.165	0.142
February 23, 2016	-0.359	0.240
March 1, 2016	-0.736	0.466
March 8, 2016	-0.780	0.430
March 15, 2016	-0.512	0.392
March 22, 2016	-0.707	0.357
March 29, 2016	-0.735	0.555
April 5, 2016	-0.789	0.501
April 12, 2016	-0.609	0.386
April 19, 2016	-0.516	0.406
April 26, 2016	-0.653	0.395
May 3, 2016	-0.596	0.486
May 10, 2016	-0.493	0.343
May 17, 2016	-0.628	0.364
May 24, 2016	-0.676	0.464
May 31, 2016	-0.647	0.463
June 7, 2016	-0.707	0.475
June 14, 2016	-0.970	0.697
June 21, 2016	-1.034	0.659
June 28, 2016	-0.979	0.762

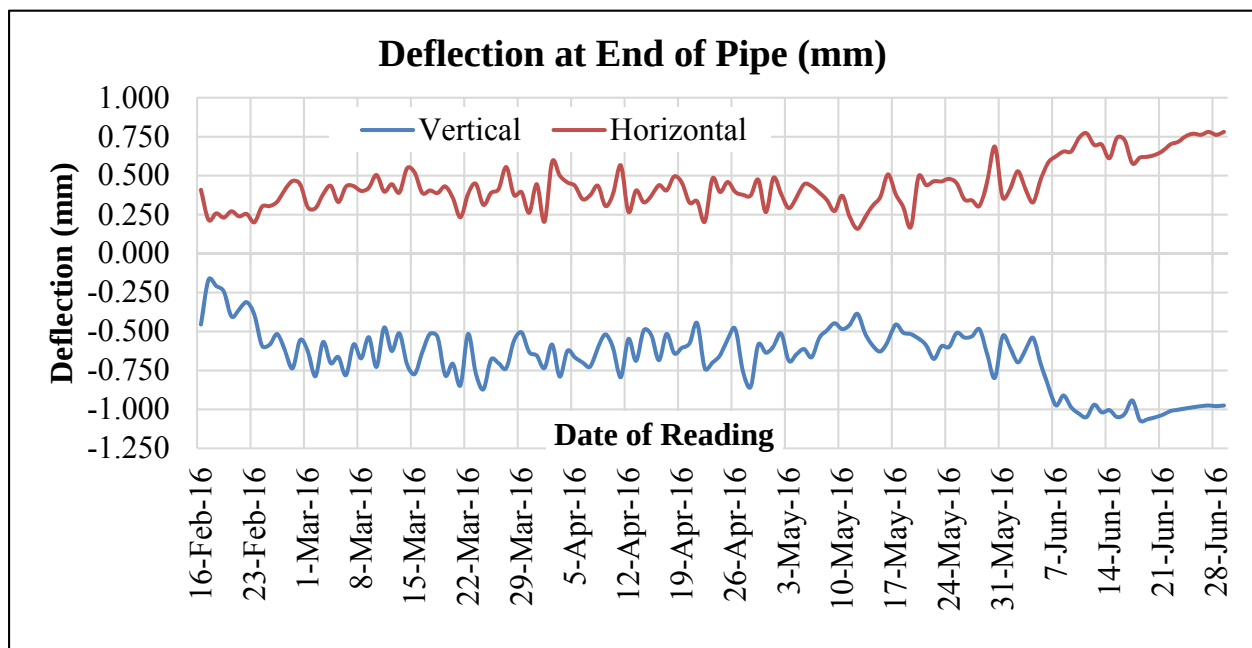


Figure 5.12 Deflection at end of pipe due to earth loading

Strain gauges installed at the joint and the end of the pipe at 23 locations measured the strain circumferentially and longitudinally, and 20 locations measured successfully. Table 5.3 presents the summary of the earth pressures at pipe joint. Figure 5.13 and Figure 5.14 illustrate graphical presentation of strain data at the joint.

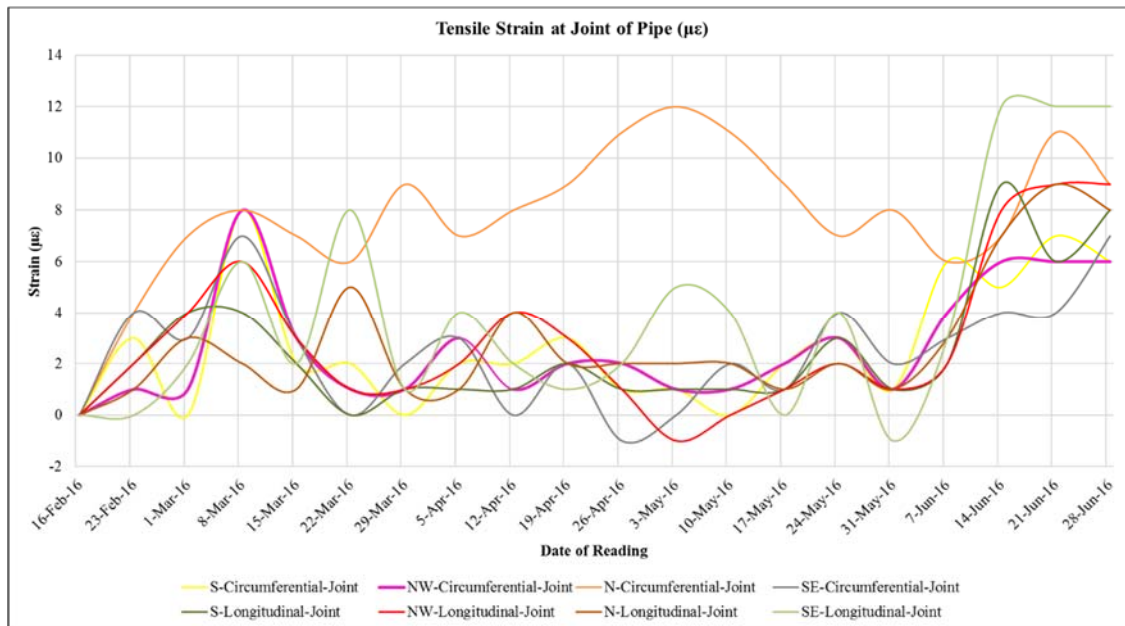


Figure 5.13 Tensile strain measurements at joint of pipe

For these figures, N (north) is the top of the pipe, S is the invert, E and W are the springline points.

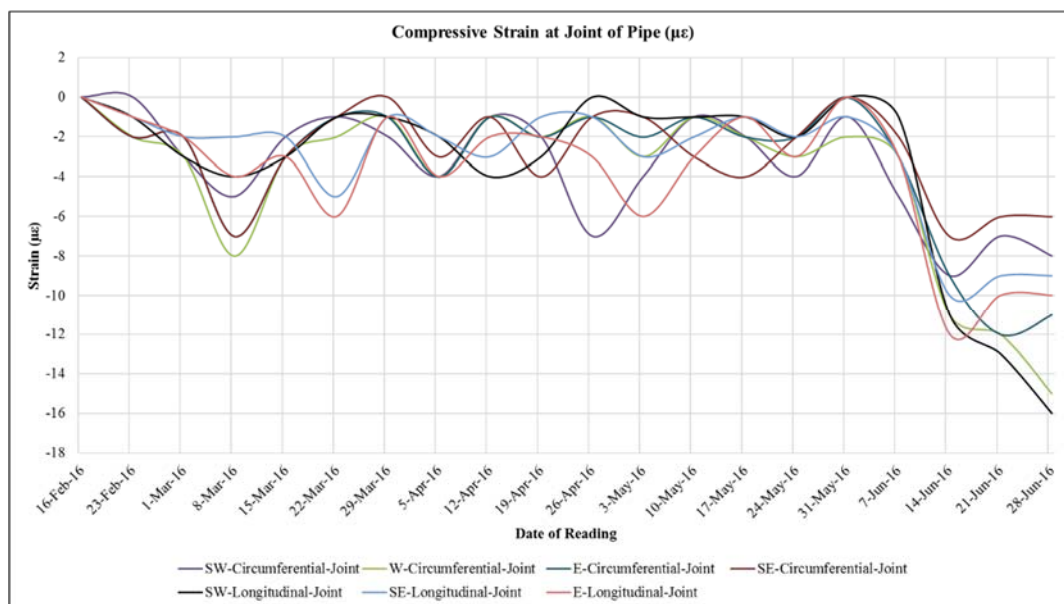


Figure 5.14 Compressive strain measurements at joint of pipe

Earth pressures were measured at four locations at both the joint and end of the pipe. The sensors were located around the pipe at crown, south springline, north springline and invert. Tables 5.3 and 5.4 present the recorded pressures at these locations. Figure 5.15 illustrates the graphical presentation of the earth pressure cell data. The data shows a generally consistent pattern of increased earth pressures translating into increased pipe deflection.

Table 5.3
Earth pressures at joint of pipe

Date	Invert South at Joint	Springline West at Joint	Crown North at Joint	Springline East at Joint
16-Feb-16	0.008	0.091	0.802	0.769
23-Feb-16	0.397	0.190	2.773	1.209
01-Mar-16	0.901	0.085	2.294	0.987
08-Mar-16	1.048	0.038	2.68	0.742
15-Mar-16	1.073	0.024	2.685	0.771
22-Mar-16	1.109	0.034	2.597	0.722
29-Mar-16	1.003	0.110	2.464	0.410
05-Apr-16	1.286	0.039	3.151	0.891
12-Apr-16	1.355	0.078	3.013	0.991
19-Apr-16	1.358	0.039	3.01	0.937
26-Apr-16	1.372	0.002	2.974	0.813
03-May-16	1.508	0.131	2.989	1.216
10-May-16	1.539	0.137	2.988	1.267
17-May-16	1.567	0.153	2.927	1.331
24-May-16	1.516	0.078	2.886	1.212
31-May-16	1.559	0.096	2.893	1.219
07-Jun-16	1.598	0.118	2.918	1.300
14-Jun-16	1.605	0.091	2.904	1.987
21-Jun-16	1.723	0.172	2.927	1.687
28-Jun-16	1.739	0.193	2.950	1.471

Table 5.4
Earth pressures at end of pipe

Date	Invert	Springline	Crown	Springline
	South at End	West at End	North at End	East at End
16-Feb-16	0.873	0.973	1.187	0.295
23-Feb-16	1.739	0.444	2.987	0.953
01-Mar-16	2.386	-0.155	3.928	0.870
08-Mar-16	2.517	0.314	4.267	1.339
15-Mar-16	2.490	0.305	4.184	1.33
22-Mar-16	2.448	0.162	4.115	1.187
29-Mar-16	2.326	0.066	3.834	1.091
05-Apr-16	2.631	0.774	4.246	1.799
12-Apr-16	2.647	0.667	4.248	1.692
19-Apr-16	2.496	0.663	4.201	1.688
26-Apr-16	2.532	0.674	4.188	1.699
03-May-16	2.641	0.694	4.259	1.719
10-May-16	2.655	0.727	4.273	1.752
17-May-16	2.644	0.686	4.273	1.711
24-May-16	2.553	0.632	4.189	1.657
31-May-16	2.594	0.681	4.233	1.706
07-Jun-16	2.590	0.725	4.238	1.750
14-Jun-16	2.605	0.654	4.759	1.321
21-Jun-16	2.690	0.898	4.284	1.885
28-Jun-16	2.709	1.109	4.309	2.567

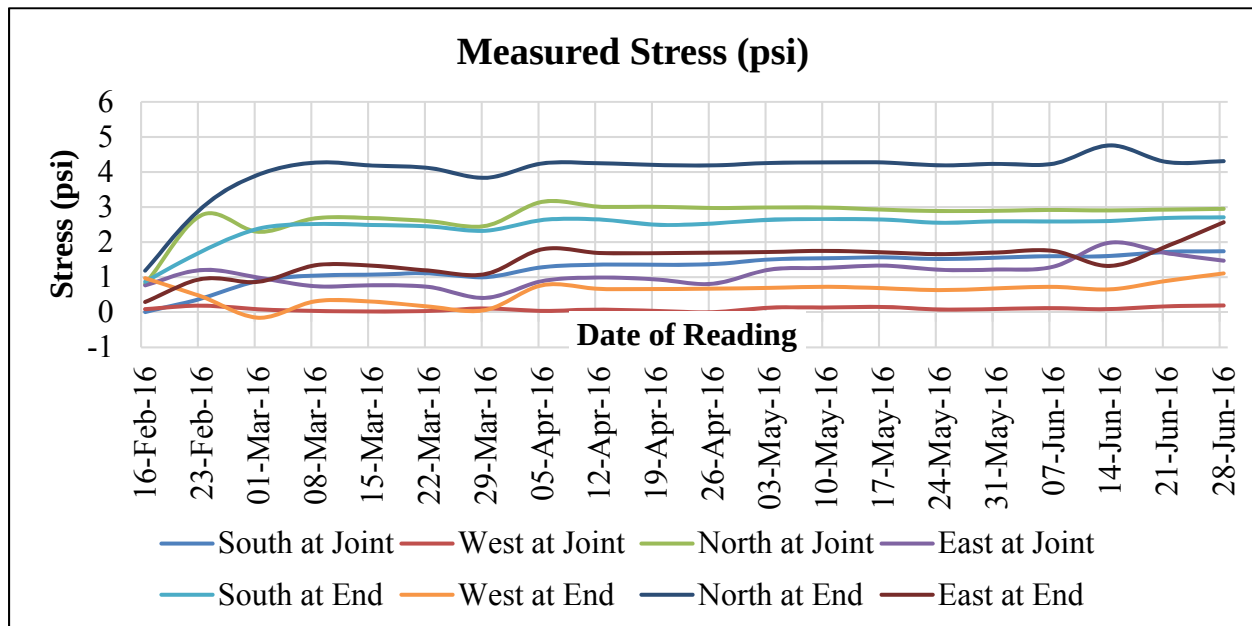


Figure 5.15 Earth pressures at joint and end of pipe over time for bedding test 2

5.3.2 Effect of Earth Plus Live Load Test 1

As a part of this project, a live load simulation was created on top of the trench where the iPVC pipe was installed. Two scenarios suggested by American Water were implemented for the first round of testing. A 20-ton truck ran on top of the trench along the length of the pipe for two hours and then halted on top of the pipe for two hours. The truck was filled with gravel to have more weight on top of the trench. The approximate load of the truck including the gravel was about 50,000 lbs. The test helped in checking the effect of the added load on the strain and deflection readings.

The test one truckload was applied on June 30, 2016. Figure 5.16 shows photographs of the live load testing. Tables 5.5, 5.6, and 5.7 present the deflection, strain, and earth pressure readings for 1 hour before, 4 hours during, 1 hour after, 1 week after, and 2 weeks after applying round 1 truck load. Figures 5.17-5.21 graphically display the vertical deflection, horizontal deflection, strain at joint, strain at end of pipe and earth pressure readings, respectively. The vertical deflection readings displayed a maximum rise of 0.944 mm and 0.931 mm at the joint and end of the pipe respectively. The horizontal deflection readings displayed a maximum rise of 0.579 mm and 0.711 mm at the joint and end of the pipe respectively. As the load was removed, there was reduction in the deflection values recorded after a couple of weeks but the pipe failed to reach to the original deflection values observed under only the earth load. The change may have been due to a change in the earth loading as gravel was added to stabilize the truck path over the pipe.

Table 5.5
Pipe deflection at joint and end of pipe due to earth and live load

Date and Time	Joint of Pipe		End of Pipe	
	Deflection (mm)		Deflection (mm)	
	Vertical	Horizontal	Vertical	Horizontal
6/30 @ 7 AM	-0.673	0.645	-0.982	0.797
6/30 @ 8 AM	-0.914	0.865	-1.104	0.912
6/30 @ 9 AM	-1.323	0.899	-1.554	1.093
6/30 @ 10 AM	-1.617	1.021	-1.913	1.413
6/30 @ 11 AM	-1.591	1.142	-1.902	1.489
6/30 @ 12 noon	-1.571	1.224	-1.895	1.508
6/30 @ 1 PM	-1.488	1.004	-1.501	1.441
7/7 @ 1 PM	-1.035	1.004	-1.230	1.109
7/14 @ 1 PM	-1.016	0.931	-1.198	1.113



Figure 5.16 Twenty-ton truck providing live load, June 30, 2015

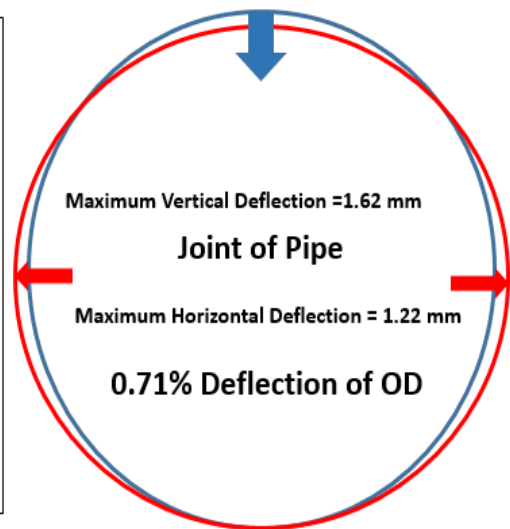
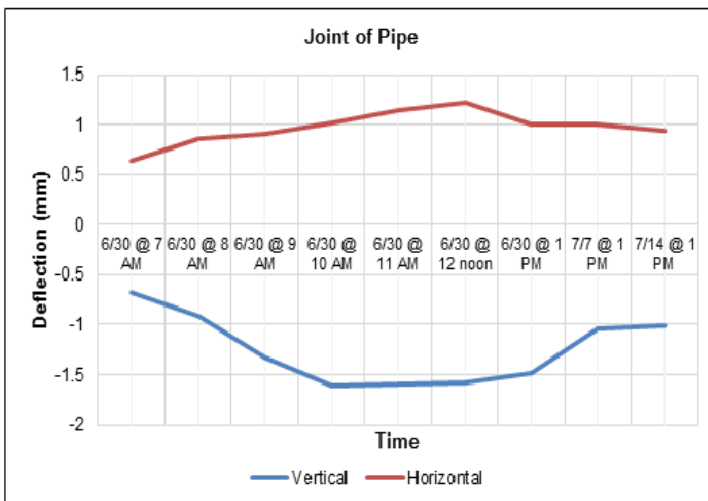


Figure 5.17 Deflection at joint of pipe due to earth and live load 1

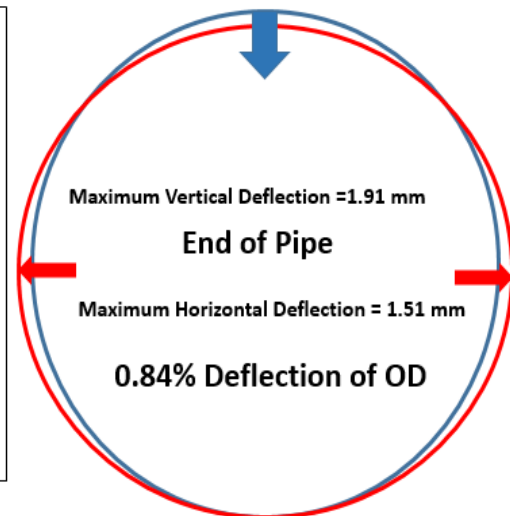
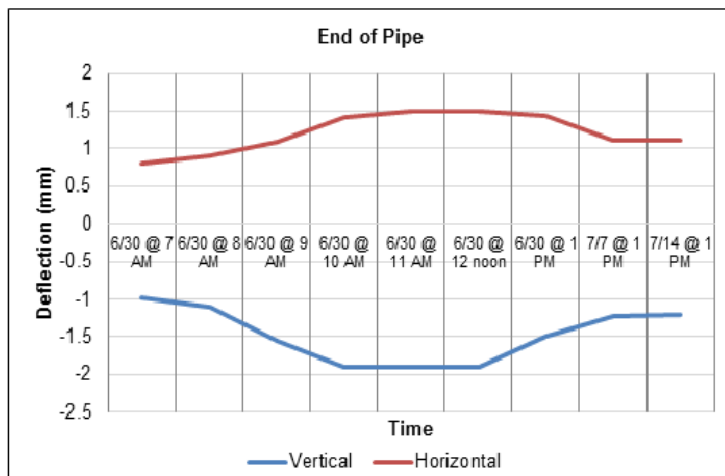


Figure 5.18 Deflection at end of pipe due to earth and live load 1

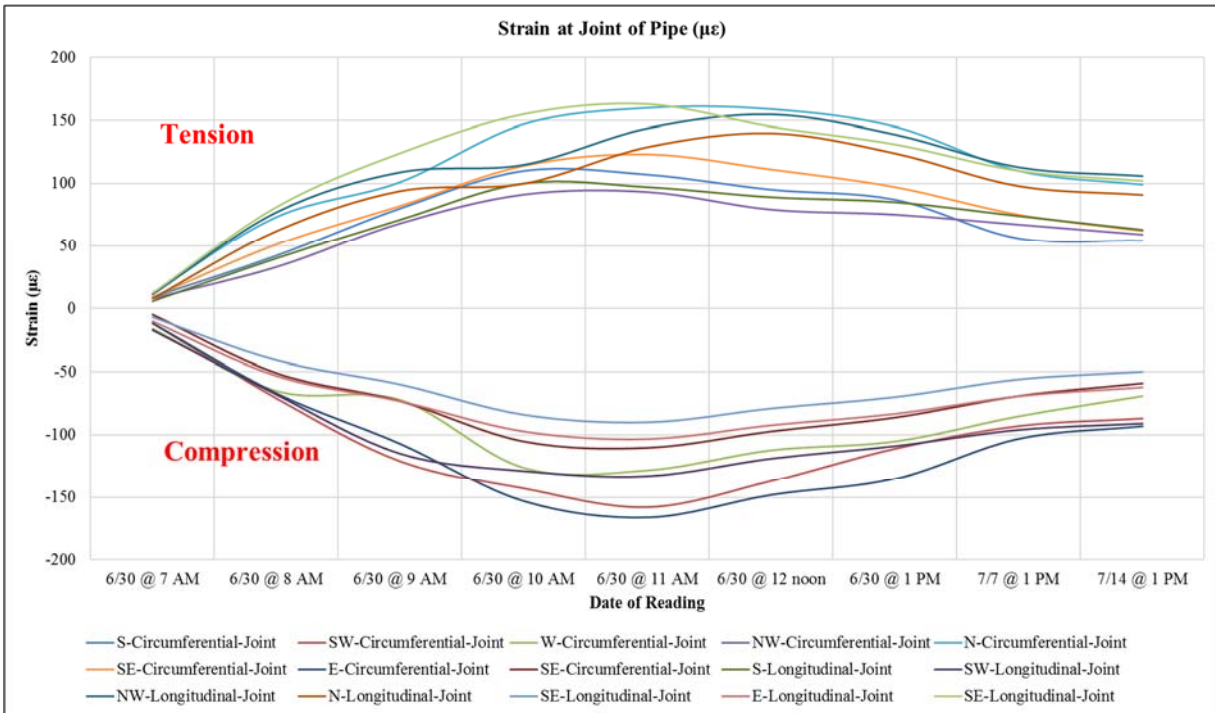


Figure 5.19 Strain measurements at joint of pipe with earth and live load 1

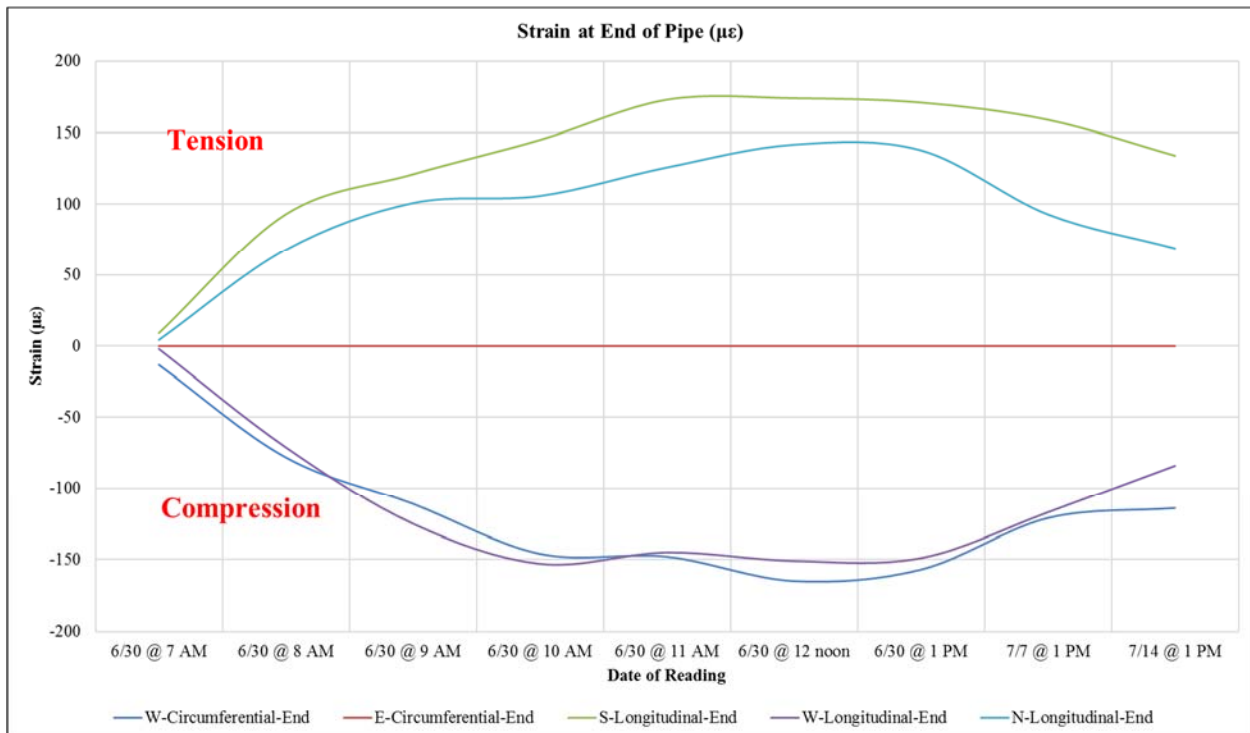


Figure 5.20 Strain measurements at end of pipe with earth and live load 1

Table 5.6
Earth pressure at joint of pipe due to earth plus live load 1

	South (invert) EPC-J-VL-1	West EPC-J-SL-2	North (crown) EPC-J-VL-3	East EPC-J-SL-4
6/30 @ 7 AM	1.732	0.175	2.925	1.456
6/30 @ 8 AM	1.825	0.244	3.587	1.537
6/30 @ 9 AM	2.152	1.856	5.189	2.121
6/30 @ 10 AM	2.325	1.957	6.974	2.564
6/30 @ 11 AM	2.334	1.948	6.444	2.547
6/30 @ 12 noon	2.182	1.759	5.314	2.325
6/30 @ 1 PM	2.630	1.722	4.176	1.856
7/7 @ 1 PM	1.699	1.203	3.686	1.752

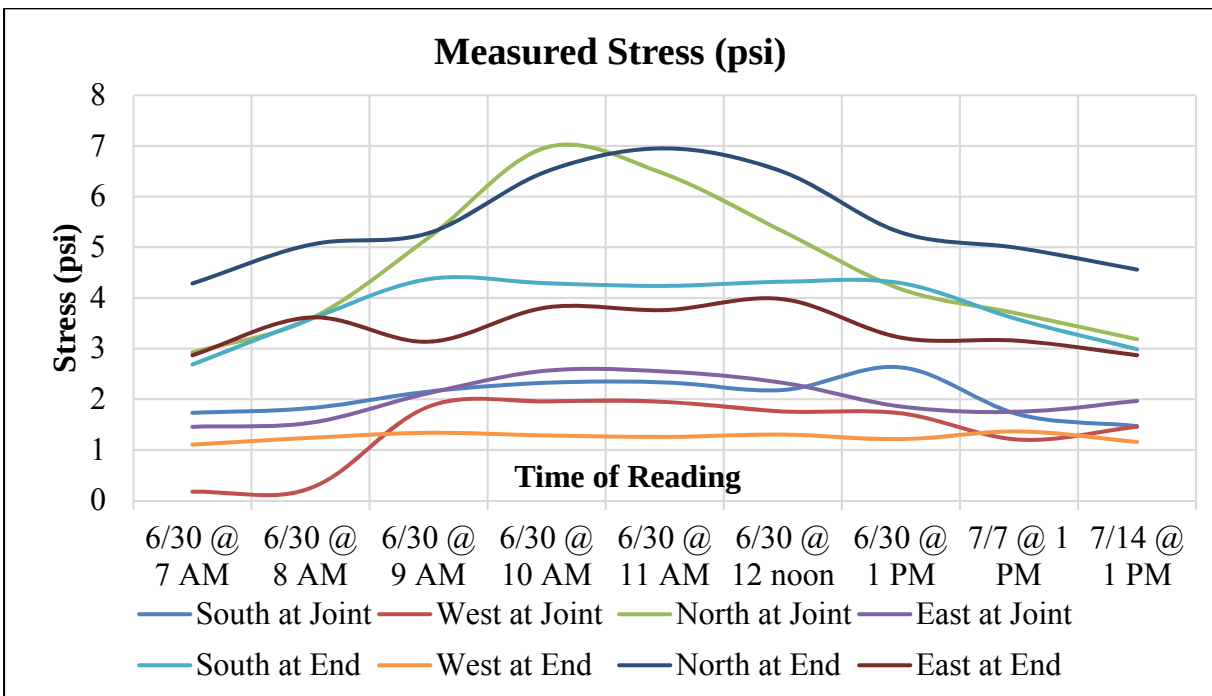


Figure 5.21 Earth pressures for bedding test 2 due to earth plus truck load 1

Table 5.7
Earth pressure at end of pipe due to earth plus live load 1

	South (invert) EPC-E-VL-6	West EPC-E-SL-7	North (crown) EPC-E-VL-8	East EPC-E-SL-9
6/30 @ 7 AM	2.685	1.104	4.285	2.869
6/30 @ 8 AM	3.582	1.239	5.052	3.615
6/30 @ 9 AM	4.371	1.337	5.280	3.135
6/30 @ 10 AM	4.289	1.284	6.497	3.812
6/30 @ 11 AM	4.237	1.257	6.951	3.760
6/30 @ 12 noon	4.319	1.302	6.489	3.976
6/30 @ 1 PM	4.292	1.212	5.291	3.216
7/7 @ 1 PM	3.569	1.365	4.984	3.154
7/14 @ 1 PM	2.987	1.157	4.560	2.869

5.3.3 Effect of Earth Plus Truck Load Round 2 on iPVC Pipe

A live load simulation was created and run for ninety minutes on top of the trench where iPVC pipe was installed. Load was applied on the top of the trench with an empty truck weighing about 28,000 pounds. The test helped to check the effect of the added load on the strain and deflection readings. The bed was stabilized with the additional of more gravel at the surface.

The second round truckload was applied on August 8, 2016. Figure 5.22 shows photographs of the round two live load testing. Tables 5.8, 5.9, and 5.10 present the deflection, strain, and earth pressure readings for one hour before, nine hours during, one hour after, one week after, and two weeks after applying round two truck loads. Three of the earth pressure cells stopped functioning prior to the test and hence there are no readings for these three pressure cells in Table 5.8. Figures 5.23 – 5.27 graphically illustrate the vertical deflection, horizontal deflection, strain at joint, strain at end of pipe and earth pressure readings, respectively. The vertical deflection readings displayed a maximum rise of 0.808 mm and 1.23 mm at the joint and end of the pipe respectively. The horizontal deflection readings displayed a maximum rise of 0.449 mm and 0.714 mm at the joint and end of the pipe respectively.



Source: Courtesy of UTA.

Figure 5.22 Twenty-ton truck creates live load on August 8

Table 5.8
Pipe deflection at joint and end of pipe due to earth plus truck load 2

Date and Time	Joint of Pipe Deflection (mm)		End of Pipe Deflection (mm)	
	Vertical	Horizontal	Vertical	Horizontal
8/8 @ 7 AM	-0.883	0.792	-0.991	0.914
8/8 @ 8 AM	-0.925	0.863	-1.112	1.067
8/8 @ 9 AM	-1.231	0.913	-1.651	1.189
8/8 @ 10 AM	-1.639	1.133	-2.103	1.547
8/8 @ 11 AM	-1.691	1.241	-2.118	1.628
8/8 @ 12 noon	-1.671	1.213	-2.221	1.589
8/8 @ 1 PM	-1.688	1.232	-2.234	1.615
8/8 @ 2 PM	-1.612	1.151	-2.148	1.539
8/8 @ 3 PM	-1.616	1.147	-2.156	1.587
8/8 @ 4 PM	-1.623	1.145	-2.149	1.541
8/8 @ 5 PM	-1.598	1.106	-2.127	1.474
8/8 @ 6 PM	-1.558	1.085	-2.101	1.229
8/15 @ 6 PM	-1.057	0.982	-1.213	1.108
8/22 @ 6 PM	-1.023	0.954	-1.206	1.086

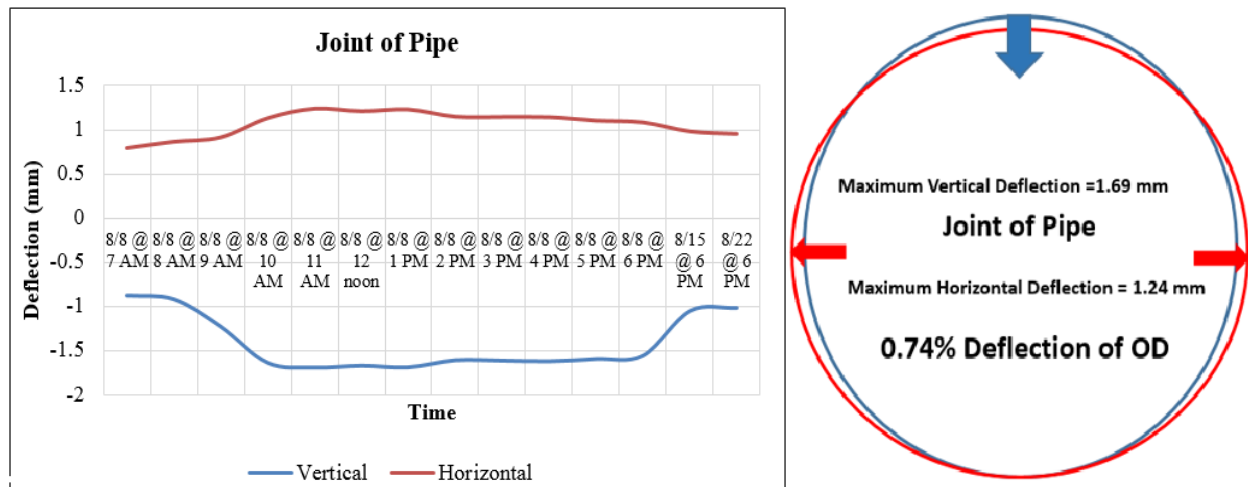


Figure 5.23 Deflection at joint of pipe due to earth plus truck load 2

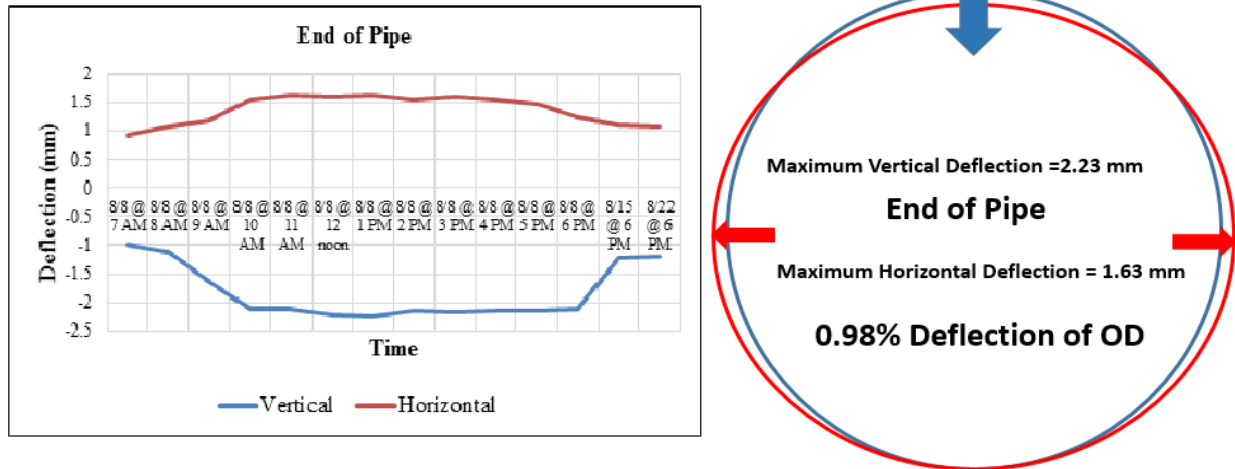


Figure 5.24 Deflection at end of pipe due to earth plus truck load 2

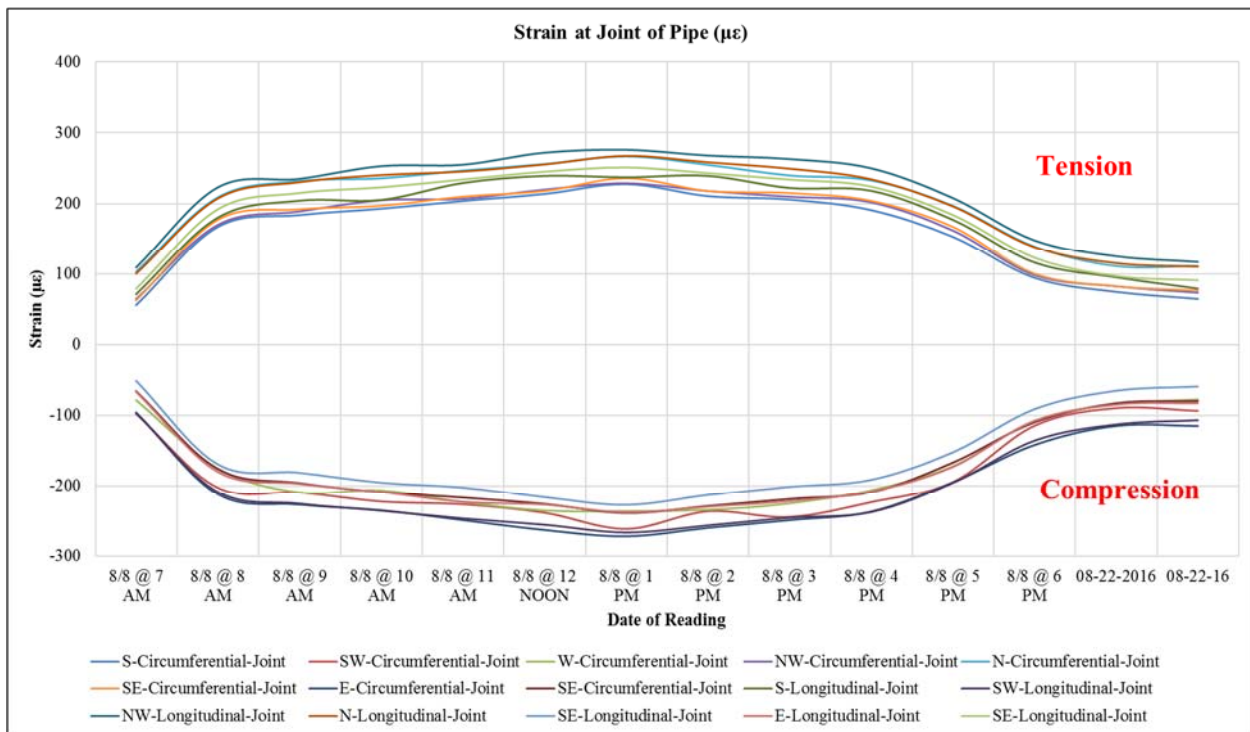


Figure 5.25 Strain measurements at joint of pipe due to earth plus live load 2

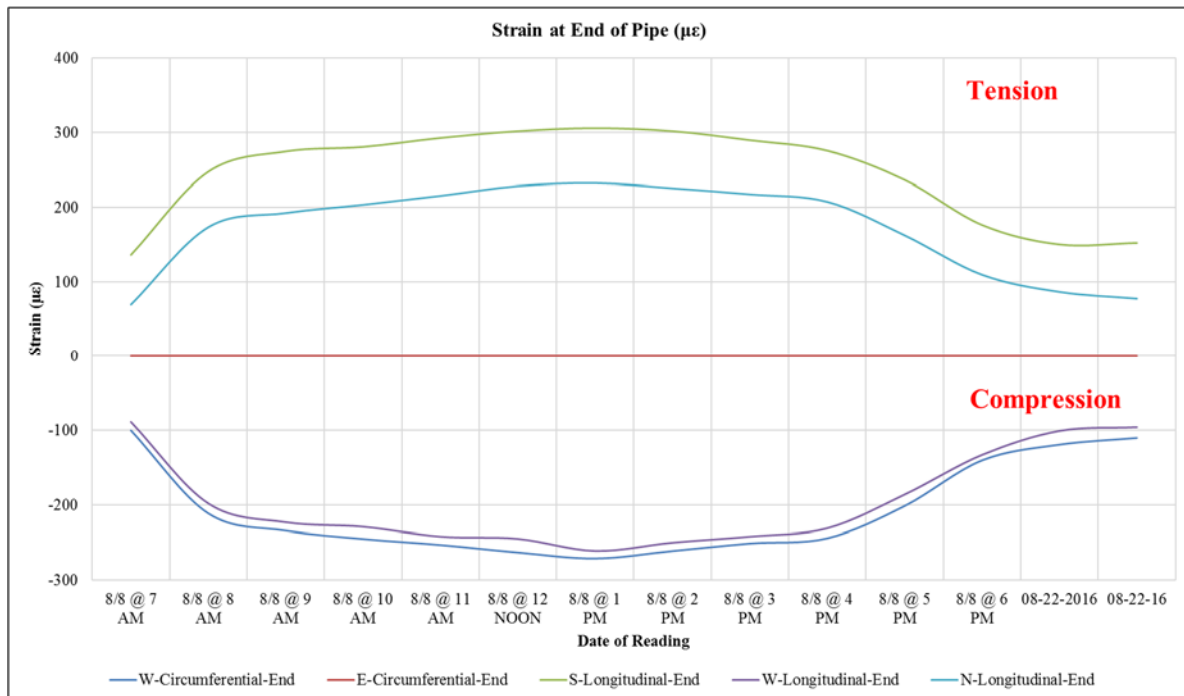


Figure 5.26 Strain measurements at end of pipe due to earth plus live load 2

Table 5.9
Earth pressure at joint of pipe due to earth plus live load 2

Date and Time	South (Invert) EPC-J-VL-1	West EPC-J-SL-2	North (Crown) EPC-J-VL-3	East EPC-J-SL-4
8/8 @ 7 AM	1.940	0.205	3.229	-
8/8 @ 8 AM	2.154	0.276	4.297	-
8/8 @ 9 AM	2.496	2.172	6.050	-
8/8 @ 10 AM	2.627	2.251	7.922	-
8/8 @ 11 AM	2.614	2.201	7.552	-
8/8 @ 12 noon	2.728	2.164	6.499	-
8/8 @ 1 PM	3.130	2.084	5.020	-
8/8 @ 2 PM	2.025	1.504	4.795	-
8/8 @ 3 PM	2.104	2.024	4.423	-
8/8 @ 4 PM	2.040	2.004	4.228	-
8/8 @ 5 PM	1.918	1.823	4.021	-
8/8 @ 6 PM	1.592	1.568	3.217	-
8/15 @ 6 PM	1.750	1.311	3.974	-
8/22 @ 6 PM	1.545	1.616	3.329	-

Table 5.10
Earth pressure at end of pipe due to earth plus live load 2

Date and Time	South (Invert) EPC-E-VL-6	West EPC-E-SL-7	North (Crown) EPC-E-VL-8	East EPC-E-SL-9
8/8 @ 7 AM	3.061	-	5.202	-
8/8 @ 8 AM	4.381	-	6.163	-
8/8 @ 9 AM	5.534	-	6.954	-
8/8 @ 10 AM	5.301	-	8.661	-
8/8 @ 11 AM	5.389	-	9.099	-
8/8 @ 12 noon	6.146	-	9.279	-
8/8 @ 1 PM	6.060	-	8.397	-
8/8 @ 2 PM	4.989	-	6.998	-
8/8 @ 3 PM	3.877	-	6.101	-
8/8 @ 4 PM	3.834	-	6.174	-
8/8 @ 5 PM	3.873	-	6.860	-
8/8 @ 6 PM	2.517	-	5.968	-
8/15 @ 6 PM	3.847	-	5.318	-
8/22 @ 6 PM	2.658	-	3.785	-

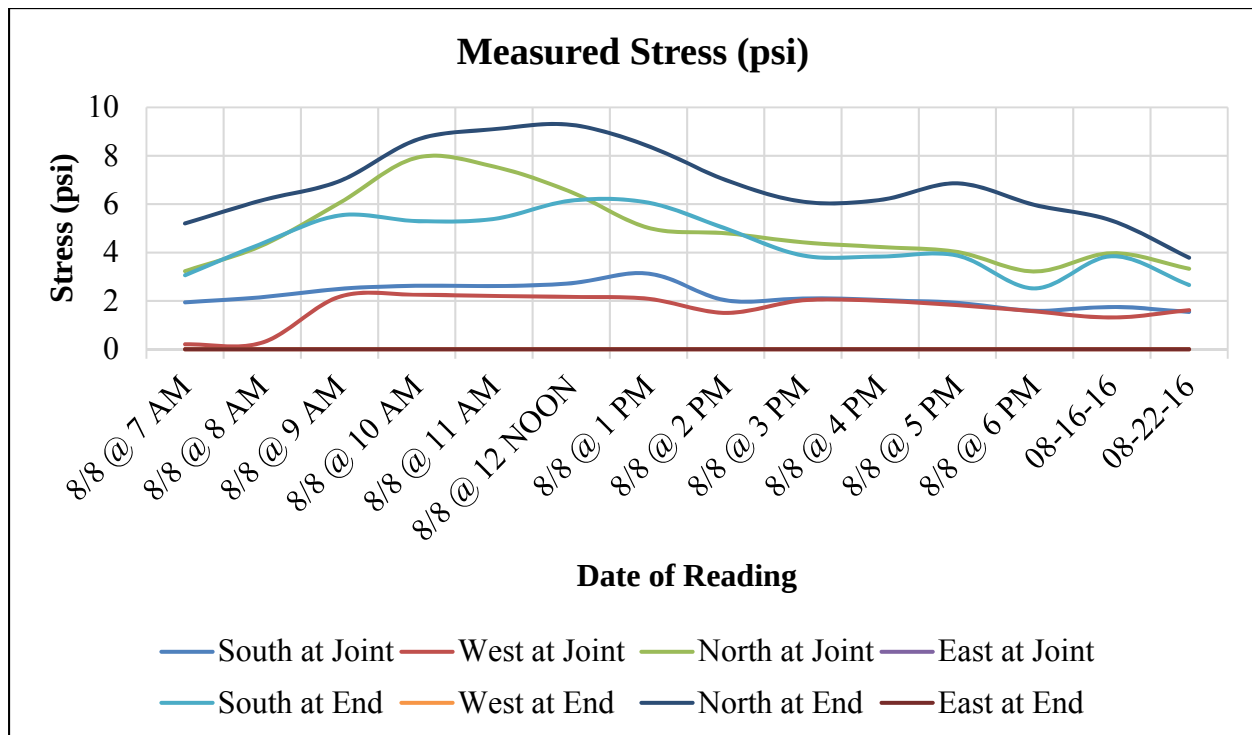


Figure 5.27 Earth pressures for bedding test 2 due to earth plus truck load 2

CHAPTER 6

DISCUSSION OF RESULTS

Chapter 4 reported the testing results of iPVC pipe and this chapter discusses the results of the laboratory tests performed. This includes the relationship of test results and key parameters required for future designing of iPVC pipe installation such as hoop stress, stiffness factor, fatigue life, bedding conditions, and deflection of iPVC pipe.

6.1 HYDROSTATIC SHORT-TERM BURST PRESSURE TEST

6.1.1 Modes of Failure

The short-term burst pressure or hydraulic short-term burst test on iPVC pipe entails a rapid increase in pressure to the pipe sample in a short time until the pipe fails. The purpose of the test was to determine the ultimate burst pressure of the iPVC pipe and to predict the nature of future pipe failure in the field.

The Microbac tests results averaged 1,033-psi pressure at failure over 123 seconds failure time. This failure pressure is 37% higher than the AWWA C900-16 and C909 requirement for DR 18 pipe, given as 755 psi. The average failure time taken to reach 755 psi for these tests was greater than the specified maximum of 70 seconds. The average pressure at failure during UTA experiment was 1,065 psi with average failure time of 84 seconds. This is 41% higher test pressure recommended by AWWA with 24% longer failure time. The combined results averaged 1,042-psi failure pressure with an average failure time of 112 seconds. This is 38% higher than the minimum pressure requirements and 60% longer failure time recognized per the ASTM testing requirements.

Microbac testing provided examples of two different types of failure, ductile and catastrophic failure. Catastrophic failure was defined as significant and multiple rupture of the pipe. Ductile failure showed evidence of pipe expansion without major fractures. Four specimen experienced ductile failure and six samples experienced catastrophic failure at Microbac while all the four samples tested at the UTA experienced catastrophic failure. The data from this test method could help in predicting the behavior of pipe (failure mode) under high hoop stress. What is interesting to note is that a slow pressure increase to failure in some of the Microbac tests resulted in the ductile failure in contrast to faster tests to failure that generated a catastrophic shattering type of failure. This suggests that large sudden increases in pressure might lead to a catastrophic failure while slower forces may generate a ductile failure.

6.1.2 Hoop Stress

The researchers applied the test data to calculate the hoop stress of the iPVC pipe. Table 6.1 presents the hoop stress, S for iPVC pipe based on Equation 3.1 for outside diameter (OD) controlled pipe.

Table 6.1
Hoop stress for iPVC pipe

Sample No.	Failure Pressure (psi)	Hoop Stress (psi)
1	1,070	9,095
2	1,050	8,925
3	1,020	8,670
4	1,050	8,925
5	1,010	8,585
6	1,030	8,755
7	1,030	8,755
8	1,010	8,585
9	1,035	8,798
10	1,020	8,670
11	1,065	9,053
12	1,060	9,010
13	1,060	9,010
14	1,075	9,138
Average	1,042	8,855
Std. Dev.	21	177

Calculation for average failed pressure:

OD = 9 inches, t = 0.5 inches, and P = 1,042 psi.

Using Equation 3.1, for hoop stress,

$$HS = \frac{1,042(9 - 2(0.5))}{2(0.5)} = 8,336 \text{ psi}$$

The hoop stress for a hydrostatic short-term burst pressure test must meet or exceed the 6,400 psi for a PVC pipe to pass the quick-burst test (Handbook of PVC Pipe Design and Construction, 2012). These test results show the iPVC exceeds the minimum criteria by more than 30%. Results suggest consistent pipe quality as well as demonstrates the surge capacity of iPVC pipe.

6.2 IMPACT TEST

The results obtained from impact test illustrate iPVC pipe robustness, specifically towards the external loads striking directly on the pipe. This test speaks to how the pipe can endure rough treatment during handling and installation. Microbac performed the first round of test results at the ASTM specified 73°F. The iPVC pipe did not shatter under a strike from a 1,200 foot-pound load. This test is technically incomplete, as the pipe ultimate impact load failed to break the pipe due to the limitation of height and weight at the Microbac lab and the strength of the iPVC pipe. The resistance to the impact load is at least 12 times greater than the value provided for conventional PVC pipe manufactured in the United States (JM Eagle has their PVC certified for an impact force of 100 foot-pounds).

To test the material further AW decided to conduct more challenging impact tests by lowering the temperature to 32°F. This temperature would be more representative of tough field conditions and verify the brittle behavior of the iPVC with the colder temperatures. The iPVC

specimens were able to withstand an impact force between 889 foot-pounds to 1,046 foot-pounds. Since the test is outside AWWA scope, there are no test data available for the conventional PVC pipes tested at 32°F. However, this is still 9 to 10.5 times stronger than PVC impact test levels at 73°F. The researchers believe that the strong impact resistance of thermoplastic pipe iPVC pipe is a reflection of the PVC resin and admixtures, the extrusion process and the pipe wall thickness.

The iPVC impact test illustrates the durability of the pipe material during handling and installation. The ruggedness of the material will be an asset during handling and field installation procedures such as trimming and live tapping. The impact resistance of the iPVC shows its ability to withstand rough handling in the field and improved suitability for service in the event of being accidental struck in subsequent excavation activity by others.

6.3 STIFFNESS TEST

The purpose of stiffness test is to verify if the iPVC pipe exhibits significant resistance to deflection when subjected to vertical loading outside the AWWA allowable deflection at 95% pipe mean diameter D. Nine samples were tested and average pipe stiffness for iPVC at 95% pipe deflection from the parallel plate test method recorded was 451 psi. This is 24% more than the allowable AWWA deflection at 95% pipe D. This test was continued to verify a second objective of the stiffness test to show no signature of cracking or failure at 60% pipe D. The critiques from the previous research study and claims by the ductile iron pipe association on the brittleness behavior of the conventional PVC, teased the researchers to continue the stiffness test beyond 60% pipe D. Not only did the iPVC pipe not crack at 60% D but did not fail, crack or show any signature of failure even after the inner walls of pipes were in contact with each other (less than 20% D). This demonstrates the flexibility of the pipe and its enhanced plastic behavior. This clearly raised expectations that the product can withstand significant load before deflecting to 95% D but that the pipe may also withstand more than the AWWA criteria of 95% D without damaging the pipe.

Studies have provided evidence that the conventional PVC pipe brittles with time. This raises an interesting question regarding the iPVC brittleness, “when will be the iPVC pipe brittleness lead to failure?” Further investigation on the iPVC pipe should be studied and evaluated to understand the pipe brittleness with time and parameters influencing the brittleness.

Pipe stiffness (PS) is the inherent resistance of flexible pipe to deflect under load. Using Equation 3.2 for pipe stiffness:

$$PS = \frac{F}{\Delta Y}$$

where: PS = pipe stiffness, psi

F = force applied, lbs./inch of sample length,

ΔY = vertical deflection, inch

Sample Calculation:

For sample R in Table 4.5, Load = 1,508 lbs., Length of sample = 7.87 inches

$F = 1,508 / 7.87 = 191.6$ lbs./inch,

$\Delta Y = D - 95\% \text{ of } D = 8.525 \text{ inches} \times 5\% = 0.426 \text{ inches}$

$$PS = \frac{F}{\Delta Y} = \frac{191.6}{0.426} = 450 \text{ psi}$$

Microbac tested ten samples reduced in diameter by 5% that supported an average 426 psi. This exceeds the minimum AWWA requirements of 364 psi at 95% diameter (AWWA 2002) by 17%. Stiffness test results are presented in Table 4.5. Figure 4.5 illustrates the load versus deflection of all the pipe samples.

The pipe stiffness (PS) calculated in Table 6.2 can be used to compute the stiffness factor (SF) defined as the product of PS and the quantity $0.149r^3$. The PS could also be used to calculate the approximate deflections under earth load. The researchers focused on two points of pipe diameter, 90 % and 95% of ID, for study. In pipe design, 95% deflection is used as criteria for pipe installation. The researchers also examined 90% to see what additional load would be required to double the diameter reduction. The PS and SF for iPVC pipe samples at 95% and 90% D are presented in Table 6.2.

Sample Calculation for SF:

For Sample mean radius r , at 95% D,

$$SF = PS \times 0.149r^3 = 451 \times 0.149 \times 4.26^3 = 5,204 \text{ inch-lbs.}$$

Table 6.2
Stiffness factor for partial iPVC pipe samples

Specimen	@ 95% D		@ 90% D	
	Pipe Stiffness	Stiffness Factor	Pipe Stiffness	Stiffness Factor
	psi	inch-lbs.	psi	inch-lbs.
R	451	5,204	396	4,570
Y	439	5,066	379	4,373
W	460	5,308	396	4,570
U	445	5,135	384	4,431
V	455	5,250	391	4,512
AS	451	5,204	388	4,477
AP	464	5,354	402	4,639
AQ	433	4,997	372	4,293
AU	463	5,343	396	4,570
Average	451	5,207	389	4493
Std. Dev.	11	103	9	95

The flexural modulus of elasticity, E can be determined from the SF values calculated using the Equation 3.4.

Although, EI of the pipe is a function of material's flexural modulus (E) and the wall thickness (t), engineers can compute PS and SF from the test resistance at a particular deflection. Hence, PS and SF values are highly dependent on the degree of deflection of pipe wall. The greater the deflection of pipe wall at which PS or SF are determined, the greater magnitude of the deviation from the true EI value. A correction factor $C = [1 + (\Delta Y/2D)]^3$ can be applied, and the PS and SF values can be related to the true EI of the pipe as long as the pipe remains elliptical. Hence, for corrected PS:

$$PS = \frac{F}{\Delta Y} C = \frac{F}{\Delta Y} \left(1 + \frac{\Delta Y}{2D}\right)^3 \quad \text{Eq. 6.1}$$

where: D = initial mean diameter, inch

Table 6.3 presents the corrected values of PS along with the SF and E for iPVC pipe. The calculated values of flexural modulus (E) could be used to study the behavior of the deflected pipe. Figures 6.1 through 6.3 graphically presents the corrected PS, SF and flexural modulus (E) for 95% and 90% deflection of D respectively.

Table 6.3
Corrected PS, SF, and E for iPVC pipe

Specimen	@95% D			@90% D		
	Corrected Pipe Stiffness	Corrected Stiffness Factor	Flexural Modulus (E)	Corrected Pipe Stiffness	Corrected Stiffness Factor	Flexural Modulus (E)
	psi	inch-lbs.	psi	psi	inch-lbs.	psi
R	488	5,631	540,586	428	4,939	474,132
Y	475	5,481	526,149	410	4,731	454,194
W	498	5,747	551,684	429	4,950	475,223
U	482	5,562	533,996	416	4,800	460,802
V	492	5,677	544,998	423	4,881	468,615
AS	488	5,631	540,553	420	4,847	465,355
AP	502	5,793	556,154	435	5,020	481,936
AQ	468	5,400	518,398	403	4,650	446,364
AU	501	5,781	554,968	429	4,950	475,223
Average	488	5,634	540,862	421	4,863	465,964
Std. Dev.	12	133	12,759	10	119	11,385

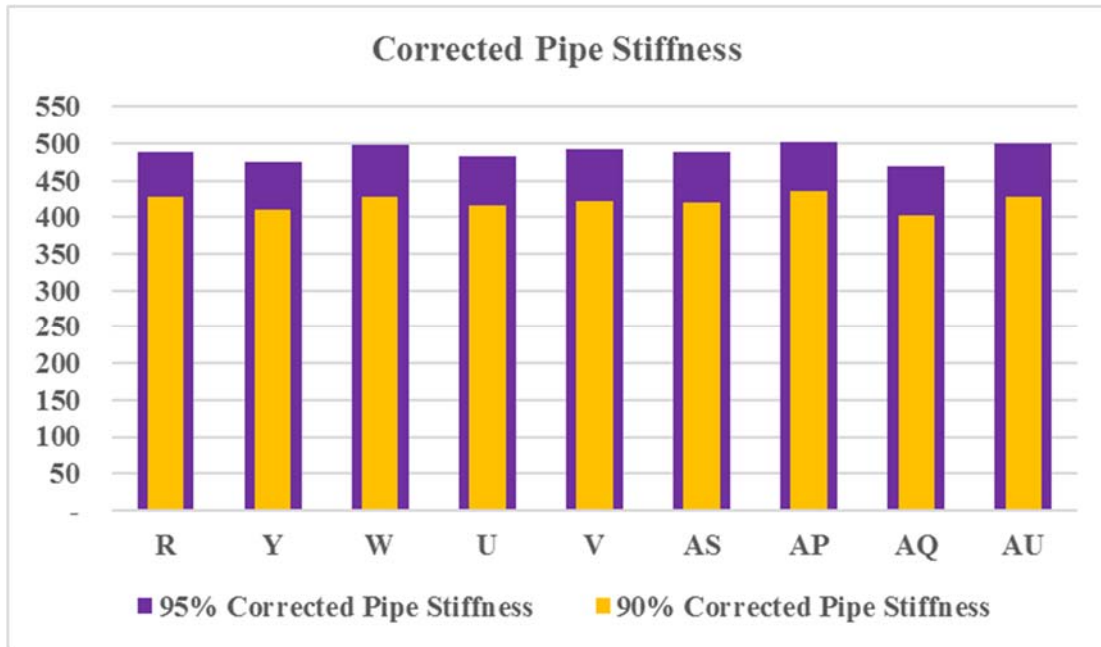


Figure 6.1 Corrected pipe stiffness (psi) results at 95% and 90% D

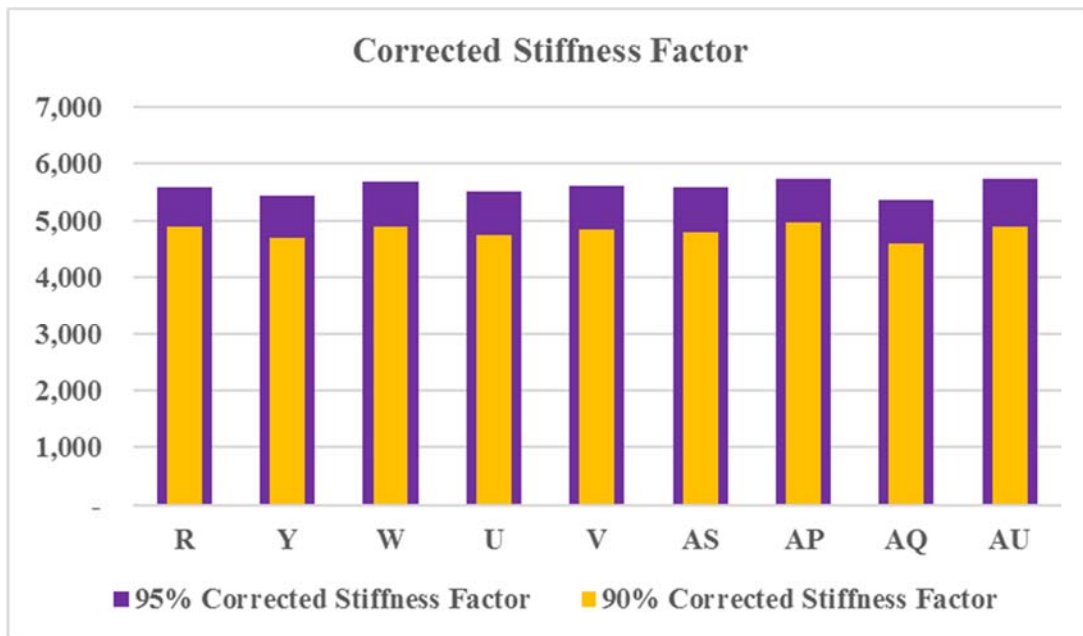


Figure 6.2 Corrected stiffness factor (inch-pounds) calculation at 95% and 90% D

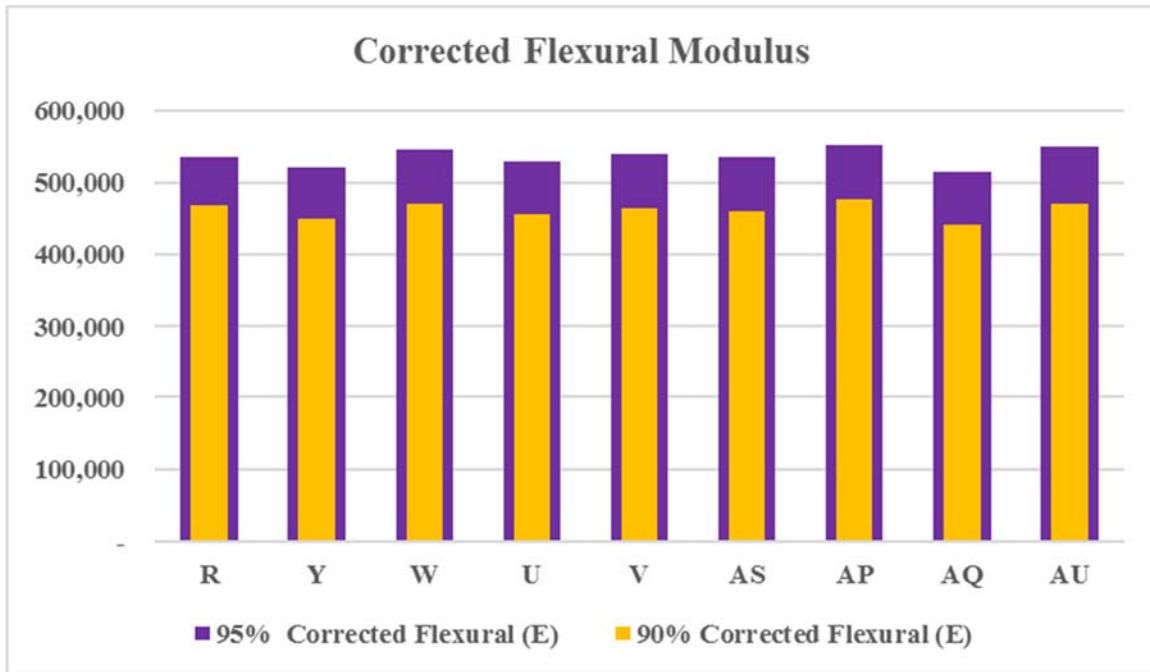


Figure 6.3 Flexural modulus results (psi) at 95% and 90% D

6.4 TENSILE TEST

The tensile test assesses physical strength of the material in tension. The Microbac Lab advised American Water, that the specimens sample for the tensile test must be prepared per Type I (mid-wall) dimensions for the PVC pipe manufactured in accordance with the PVC compound with cell classification 12454-B and higher, and not type III samples. The research team decided to pursue testing both type I and type III samples to study the contrast in the tensile test approach. However, throughout this report, the discussion of the tensile test results is limited to the type I samples only. Figure 6.4 illustrates the load versus deformation during the test. Slope 1 index and slope 2 index presents the elastic modulus region or elastic deformation region of the iPVC, peak index point represents the yield strength and the curve between peak index and break index is the plastic deformation of the pipe material. The break point presents the failure of the material and the ultimate tensile strength point for iPVC pipe material.

The average tensile strength observed for the type I test was 7,930 psi with a modulus of elasticity of 461,000 psi, exceeding the manufacturer's results provided before the project. The testing results also exceeded the AWWA C900-16 pipe requirement by 13% in the tensile strength (7,000 psi) and the modulus of elasticity (400,000 psi) by 15%. The tensile test results demonstrate that the pipe is more ductile material than conventional PVC pipe material (per AWWA C-900). This increased ductility property appears to be in evidence during the hydrostatic burst test observed with the ductile failures of the PVC pipe (Figure 4.3 ballooning).

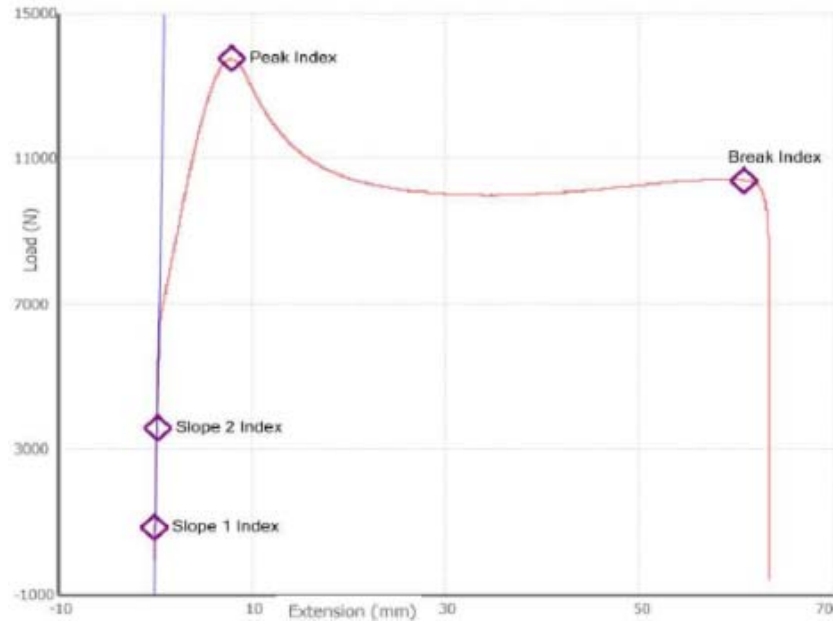


Figure 6.4 Load vs extension for the tensile testing for full wall specimen, Microbac Lab

6.5 FATIGUE TEST

UTA performed a high pressure fatigue test on an 8-inch diameter iPVC pipe specimen 10 feet long provided by PPII. The pressure cycled between 150 and 225 psi at 8-10 seconds intervals producing a saw-tooth waveform pattern of surge (Figure 6.5). Table 6.4 presents the changes in circumference due to the pressure surges. Although, measurements were taken at regular intervals, the table presented highlights only the cycles when a change in the circumference was observed.

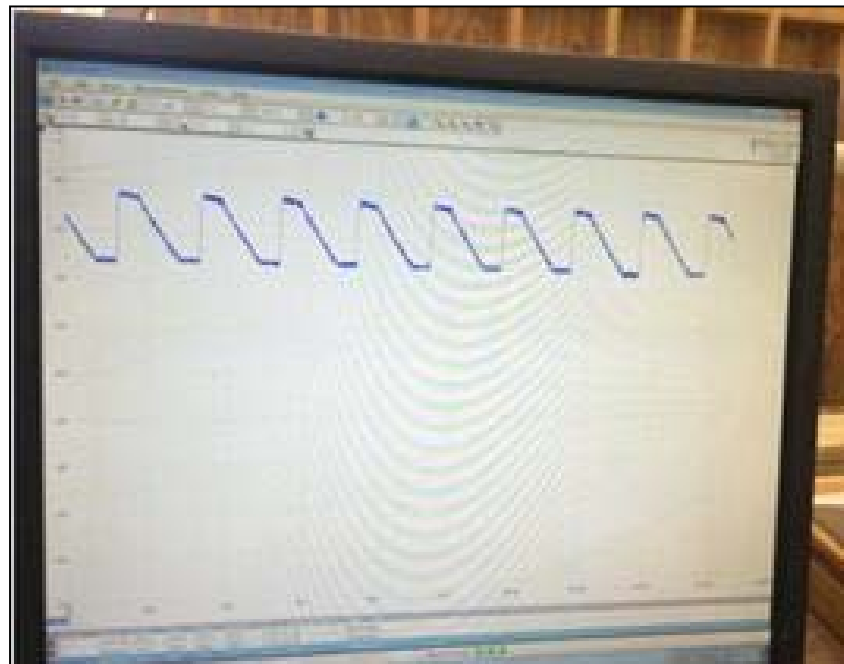


Figure 6.5 Pressure recordings of pipe during fatigue test

Table 6.4
Circumference values during fatigue test

Number of Cycles	Circumference (cm)														
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
0	72.6	72.6	72.6	72.6	72.6	72.6	72.6	72.6	72.6	72.6	72.6	72.6	72.6	72.6	72.6
39,653	72.8	72.8	72.8	72.7	72.7	72.7	72.7	72.7	72.7	72.7	72.8	72.8	72.7	72.7	72.6
284,035	72.8	72.8	72.8	72.8	72.8	72.7	72.7	72.7	72.7	72.7	72.8	72.8	72.7	72.7	72.6
Test stopped for 24 hours to evaluate change in circumference reverses if test interrupted															
284,035	72.6	72.6	72.6	72.6	72.6	72.6	72.6	72.6	72.5	72.6	72.6	72.6	72.6	72.5	72.4
586,618	72.8	72.8	72.7	72.7	72.7	72.6	72.6	72.6	72.7	72.7	72.8	72.6	72.6	72.6	72.6
696,835	72.8	72.8	72.7	72.7	72.7	72.6	72.6	72.7	72.7	72.7	72.7	72.6	72.6	72.6	72.6
1,133,076	72.8	72.8	72.8	72.7	72.7	72.7	72.6	72.8	72.7	72.7	72.7	72.6	72.6	72.7	72.7
1,348,007	72.8	72.8	72.7	72.7	72.7	72.6	72.6	72.7	72.7	72.7	72.7	72.5	72.6	72.6	72.7
1,542,838	72.8	72.8	72.8	72.8	72.8	72.8	72.8	72.9	72.9	72.9	72.9	72.9	72.9	72.9	72.9
1,673,193	72.8	72.8	72.8	72.8	72.8	72.8	72.8	72.8	72.8	72.8	72.8	72.8	72.8	72.8	72.8
1,831,019	72.9	72.9	72.9	72.9	72.8	72.9	72.9	72.9	72.9	72.9	72.8	72.9	72.9	72.9	72.8
1,886,382	72.9	72.9	72.9	72.9	72.8	72.9	72.9	72.9	72.9	72.9	72.8	72.8	72.8	72.8	72.8
1,941,541	72.9	72.9	72.9	72.9	72.8	72.9	72.8	72.8	72.8	72.8	72.8	72.9	72.9	72.9	72.8
1,988,986	72.8	72.8	72.8	72.8	72.8	72.8	72.8	72.8	72.8	72.8	72.8	72.7	72.7	72.7	72.7
2,093,509	72.9	72.9	72.9	72.9	72.8	72.8	72.9	72.8	72.8	72.8	72.8	72.8	72.8	72.7	72.7
2,139,469	72.9	72.9	72.9	72.9	72.9	72.9	72.9	72.9	72.9	72.8	72.8	72.8	72.8	72.7	72.7
2,238,451	72.9	72.9	72.9	72.9	72.9	72.9	72.9	72.9	72.9	72.9	72.8	72.9	72.8	72.8	72.8
Test stopped for 24 hours to evaluate change in circumference reverses if test interrupted															
2,238,451	72.8	72.8	72.7	72.7	72.7	72.7	72.7	72.7	72.7	72.7	72.7	72.7	72.6	72.6	72.6
Test continued as directed by PPII with intent to run to 4 million cycles															
2,238,451	72.7	72.7	72.7	72.7	72.7	72.6	72.6	72.6	72.6	72.6	72.6	72.6	72.6	72.6	72.6
2,243,301	72.8	72.8	72.7	72.7	72.7	72.7	72.7	72.7	72.6	72.6	72.6	72.6	72.6	72.6	72.6

After 2.23 million surge cycles, the incremental changes in the circumferential pipe was 2 mm. (0.08 inches) at seven locations (A through G) and 3 mm. (0.12 inches) at locations (H through O). The maximum increment is 4% of the overall circumferential size of the pipe (76.2 cm or 28.6 inch). These changes are marginal, and the pipe exhibits resistance to the induced surge pressure of 150-250 psi. When the pressure was removed, the pipe appeared to recover to near original dimension.

The fatigue life of 8-inch DR 18 iPVC pipe could be estimated based on the equations suggested by Petroff (2013) in Section 3.6.2 (Eq. 3.6 and Eq. 3.7). The equations are as follows:

$$\text{Number of Cycles} = 10^{\frac{1.708 - \log\left(\frac{\text{Peak Stress}}{145}\right)}{0.101}} \quad \text{Eq. 6.2}$$

$$\text{Peak Stress} = (P_{\text{pumping}} + P_{\text{surge}}) \times \frac{(DR-1)}{2} \quad \text{Eq. 6.3}$$

The above equations should be limited to predict the anticipated number of cycles for failure of the pipe due to fatigue for experimental conditions only. The hydraulic transients during operation of the pipe result in the total pressure (pumping plus surge) to exceed the steady-flow working pressure. AWWA C900 recommends a surge allowance of 1.0 x Pressure Class (PC) of the pipe for occasional surges and a surge allowance of 0.5 x PC for frequent recurring surges.

ASTM D2837-13e1 Standard Test Method for Obtaining Hydrostatic Design Basis for Thermoplastic Pipe Materials or Pressure Design Basis for Thermoplastic Pipe Products helps

obtain the hydrostatic design basis (HDB) and long-term hydrostatic strength (LTHS) that could be used in the above equations to predict the fatigue life of the pipe. LTHS is defined in ASTM D2837-13e1 as “the estimated tensile stress in the wall of the pipe in the circumferential orientation that when applied continuously will cause failure of the pipe at 100,000 hrs. This is the intercept of the stress regression line with the 100,000 hours “coordinate.” HDB is the categorized value of the material’s LTHS (ASTM D2837-13e1, 2013).

Hydrostatic design stress (HDS) is defined as the estimated maximum tensile stress the material is capable of continuously withstanding with a high degree of certainty that failure of the pipe will not occur as per ASTM D2837-13e1. These values could be used in the above equations by Petroff (2013) to predict the number of cycles to failure of pipe due to fatigue stress generated by transient surges.

The 50-year LTHS value for iPVC pipe is 3,955 psi (27.27 MPa) (per tests arranged by PPII, Korea). Based on the LTHS value, from Figure 5.6, the HDB value for iPVC pipe is 4,000 psi (27.58 MPa). This HDB stress is circumferential when internal hydrostatic water pressure is applied. The Figure 6.6 provides the hydrostatic design basis values corresponding to calculated LTHS values.

Range of Calculated LTHS Values		Hydrostatic Design Basis	
psi	(MPa)	psi	(MPa)
190 to < 240	(1.31 to < 1.65)	200	(1.38)
240 to < 300	(1.65 to < 2.07)	250	(1.72)
300 to < 380	(2.07 to < 2.62)	315	(2.17)
380 to < 480	(2.62 to < 3.31)	400	(2.76)
480 to < 600	(3.31 to < 4.14)	500	(3.45)
600 to < 760	(4.14 to < 5.24)	630	(4.34)
760 to < 960	(5.24 to < 6.62)	800	(5.52)
960 to <1200	(6.62 to < 8.27)	1000	(6.89)
1200 to <1530	(8.27 to <10.55)	1250	(8.62)
1530 to <1730	(10.55 to <11.93)	1600	(11.03)
1730 to <1920	(11.93 to <13.24)	1800	(12.41)
1920 to <2160	(13.24 to <14.89)	2000	(13.79)
2160 to <2400	(14.89 to <16.55)	2250	(15.51)
2400 to <2690	(16.55 to <18.55)	2500	(17.24)
2690 to <3020	(18.55 to <20.82)	2800	(19.30)
3020 to <3410	(20.82 to <23.51)	3150	(21.72)
3410 to <3830	(23.51 to <26.41)	3550	(24.47)
3830 to <4320	(26.41 to <29.78)	4000	(27.58)
4320 to <4800	(29.78 to <33.09)	4500	(31.02)
4800 to <5380	(33.09 to <37.09)	5000	(34.47)
5380 to <6040	(37.09 to <41.62)	5600	(38.61)
6040 to <6810	(41.62 to <46.92)	6300	(43.41)
6810 to <7920	(46.92 to <54.62)	7100	(48.92)

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Figure 6.6 Hydrostatic design basis values corresponding to LTHS values

As per M23 PVC Pipe Design and Installation Manual (AWWA 2002),

$$\text{HDS} = \text{HDB}/\text{SF} \quad \text{Eq. 6.4}$$

where: SF = safety factor = 2.5

Thus, HDS = $4000/2.5 = 1,600$ psi

Considering HDS as our peak stress and using Equation 6.2,

Number of cycles to failure = $10^{\{(1.708 - \log_{10}(1600/145))/0.101\}} = 3,860,000$

Based on a conservative assumption of 50 surges/day (Divyashree, 2014), the experimental fatigue life of 8-inch DR 18 iPVC pipe suggest a life of more than 210 years. The predicted 210-year design life excludes parameters such as soil conditions, operating pressures, number of connections, pump operation, etc. that could result in a lower life of the pipe than this estimate.

The HDB testing is less rigorous on the pipe wall as compared to the fatigue test performed in this research project. The 190-year life is a prediction based on the HDB testing of iPVC pipe. If we consider the fatigue testing at UTA, over 2,238,000 cycles were monitored in the research. The test proves that the pipe could withstand more than 2,238,000 surges without any failure for a surge pressure range of 150 psi to 225 psi. If we consider the same number of surges per day as earlier, i.e., 50 surges/day (more than 2 every hour), the pipe would have a fatigue life of at least 122.5 years based upon the following computation:

Total surges experienced by pipe without failure = 2,238,000

Daily surge occurrence = 50 surges

Fatigue Life of iPVC pipe = $2,238,000 \text{ surge cycles} / 50 \text{ surges per day}$
 $= 44,760 \text{ days} = 122.5 \text{ years}$

The above design life is for the iPVC pipe sample considered in this research project. The iPVC pipe sample used for the testing was the 8-inch ID DR 18 with a length of 10 feet. For another diameter and DR of iPVC pipe, the fatigue testing might have different results. It is understood that fatigue is only one of several possible causes that contribute to the deterioration and failure of PVC pipe. However, if it is a primary cause for conventional PVC, it appears iPVC offers great resiliency to this factor.

Further, the maximum surge pressure in the iPVC for a change in flow velocity of 2 feet /second may be calculated using the following equations:

$$a = \frac{4,660}{\sqrt{1 + \frac{k}{E}(DR-2)}} \quad \text{Eq. 6.5}$$

where: a = pressure wave velocity, feet /second

k = fluid bulk modulus, psi (300,000 psi for water)

E = modulus of elasticity of the pipe, psi (461,000 psi for iPVC pipe)

DR = dimension ratio for iPVC pipe (DR = 18 for iPVC pipe)

$$P_s = \frac{a(\Delta V_{\max})}{2.31g} \quad \text{Eq. 6.6}$$

where: P_s = pressure surge, psi

$\Delta V_{\max}$ = maximum velocity change, feet/second,

For conventional PVC, $V_{\max} = 2$ feet/second

g = acceleration due to gravity, 32.2 feet/second²

Substituting the values in Eq. 6.5,

$$a = \frac{4,660}{\sqrt{1 + \frac{300,000}{461,000}(18 - 2)}} = 1,380 \text{ ft/s}$$

Further, using Eq. 6.6,

$$P_s \text{ for iPVC} = \frac{1,380(2)}{2.31(32.2)} \sim 37 \text{ psi}$$

Per AWWA M23 the above information can be used by the designers to select the type and proper location of protection devices against the surge pressures. This includes the ability to evaluate surge-reducing alternatives such as variable speed pumps or surge tanks. The fatigue performance of iPVC pipe could be determined by the actual surges experienced (occasional and recurring) in the field. The pipe experiences surge due to sudden shutdown of pump, valves, or due to consumption changes.

PPII decided to continue the fatigue test beyond the initial project scope of 2 million cycles to 4 million cycles at the same pressure rating and this has been accomplished. No failures or major anomalies in the pipe were reported in these subsequent stages, thus displaying continued resistance to recurring surge. It should be noted that the test was continued after data was collected and ran for over 4 million cycles suggesting an even larger value. The pipe used for the surge test will be returned to PPII for further analysis beyond the scope of this study.

6.6 BEDDING TEST

The researchers designed a bedding test to monitor iPVC pipe for three months with dead load and with some additional live load to understand the behavior and performance of the pipe deflection underground in clay backfill. The secondary objective of the test was to validate the stiffness test outside the laboratory. The test provided deflection and load data as experienced by the pipe wall under earth load as well as under earth load plus the truckload. The field data was compared to theoretical values derived by the Modified Iowa equation that is based on the dimension ratio of the pipe and modulus of elasticity as well as Spangler's equation that is based on the pipe stiffness value of the pipe.

6.6.1 Deflection of iPVC Pipe Due to Earth Load

The pipe stiffness determined in this research project can be used to calculate approximate deflection of the pipe under earth load and earth load plus live load. From Eq. 3.6,

$$\% \text{ Deflection} = \frac{(1.0 \times 4.17 + 0) 0.1 \times 100}{\{2(461,000)/[3(18 - 1)^3]\} + 0.061(400)} = \frac{41.7}{87.01} = 0.48 \% = 1.09 \text{ mm}$$

where for iPVC pipe:

deflection lag factor of 1.0 is used, which is typical for a flexible pipe

bedding constant of 0.1 is used, which is typical for a flexible pipe
 $W_L = 0$ for only dead load calculations;
 $W_p = 4.17$ psi from JM Eagle 2016 as the unit weight of soil used for backfilling in the bedding test is 120 lbs./ft³ and the height of cover for the testing is 5 feet;
 $PS = 516$ psi from Table 5.4, and
 $E' = 400$ psi is considered from following Figure 6.7 after classifying the soil based on the soil testing carried out in the laboratory

Soil type-pipe bedding material (Unified Classification System) ¹	E' for degree of compaction of bedding (lb/in ²)			
	Dumped	Slight < 85% Proctor <40% relative density	Moderate 85% - 95% Proctor 40% - 70% relative density	High > 95% proctor >70% relative density
Fine grained soils (LL>50) ² Soils with medium to high plasticity CL, ML, ML-CL,	No data available, consult a competent soil engineer; otherwise use E' = 0			
Fine grained soils (LL<50) Soils with medium to no plasticity CL, ML, ML-CL, with less than 25% coarse grained particles	50	200	400	1000
Fine grained soils (LL<50) Soils with medium to no plasticity CL, ML, ML-CL, with more than 25% coarse grained particles. Coarse grained soils with fines GM, GC, ,SM, SC ³ , contains more than 12% fines.	100	400	1000	2000
Coarse grained soils with little or no fines GW, GP, SW, SP ³ , contains less than 12% fines	200	1000	2000	3000
Crushed Rock	1000	3000		
Accuracy in terms of percentage deflection ⁴	± 2 %	± 2 %	± 1 %	± 0.5 %
¹ ASTM Designation D2487, USBR Designation E-3				
² LL = Liquid limit				
³ Or any borderline soil beginning with one of these symbols (i.e., GM-GC-SC).				
⁴ For ± 1% accuracy and predicted deflection of 3%, actual deflection would be between 2% and 4%				
Note:				
A. Values applicables only for fills less than 50 feet.				
B. Table does not include safety factor				
C. For use in predicting initial deflections only, appropriate deflection lag factor must be applied for long term deflections.				
D. If bedding falls on the borderline between two compaction catagories, select lower E' value or average the two values				
E. Percentage proctor based on laboratory maximum dry density from test standards using above 12500 ft-lb/ft ² (ASTM D-698, AASHTO T-99, USBR Designation E-11)				

Figure 6.7 Table of soil E' values

Calculation:
 $De = 1.0$
 $K = 0.1$
 $W_p = 4.17$ psi
 $PS = 516$ psi
 $E' = 400$ psi

Substituting in Eq. 3.5,

$$\% \text{ Deflection} = \frac{(1.0)(0.1)(0 + 4.17)(100)}{0.149(516) + 0.061(400)} = \frac{41.7}{101.28} = 0.41 \% = 0.94 \text{ mm}$$

Now, using Eq. 3.6, the predicted percent deflection based on the DR and the E of iPVC pipe could be calculated as:

DR = 18 for iPVC pipe,

E = 461,000 psi for iPVC pipe from Table 4.6

E = 461,000 psi for iPVC pipe from Table 4.6

$$\% \text{ Deflection} = \frac{(1.0 \times 4.17 + 0) 0.1 \times 100}{\{2(461,000)/[3(18 - 1)^3]\} + 0.061(400)} = \frac{41.7}{87.01} = 0.48 \% = 1.09 \text{ mm}$$

The maximum stress experienced was 4.759 psi on crown part at the end of the iPVC test pipe. This exceeds the calculated soil load of 4.17 psi from by 14%.

6.6.2 Deflection of iPVC Pipe Due to Dead Plus Live (Truck) Load

As explained earlier, a live load simulation was created on top of the trench with a 20-ton truck. The truck was run on top of the trench along the length of the pipe for 2 hours and then halted on top of the pipe for 2 hours. The expected live load transmitted to the pipe from the traffic could be considered in predicting the percent deflections using Eq. 3.5 and Eq. 3.6.

Using Eq. 3.5, and considering all the values used in Section 6.5.1,

W_L = 1.74 psi from Figure 5.9,

$$\% \text{ Deflection} = \frac{(1.0)(0.1)(1.74 + 4.17)(100)}{0.149(516) + 0.061(400)} = \frac{59.1}{101.28} = 0.58 \% = 1.33 \text{ mm}$$

Also, using Eq. 3.6,

$$\% \text{ Deflection} = \frac{(1.0 \times 4.17 + 1.74) 0.1 \times 100}{\{2(461,000)/[3(18 - 1)^3]\} + 0.061(400)} = \frac{59.1}{87.01} = 0.68 \% = 1.55 \text{ mm}$$

6.6.3 Comparison of Deflection Values

Figure 6.8 and Figure 6.9 provide the deflection values obtained by the theoretical methods, FEM analyses and field test data for iPVC pipe for dead load vertically and horizontally respectively. The deflection calculated by the theoretical methods (Spangler's equation and Modified Iowa equation) assume an identical change in the vertical and horizontal directions. Vertical deflection was reduced (negative) while horizontal deflection expanded (positive) throughout the testing.

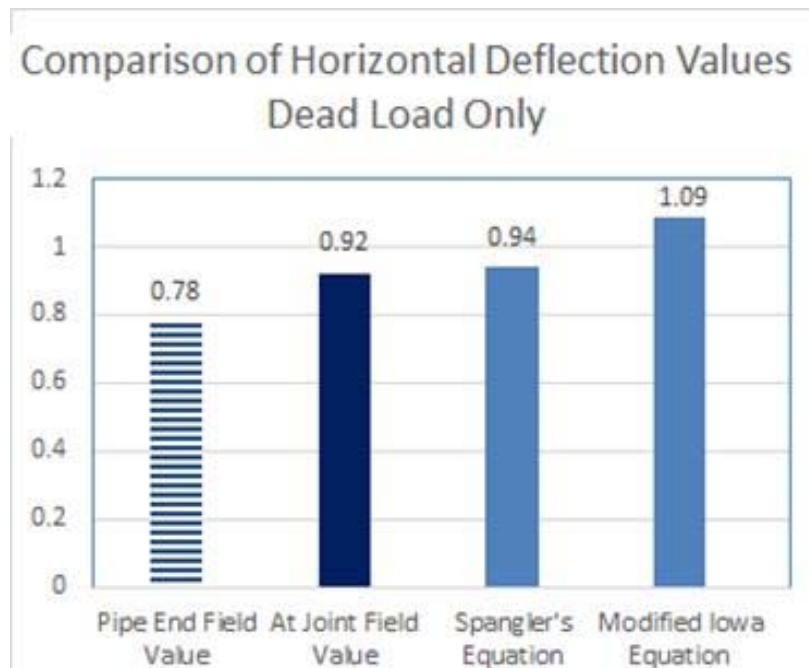


Figure 6.8 Vertical deflection values for earth load application

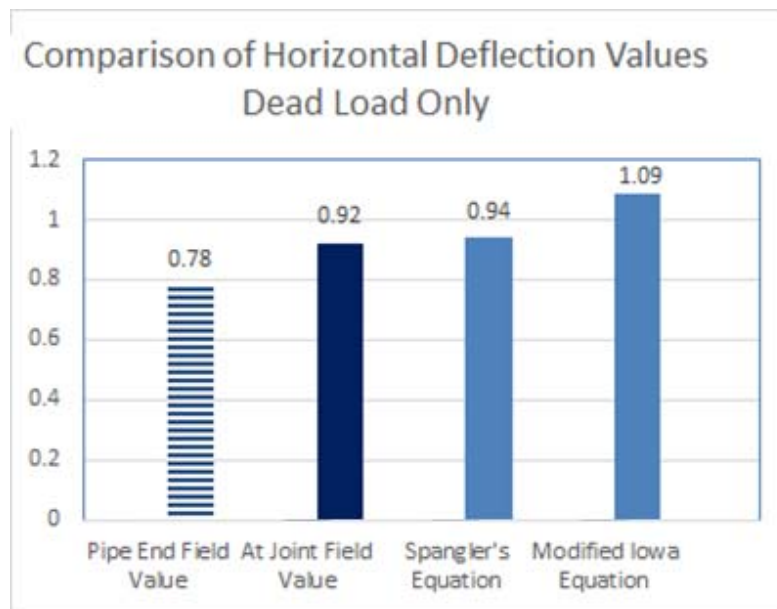


Figure 6.9 Horizontal deflection values for dead load application

Figure 6.9, Figure 6.10, Tables 6.5, and 6.6 compare the deflection values obtained by the theoretical methods and field test data for iPVC pipe for the live load, earth plus gravel loaded truckload application in vertical and horizontal respectively.

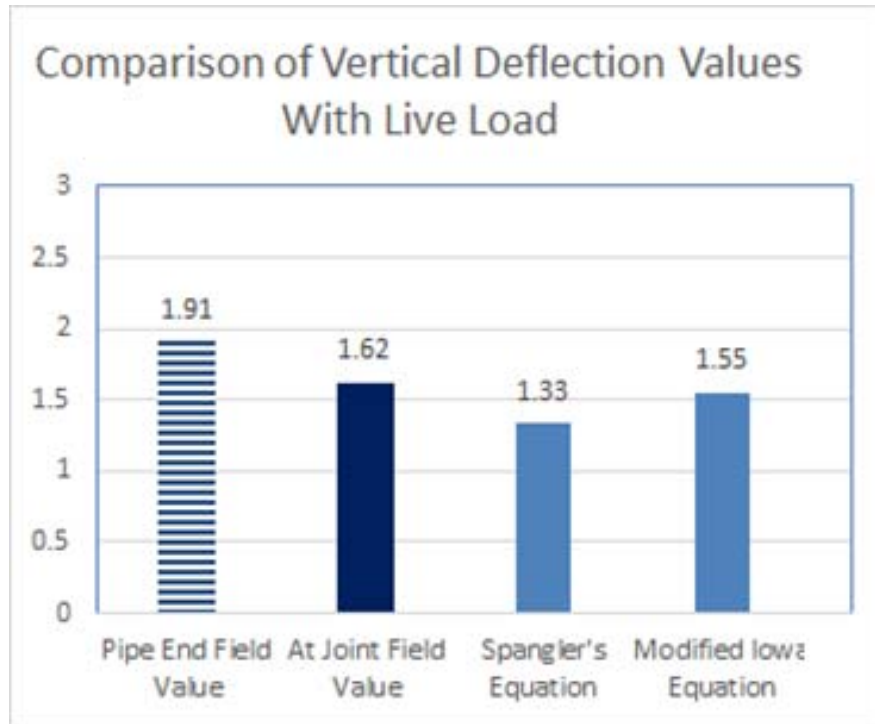


Figure 6.10 Vertical deflection values for live load application

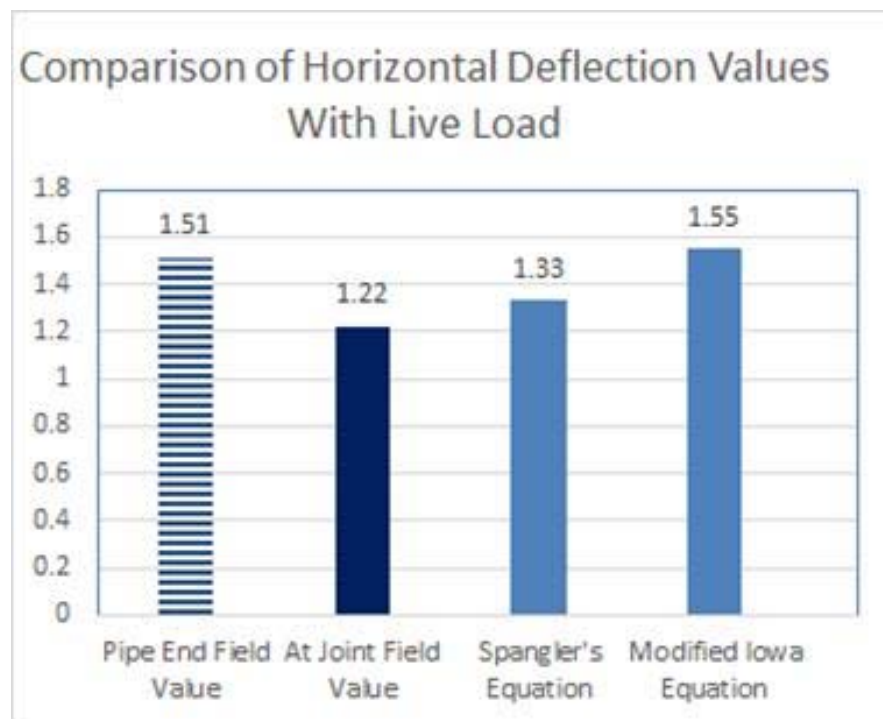


Figure 6.11 Horizontal deflection values for dead load application

6.6.4 Summary of Bedding Test

Figure 6.10 and Figure 6.11 provides the maximum deflection experience by the pipe during the bedding test under defined scenarios and theoretical equations. The maximum deflection discussed is the data that is analyzed, not the average deflection pipe experienced by the iPVC pipe. The maximum deflection may be a momentary deflection experienced by the pipe. For instance, during the experiment the pipe has experience as low as -0.10 mm though --1.69 mm, for comparison purpose only the -1.69 mm is considered.

From the figure, the maximum deflection experienced by the pipe at the joint was recorded during the full truckload break application scenario (-1.69 mm vertical and 1.24 mm horizontal). The maximum vertical deflection at the pipe ends were recorded during the full truckload at stationary on the trench top (-2.22 mm) and maximum horizontal deflection at the pipe end was recorded during the full truckload break application scenario.

The iPVC pipe maximum deflection from field data, deflection obtained from the theoretical equations has demonstrated pipe performance against the vertical load acting on the pipe at the joint. The maximum deflection at the pipe ends during the experiment is slightly higher than the theoretical. This may be due to the pipe being suspended freely at the ends without continuation could have added additional deflection to the pipe.

Table 6.5
Earth load comparison of field test data and calculations

Earth Load Only at Joint	Vertical/Horizontal	Field Test	Spangler's Equation	Modified Iowa Equation
Deflection (mm)	Vertical	-0.89	-0.94	-1.09
	Horizontal	0.92	0.94	1.09
Earth Pressure (psi)	Vertical	3.20	4.17	4.17
	Horizontal	2.60		
Earth Load Only at Pipe End	Vertical/Horizontal	Field Test	Spangler's Equation	Modified Iowa Equation
Deflection (mm)	Vertical	-1.07	-0.94	-1.09
	Horizontal	0.78	0.94	1.09
Earth Pressure (psi)	Vertical	4.76	4.17	4.17
	Horizontal	2.57		

Table 6.6
Live and earth load comparison of field test data and calculations

Live & Dead Load at Joint	Vertical/Horizontal	Field Test	Spangler's Equation	Modified Iowa Equation
Deflection (mm)	Vertical	-1.69	-1.33	-1.55
	Horizontal	1.24	1.33	1.55
Earth Pressure (psi)	Vertical	6.97	5.91	5.91
	Horizontal	2.56		
Live & Dead Load at Pipe End	Vertical/Horizontal	Field Test	Spangler's Equation	Modified Iowa Equation
Deflection (mm)	Vertical	-2.23	-1.33	-1.55
	Horizontal	1.63	1.33	1.55
Earth Pressure (psi)	Vertical	6.95	5.91	5.91
	Horizontal	3.98		

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

7.1.1 Summary

The results from standard tests (fatigue, impact, short-term burst pressure, stiffness, and tensile tests) considered in this research confirmed that the iPVC pipe is suitable for use in the North American Water industry. Users can expect the pipe to be more robust during handling, installation, and in operation than conventional PVC. The pipe is projected to have a very long life based on fatigue tests. During the formal fatigue test, minimum changes in the circumferential dimensions and no failure observed after 2.23 million cycles of high-pressure surges and the pipe tested was extended to 4 million cycles. An issue thought to shorten the life of standard PVC is the impact of surge.

One of the concerns for users of conventional PVC is that the pipe failures tend to propagate into a failure that runs the length of the pipe. Such longitudinal failures tend to cause more water loss, more damage and have higher repair costs than other types of breaks on other types of pipe. The hydrostatic burst tests performed on this pipe in this project do suggest that the PPII pipe offers more strength longitudinally to the pipe. Catastrophic fracturing with high-speed build-up of pressure were multi-directional. Slower build of pressure caused the pipe to expand before splitting slightly with minimal leakage.

The bedding test confirmed that the pipe performs well under load with slight deformation in a poor soil backfill. This suggests that a need for imported backfill is reduced to extremely poor material and heavy live load or as required by local conditions. The researchers validated the use of the Modified Iowa equation by field tests to evaluate the need of special backfill.

The pilot installations demonstrated that the iPVC pipe installation is much like conventional PVC pipe. The challenge remains for the researchers to evaluate the economic benefits that may manifest in reduced construction requirements for backfill and increased strength that would translate into longer life and resistance to wear and tear from surge, load, and changing conditions.

7.1.2 Conclusions from Burst Test

The average (UTA and Microbac results) burst failure pressure 1,051.5 psi and burst failure time was 103 seconds for iPVC. The results exceed the AWWA requirements by 40% in pressure but with a 76% increase to the failure time. The extended failure pressure supports improved performance over an extended life.

During burst test, two types of failures were observed. There were failures characterized as catastrophic where the pipe literally shattered in multiple directions. There were failures called ductile failure as the iPVC pipe expanded before showing a split or pinhole. The catastrophic failure suggests that the pipe has strength in multiple directions, as it showed no particular single directional path of breaking. The pinhole leak and pipe ballooning seen in the ductile failures suggest the pipe is more ductile and may provide warning of failure with dimensional change.

The level of performance was well in excess of conventional PVC pipe. The calculated hoop stress was 8,855 psi; this is 38% higher than the minimum AWWA hoop stress requirement

of 6,757 psi for DR 18 PVC pipe. The higher hoop stress supports the premise that the pipe is far more resistant to surge as well as constant higher internal pressures.

7.1.3 Conclusions from Impact Test

The impact test conducted at 73°F failed to break the iPVC pipe samples feet with tup weighing 100 pounds drop from a height of 12 feet (maximum height and weight available at the plastics testing laboratory). The impact energy of 1200 foot-pounds is 12 times stronger than the recognized conventional PVC criteria. Only, one specimen broke at 673 foot-pounds; researchers suspect, this outlier might be a manufacturing defect or flaw induced from shipping samples from Korea.

The lab conducted the impact test at 32 °F in order to gauge the pipe performance in a more adverse environment, acknowledging that PVC is more brittle in colder temperatures. The pipe samples failed between 889 foot-pounds and 1,040 foot-pounds with an average impact value of 923 foot-pounds, still about 9 to 10 times stronger than the recognized conventional PVC manufactured in USA. This represents at least a 15% strength reduction with a 40-degree drop in the temperature.

The improved resistance to the impact of iPVC pipe suggest the pipe is rugged and provides confidence, that the pipe can assist handling and installation procedures (tapping, cutting and pipe laying) especially during the cold season's installation. The higher resistance can benefit the damage due to accidental struck in subsequent excavation by the third party.

7.1.4 Conclusions from Stiffness Test

The stiffness test provides insights of the iPVC pipe ruggedness for vertical loading acting directly on the pipe. The stiffness test for iPVC pipe at 95% pipe OD deflection is 451 psi and exceeds AWWA minimum deflection by 24% indicating the pipe can perform well under loading acting directly on to the pipe. The lab saw no cracking or failure of the pipe at the 60% pipe OD (AWWA requirement) level. The experiment was continued to less than 20% pipe OD until the top and bottom of the pipe were in contact. An average load of 10,500 pounds was applied at 20% and beyond deflection and there was no evidence of failure or cracking at this extreme.

This resilience under load suggests that the iPVC may be better able to support increased deflection. The 5% deflection level for PVC design is based upon the characteristics of conventional PVC. This pipe may support a 10% deflection though this is only speculation. Nevertheless, the higher pipe stiffness results in decreased deflection of pipe, decreased reliance on soil to carry the load to minimize deflection and less distortion of pipe shape

7.1.5 Conclusions from Tensile Test

The average tensile strength and modulus of elasticity of the iPVC material exceeded the standard by 13% and 15% percent respectively. The higher tensile strength can influence the pressure capacity during lower operating temperature. The tensile test was performed using type I and type III samples but the type I samples were found to be most appropriate.

7.1.6 Conclusions from Fatigue Test

The pipe did not fail after completion of 2.3 million cycles for induced pressure between 150 psi to 225 psi in an interval 10 seconds to 12 seconds at rate of 5 to 6 cycles per minute. The

iPVC pipe has experienced small change in its circumferential diameter (5 mm. or 0.2 inches only) primarily with pressurizing the pipe. The pipe has provided excellent resistance for the operated surge pressure. The allowable (maximum) surge for iPVC pipe at 2 feet per second water velocity is 37 psi. Calculations were made here based upon 2.3 million cycles although the test has continued towards a new goal of 4 million cycles (currently 2.95 million cycles). Considering 50 surges per day and excluding the influence of operational parameters on the pipe, the service life of 8 inches DR 18 iPVC pipe was predicted as 122.5 years if surge is the primary driver for pipe failure.

7.1.7 Conclusions from Bedding Test

The maximum deflection at the joint recorded was negative 1.69 mm vertical and 1.24 mm horizontal under vertical earth pressure of 7.55 psi induced during braking of fully loaded truck scenario. The maximum deflection at the free end of pipe recorded was 2.22 and 1.59 under vertical earth pressure of 5.39 psi induced during the fully loaded truck at stationary scenario. The maximum deflection was approximately 1.1% ID deflection where 5% is permitted.

Due to the pipe being suspended freely without continuation, the maximum deflection at the pipe ends are higher than the maximum deflection of the pipe at the joint and represent a worst-case scenario. There was good correlation with Spangler and modified Iowa equations.

7.1.8 Conclusions from Pilot Installations

Missouri American Water installed 1500 feet of pipe and found that the installation procedures such as tapping, trimming and pipe handling of the iPVC pipe similar to the conventional PVC pipe installation. Some modifications were made as a result of the installation. The longer beveled ends at the spigot, which assisted in the pipe joining during installation presented issues to directly connect with mechanical joint fittings (short piece was trimmed to achieve joints with fitting). The installed pipe continues to be monitored. This includes about 200 feet of pipe that was backfilled using native soil to verify iPVC pipe performance with “substandard” backfill.

New Jersey American Water installed 2000 feet of iPVC pipe and confirmed that the installation is straightforward. The pipe was installed with a municipal street unlike the pipe in St. Louis County, MO that was mostly off road. PPII introduced a new gasket from Germany designed for PVC-O pipe that allowed for deflecting the pipe at the joint and easy disconnect of pipe after the pipe was connected. This raised an interesting option to deflect pipe at the joint that had not been part of the PPII installation guidelines.

7.2 FUTURE RECOMMENDATIONS

Throughout the testing of the iPVC pipe, there was a strong desire on the part of the researchers to make comparisons with other products particularly the thinner walled extruded PVC-O pipe. It was somewhat surprising to find a lack of published testing results on the PVC products given the performance of the material across the water industry. The limited funding for this project were heavily invested in describing the character of iPVC and not the other products. It is recommended that the WRF engage in some comparative testing but the researchers believe it is incumbent upon the manufacturers to make third party testing available particularly if the product significantly exceeds AWWA standards. The results in this study is compared with the

AWWA requirements; a similar study of iPVC pipe, AWWA PVC C900 and C909 (North American manufacturer) may assist the utilities across the North America in selection of PVC pipe for drinking water application

Testing was limited and more opportunities do exist. The entire test in this research project was performed on an 8-inch DR 18 iPVC pipe. A different diameter size and different DR levels could be studied to verify any variations in the test results. The iPVC pipe proved very difficult to test completely. The impact test at 73 F on the iPVC pipe did not experience failure; this test should be repeated to quantify the actual impact load at failure.

The bedding test was performed on the native locally available soil; this test may be repeated in different types of soils and bedding materials with controlled laboratory testing and with highway simulation (similar to this research study). The bedding test was conducted on an empty pipe. Future tests can be performed on pressurized to understand deflection under live load with internal forces also at work. The bedding test setup did not have sensors to measure the temperature change in the soil. It would have been interesting to measure the impact of temperature on the deformation of iPVC pipe in the field.

More experimentation with gasketed joints should be considered. It appears that the pipe can be deflected at the joints. It should be possible to perform analysis of restrained joints. Pyungwha Pipe Industry (PPII), manufacturer of iPVC pipe, has assessed the seismic property of iPVC pipe and concluded that the product is safe at potential seismic zones (up to magnitude 7 on the Richter scale) and soft ground conditions. A full-scale testing program to assess the seismic performance of iPVC pipe should be conducted to verify the results obtained by PPII.

The current fatigue test continues with a goal of 4 million cycles. The testing has been conducted on a 10-foot joint less pipe and variations in pipe length could be tested. Perhaps the immediate testing to consider is a retest of the pipe currently undergoing surge to see how the characteristics of the pipe have changed.

The 200 feet pipe installation outside AWWA C605 requirements at MOAW must be verified by conducting tests after anticipated $\frac{1}{4}$ designed service life of pipe. This may assist to understand performance or anomalies (any decrease in the strength) of the pipe.

APPENDIX A

IPVC PIPE TEST SUPPLEMENTARY DATA

IMPACT TEST DATA

Table below presents the information for the additional test conducted outside the research scope.

Table A.1
Impact test result at 32 °F at Microbac

Specimen	Weight Pounds	Height Feet	Impact Energy Foot-Pounds	Results
O	85	11.2	953	Pass
M	85	10.5	889	Pass
J	85	11.0	932	Pass
D	85	11.5	974	Pass
C	85	11.5	974	Pass
BR	85	10.5	889	Fail
BO	40	10.8	433	Pass
BM	85	10.0	847	Pass
BK	85	10.5	889	Pass
BI	85	10.5	889	Fail
BB	85	10.5	889	Fail
B	85	10.5	889	Pass
AY	85	10.5	889	Pass
AT	85	10.2	868	Pass
AR	85	10.5	889	Fail
AO	40	11.1	443	Pass
AM	85	11.5	974	Pass
AL	85	10.7	910	Pass
AH	85	10.5	889	Pass
AH	85	10.7	910	Pass
AF	85	10.5	889	Pass
AE	85	10.7	910	Fail
AD	85	11.2	953	Fail
AC	85	10.5	889	Pass
AA	85	10.5	889	Fail

STIFFNESS TEST DATA

Figure below presents the load vs deflection relationship for the specimens tested at Microbac Lab.

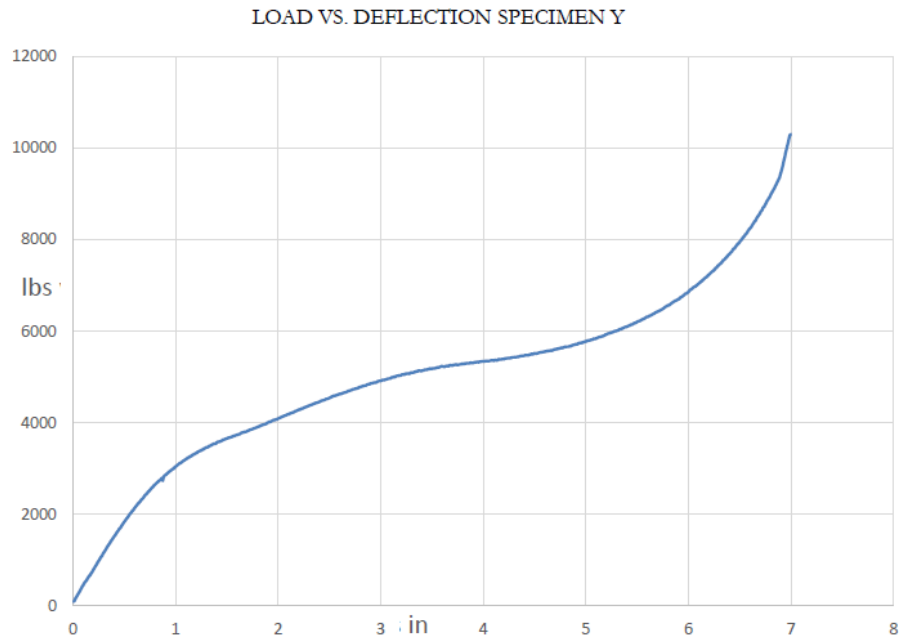


Figure A.1 Load vs deflection for specimen Y

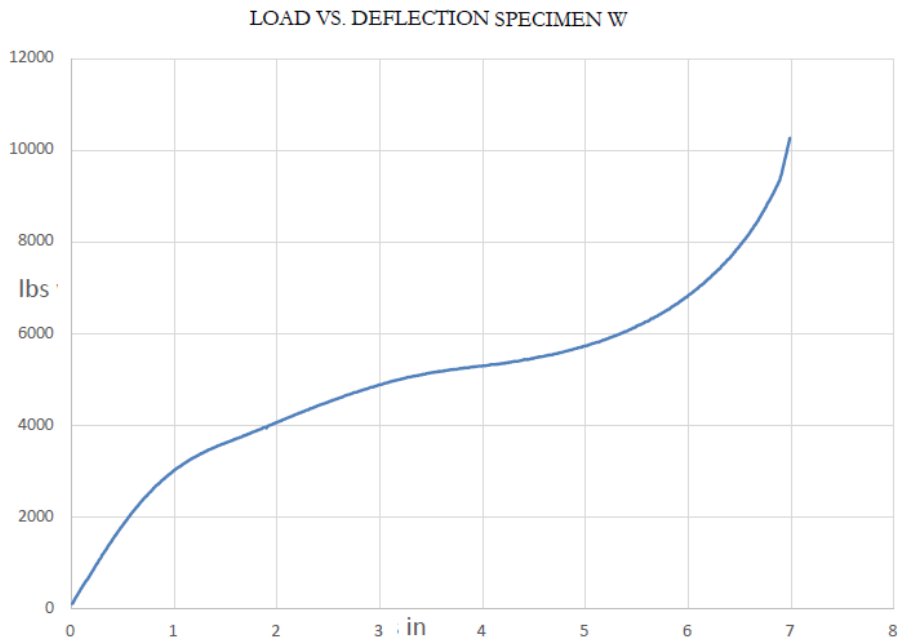


Figure A.2 Load vs deflection for specimen W

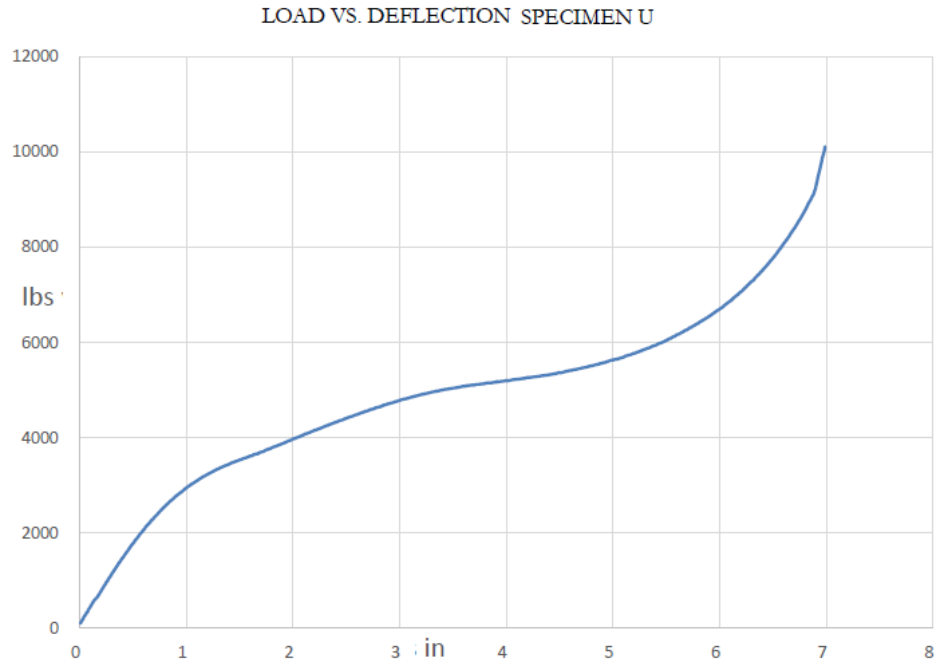


Figure A.3 Load vs deflection for specimen U

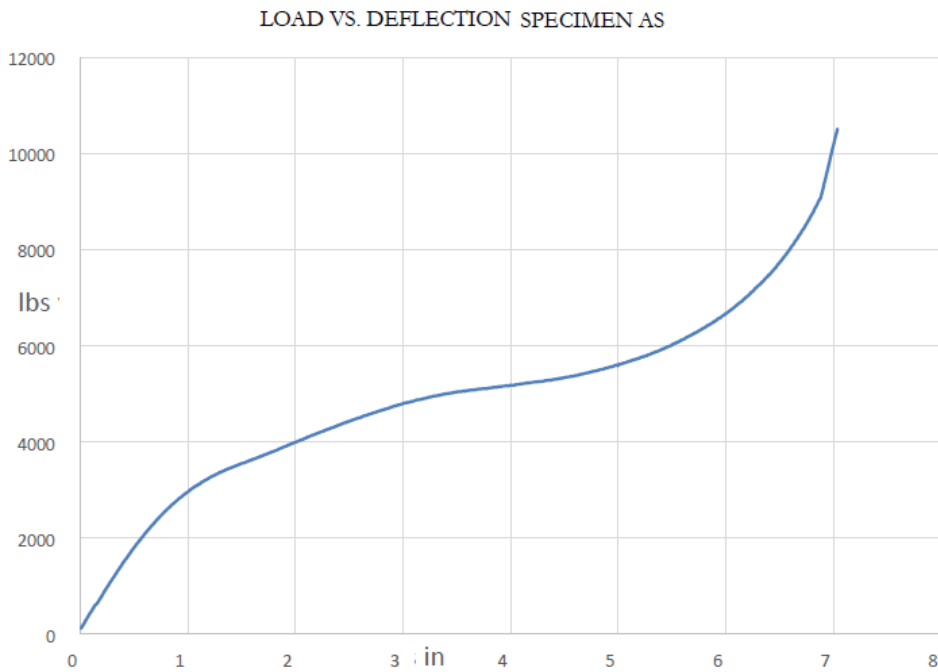


Figure A.4 Load vs deflection for specimen AS

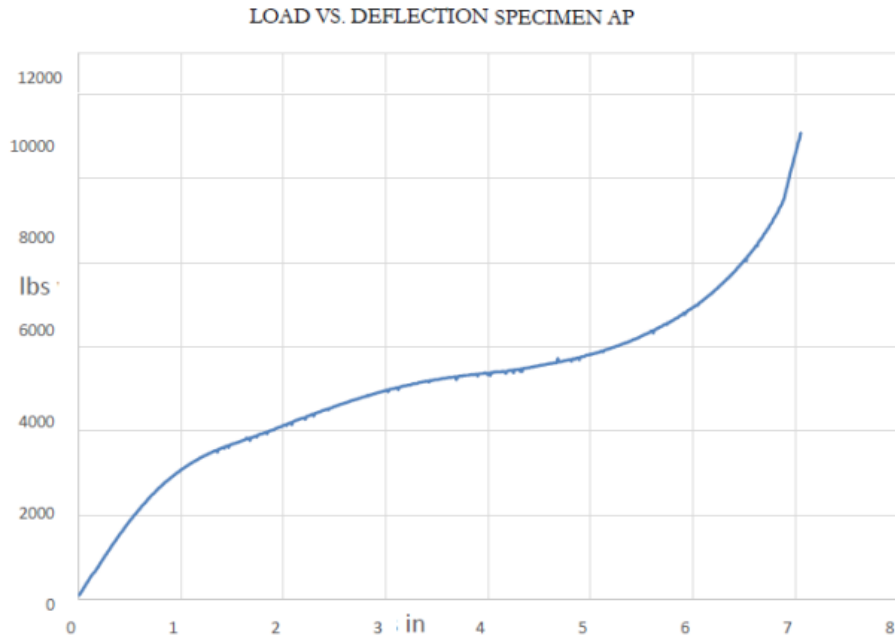


Figure A.4 Load vs deflection for specimen AP

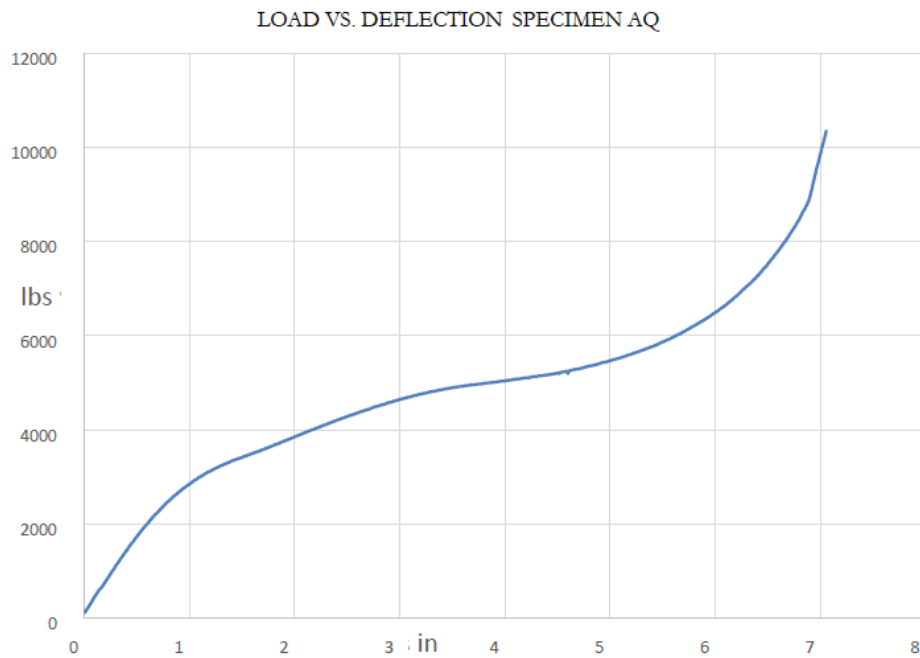


Figure A.5 Load vs deflection for specimen AQ

APPENDIX B

BEDDING TEST SPECIFICATIONS AND STRAIN DATA

BEDDING TEST INSTRUMENTATION

The figures below present the instrumentation used during the bedding test.



Source: Courtesy of Geokon.

Figure B.1 Geokon earth pressure cell

Technical Specifications							
	4800	4810	4815	4820	4830	4855	3500
Transducer Type	Vibrating Wire	Vibrating Wire	Vibrating Wire	Vibrating Wire	Vibrating Wire	Vibrating Wire	Semiconductor
Output	2000-3000 Hz	2000-3000 Hz	2000-3000 Hz	2000-3000 Hz	2000-3000 Hz	2000-3000 Hz	2 mV/V, 0-5 VDC or 4-20 mA
Standard Ranges ¹	70, 170, 350, 700 kPa; 1, 2, 3, 5, 7.5, 20 MPa	350, 700 kPa; 1, 2, 3, 5 MPa	350, 700 kPa; 1, 2, 3, 5 MPa	350, 700 kPa; 1, 2, 3, 5 MPa	70, 170, 350, 700 kPa; 1, 2, 3, 5 MPa	2, 3, 5, 7.5, 10, 20 MPa	100, 250, 400, 600 kPa; 1, 2, 5, 6 MPa
Over Range	150% F.S. (max)	150% F.S. (max)	150% F.S. (max)	150% F.S. (max)	150% F.S. (max)	150% F.S. (max)	150% F.S. (max)
Resolution	±0.025% F.S.	±0.025% F.S.	±0.025% F.S.	±0.025% F.S.	±0.025% F.S.	±0.025% F.S.	Infinite
Accuracy ²	±0.1% F.S.	±0.1% F.S.	±0.1% F.S.	±0.1% F.S.	±0.1% F.S.	±0.1% F.S.	±0.5% F.S.
Linearity	< 0.5% F.S.	< 0.5% F.S.	< 0.5% F.S.	< 0.5% F.S.	< 0.5% F.S.	< 0.5% F.S.	< 0.5% F.S.
Thermal Effect on Zero	< 0.05% F.S.	< 0.05% F.S.	< 0.05% F.S.	< 0.05% F.S.	< 0.05% F.S.	< 0.05% F.S.	< 0.05% F.S.
Typical Long-Term Drift	< 0.02% F.S./yr	< 0.02% F.S./yr	< 0.02% F.S./yr	< 0.02% F.S./yr	< 0.02% F.S./yr	< 0.02% F.S./yr	< ±0.02% F.S./yr
Cell Dimensions ³ (H × D)	6 × 230 mm	12 × 230 mm	26 × 230 mm	12 × 150 mm	12 × 150 mm	50 × 600 mm	6 × 230 mm
Transducer Dimensions (L × D)	150 × 25 mm	150 × 25 mm	150 × 25 mm	150 × 25 mm	150 × 25 mm	(included in above)	150 × 32 mm
Excitation Voltage	2.5-12 V swept square wave	2.5-12 V swept square wave	2.5-12 V swept square wave	2.5-12 V swept square wave	2.5-12 V swept square wave	2.5-12 V swept square wave	10 V maximum
Excitation Frequency	1400-3500 Hz	1400-3500 Hz	1400-3500 Hz	1400-3500 Hz	1400-3500 Hz	1400-3500 Hz	n/a
Material	316 Stainless Steel	316 Stainless Steel	316 Stainless Steel	316 Stainless Steel	316 Stainless Steel	316 Stainless Steel	316 Stainless Steel
Temperature Range ¹	-20°C to +80°C	-20°C to +80°C	-20°C to +80°C	-20°C to +80°C	-20°C to +80°C	-20°C to +80°C	-20°C to +80°C

Note: PSI = kPa × 0.14503, or MPa × 145.03
¹ Other ranges available on request.
² Stated accuracy is for the pressure transducer alone. The total system accuracy (pressure transducer + pressure cell) is subject to site-specific variables.
³ Other sizes available on request.

Source: Courtesy of Geokon.

Figure B.2 Technical specification of the Geokon earth pressure cell



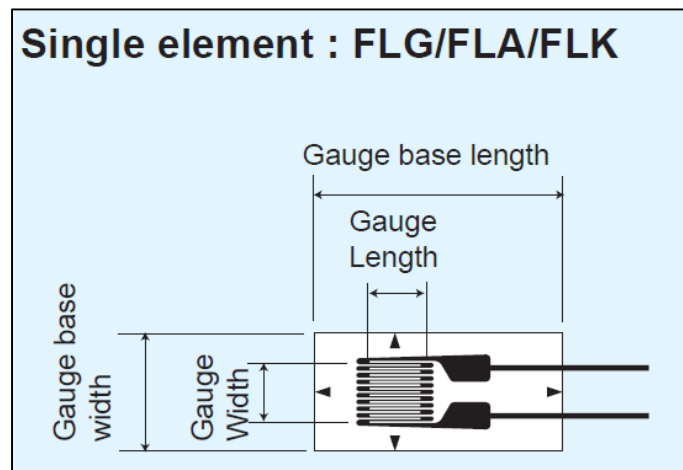
Source: Courtesy of Vishay Precision Group.

Figure B.3 Vishay deflectometer (used as displacemnet sensors)

SPECIFICATIONS							
MODEL		CDS-05	CDS-10	CDS-20	CDS-30	CDS-40	CDS-50
Measurement Range	in [mm]	5 [127 mm]	10 [254 mm]	20 [508 mm]	30 [762 mm]	40 [1016 mm]	50 [1270 mm]
Accuracy	% FS	0.25	0.15	0.10	0.10	0.10	0.10
Resolution				Analog (Effectively infinite, limited only by instrumentation)			
Repeatability				Greater of ± 0.001 in [± 0.025 mm] or 0.02% FS			
Cable Retraction Force (min)	oz. [N]	3.5 [1.0]	8.4 [2.3]	8.4 [2.3]	6.3 [1.8]	4.2 [1.1]	3.5 [1.0]
Cable Extension Force (max)	oz. [N]	6.5 [1.8]	15.6 [4.3]	15.6 [4.3]	11.7 [3.3]	7.8 [2.2]	6.5 [1.8]
Cable Acceleration	g	3	11	11	5	4	3
Vibration	g, Hz	Up to 10, 0 - 2000					
Shock	g, mS	100, 0.1					
Sensor		Plastic-hybrid precision potentiometer					
Resistance	ohms	500					
Maximum Supply Voltage - Potentiometer	V	30					
Maximum Supply Voltage - Bridge	V	30					
Output - Bridge	mV/V FS	3.0 typical					
Case		Powder-painted aluminum alloy					
Cable		Nylon-coated stainless steel, 0.019 in [0.48 mm] diameter					
Electrical Connector		RJ-45 receptacle					
Weight	lb [kg]	2 [1] typ.					
Operating Temperature	°F [°C]	- 40 to + 200 [- 40 to 93]					
TC of Sensor	ppm/°F [ppm/°C]	88 [157]					
Humidity	% RH	100 at 90 °F [32 °C]					

Source: Courtesy of Vishay Precision Group.

Figure B.4 Technical specifications of the Vishay deflectometer



Source: Courtesy of Tokyo Sokki Kenkyujo Co., Ltd.

Figure B.5 Strain gauges from Tokyo Sokki Kenkyujo Co., Ltd.

Type	Gauge length (mm)	Gauge width (mm)	Backing length (mm)	Backing width (mm)	Resistance (Ω)	Lead wire pre-attached	Type name of lead wire preattached
FLA-1-11 FLA-1-17 FLA-1-23	1	1.3	5	2.5	120	Paralleled 1m Paralleled 3m Paralleled 5m 3-wire 3m 3-wire 5m	-1L -3L -5L -3LT -5LT
FLA-2-11 FLA-2-17 FLA-2-23	2	1.5	6.5	3	120	Paralleled 1m Paralleled 3m Paralleled 5m 3-wire 3m 3-wire 5m	-1L -3L -5L -3LT -5LT
FLA-3-11 FLA-3-17 FLA-3-23	3	1.7	8.8	3.5	120	Paralleled 1m Paralleled 3m Paralleled 5m 3-wire 3m 3-wire 5m	-1L -3L -5L -3LT -5LT
FLA-5-11 FLA-5-17 FLA-5-23	5	1.5	10	3	120	Paralleled 1m Paralleled 3m Paralleled 5m 3-wire 3m 3-wire 5m	-1L -3L -5L -3LT -5LT
FLA-6-11 FLA-6-17 FLA-6-23	6	2.2	12.5	4.3	120	Paralleled 1m Paralleled 3m Paralleled 5m 3-wire 3m 3-wire 5m	-1L -3L -5L -3LT -5LT

Source: Courtesy of Tokyo Sokki Kenkyujo Co., Ltd.

Figure B.6 Technical specifications of strain gauges from Tokyo Sokki Kenkyujo Co., Ltd.

Technical Specifications			
	Single-Channel	4-Channel	16-Channel
	LC-2, LC-2A	LC-2x4	LC-2x16
Measurement Accuracy	±0.05% F.S. (450-4000 Hz)	±0.05% F.S. (450-4000 Hz)	±0.05% F.S. (450-4000 Hz)
Measurement Resolution	1 part in 20,000	1 part in 20,000	1 part in 20,000
Program Memory	24K FLASH	24K FLASH	24K FLASH
Data Memory	320K EEPROM	320K EEPROM	320K EEPROM
Data Connection	RS-232, USB or RS-485	RS-232, USB or RS-485	RS-232, USB or RS-485
Storage Capacity (Arrays)	16,000 ¹	10,866	3,555
Temperature Range	-30°C to +50°C	-30°C to +50°C	-30°C to +50°C
Temperature Measurement	(accuracy) 2.0% F.S. (resolution) 0.1°C	(accuracy) 2.0% F.S. (resolution) 0.1°C	(accuracy) 2.0% F.S. (resolution) 0.1°C
Communication Speed	9600 bps	9600 bps	9600 bps
Communication Parameters	8 data bits, no parity, 1 stop bit	8 data bits, no parity, 1 stop bit	8 data bits, no parity, 1 stop bit
Power Supply	3 VDC (2 Alkaline 'D' cells)	3 VDC (2 Alkaline 'D' cells)	3 VDC (4 Alkaline 'D' cells)
Communication Current	< 100 mA	< 100 mA	< 100 mA
Measurement Current	< 200 mA	< 200 mA	< 200 mA
Quiescent Current	< 500 µA	< 500 µA	< 500 µA
Scan Interval	3 - 86,400 seconds (24 hours)	10 - 86,400 seconds (24 hours)	30 - 86,400 seconds (24 hours)
Operating Time (20°C)	3 days - 3 years, depending on scan interval	8 days - 2 years, depending on scan interval	8 days - 2 years, depending on scan interval
Sensor Connection	(LC-2) Hard wired (LC-2A) 10-pin Connector	Hard wired	Hard wired
L x W x H	122 x 120 x 91 mm	260 x 160 x 91 mm	318 x 277 x 159 mm ²

¹8,000 arrays when used with LogWare software.

²Does not include mounting flange.

Source: Courtesy of Geokon.

Figure B.7 Technical specifications of Geokon™ 8002.16

LCD DISPLAY
64 x 128 white LED-backlit display

LED PANEL
32 individual red/green LEDs; one per channel

KEYPAD
Membrane. 20-key; 12-key numeric keypad, 5 key navigation keypad, and three soft-keys

INPUT POWER
11–32 VDC, 30A max

POWER INDICATION
Green LED (illuminated when power is on)

ETHERNET INTERFACE
IEEE 802.3, 802.3u 10Base-T, 100Base-TX, half- and full-duplex, auto-detect

COMPACT FLASH® CAPACITY
1 GB supplied (removable)

PROCESSOR
250 MHz floating point digital signal processor

MEMORY
64 MB SDRAM

INTERNAL COMMUNICATION
Asynchronous command bus, synchronous data bus

SYSTEM SYNCHRONIZATION
Connections: Sync In, Sync Out
Topology: Daisy-chain
Cable Connection: TIA/EIA RJ-45, Category 5
Max. Distance: 100m

SYSTEM CALIBRATION REFERENCE
Firmware-controlled
Drift: 1.9 ppm/°C ± 0.6 µV/°C typical, 9.4 ppm/°C ± 2.1 µV/°C maximum
Resolution: 150 µV nominal
Voltage Range: ±5V

DIMENSIONS
7.5 H x 7.1 W x 13.5 D in (190 x 180 x 343 mm)

WEIGHT
10.1 lb (4.6 kg)

STRAIN GAGE INPUT CARDS

A choice of two Strain Gage Input Cards (7003-8-SG or 7003-8-SG-A) are used in conjunction with the Model 7003-8-A-I Analog Input Card to perform bridge excitation, bridge completion, shunt calibration, and signal conditioning for eight quarter, half, and full bridges. Note that the 7003-8-SG-A Strain Gage Input Card with Analog Output has an analog output which provides an amplified representation of the input source.

CHANNELS

Eight per card

INPUTS

Software selectable for S+/S-, VCAL+/VCAL-, or excitation

Strain Gage: 120Ω, 350Ω, 1000Ω quarter-bridges; 60Ω to 5000Ω half- and full-bridges

Input Impedance: 220 MΩ nominal each input

Source Current: ±5 nA per volt excitation

ANALOG OUTPUT (MODEL 7003-8-SG-A ONLY)

Fixed Gain: 50.3 V/V ±1%

Output Range: ±10V min

Output Load: 2000Ω min

Bandwidth: DC to 4.2 kHz (–3 dB ±0.25 dB)

MEASUREMENT RANGE AND RESOLUTION

Total range depends on excitation setting (see table).

Resolution: 0.5 µε (GF=2)

EXCITATION VOLTS	MEASURING RANGE	
	Includes Full Scale Imbalance	
	µε @ GF=2	mV/V
0	48,000	24*
0.25	100,000	50
0.5	96,000	48
0.75	70,000	35
1	48,000	24
2	24,000	12
3	16,000	8
4	50,000	25
5	40,000	20
6	35,000	17.5
7	30,000	15
8	25,000	12.5
9	20,000	10
10	20,000	10

Source: Courtesy of Geokon.

Figure B.8 Technical specifications of Geokon™ 8002-16

STRAIN GAUGE READINGS FROM BEDDING TEST

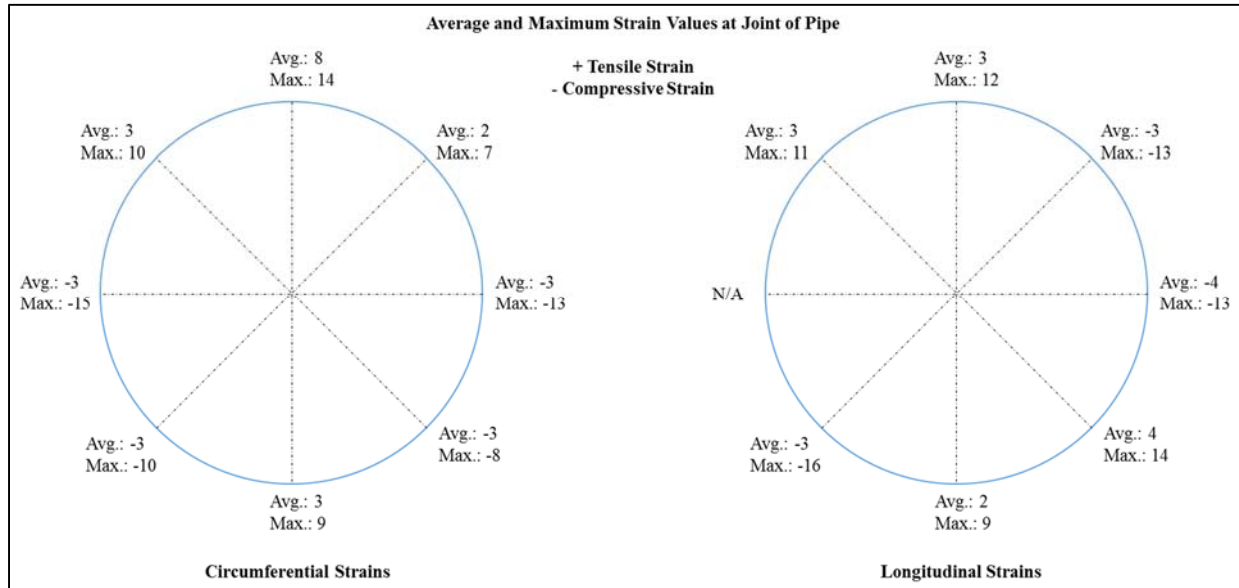


Figure B.9 Average and maximum strain at joint of pipe (units in psi)

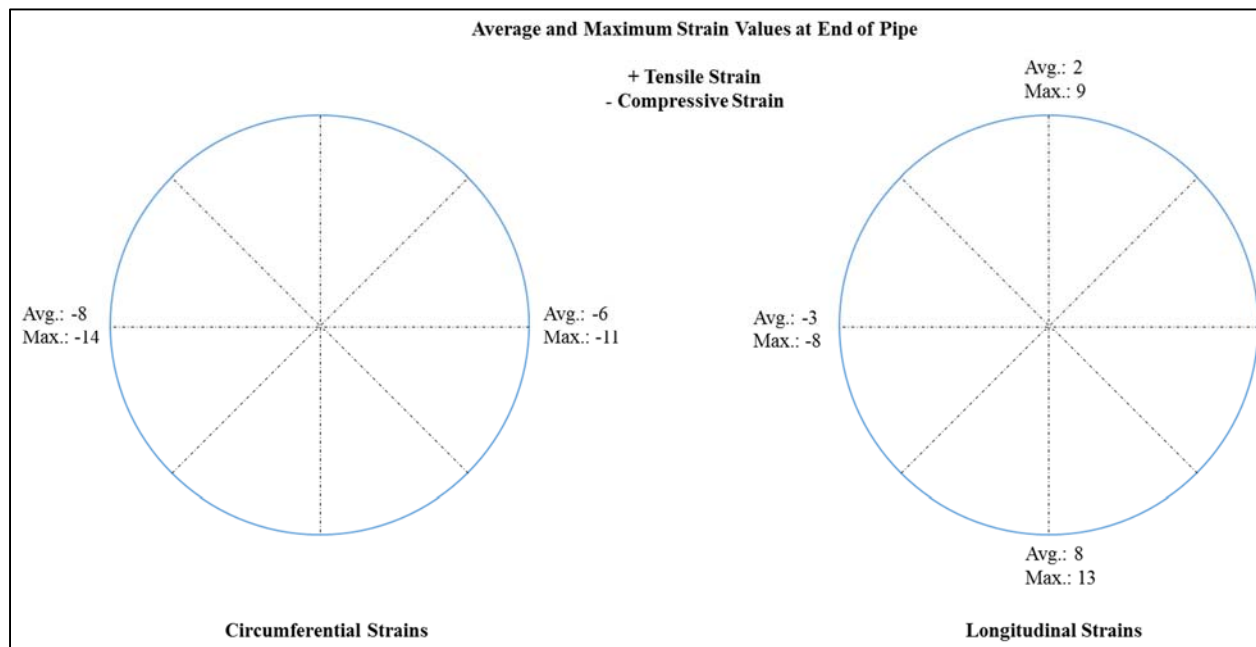


Figure B.10 Average and maximum strain at end of pipe (units in psi)

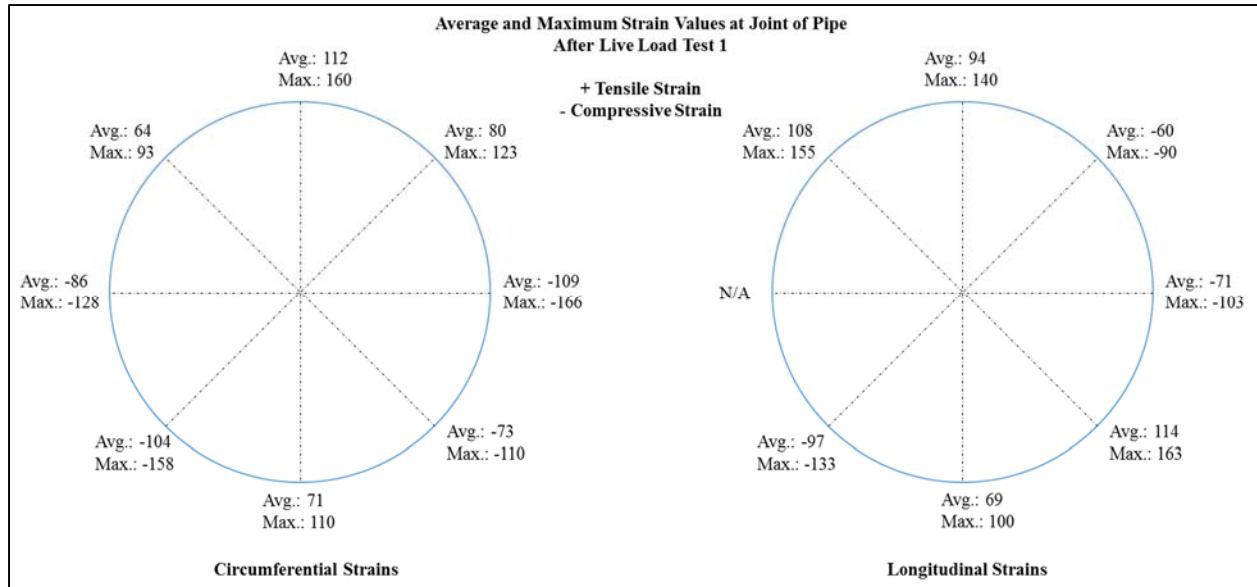


Figure B.11 Average and maximum strain at joint of pipe after live load test 1 (units in psi)

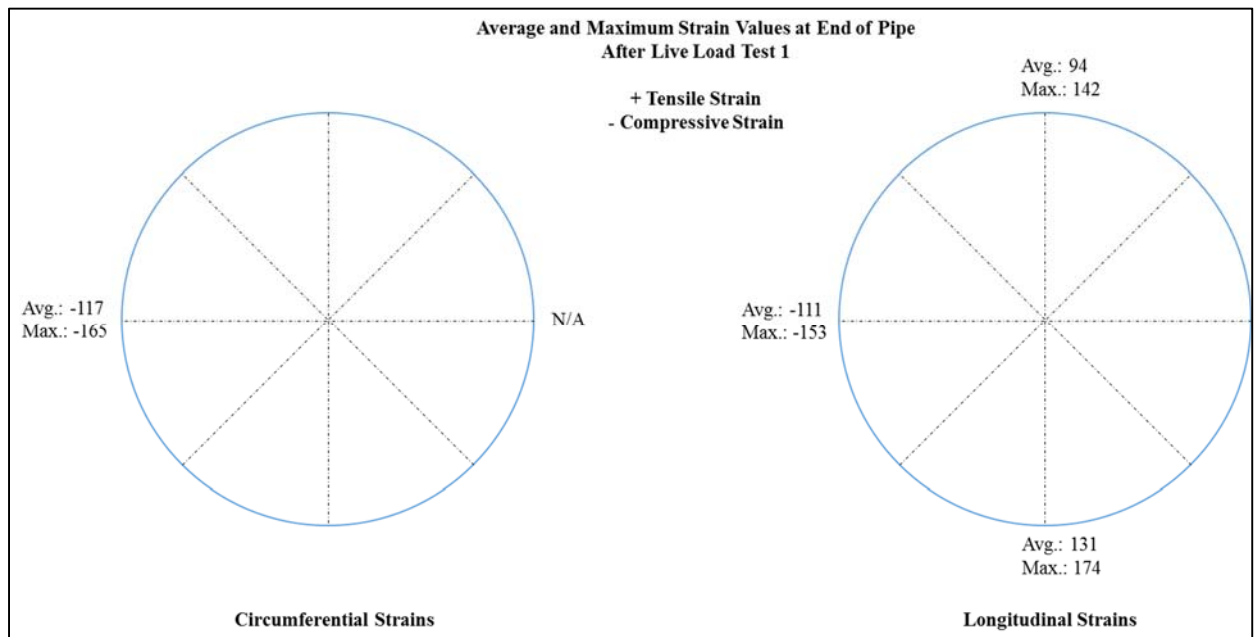


Figure B.12 Average and maximum strain at end of pipe after live load test 1 (units in psi)

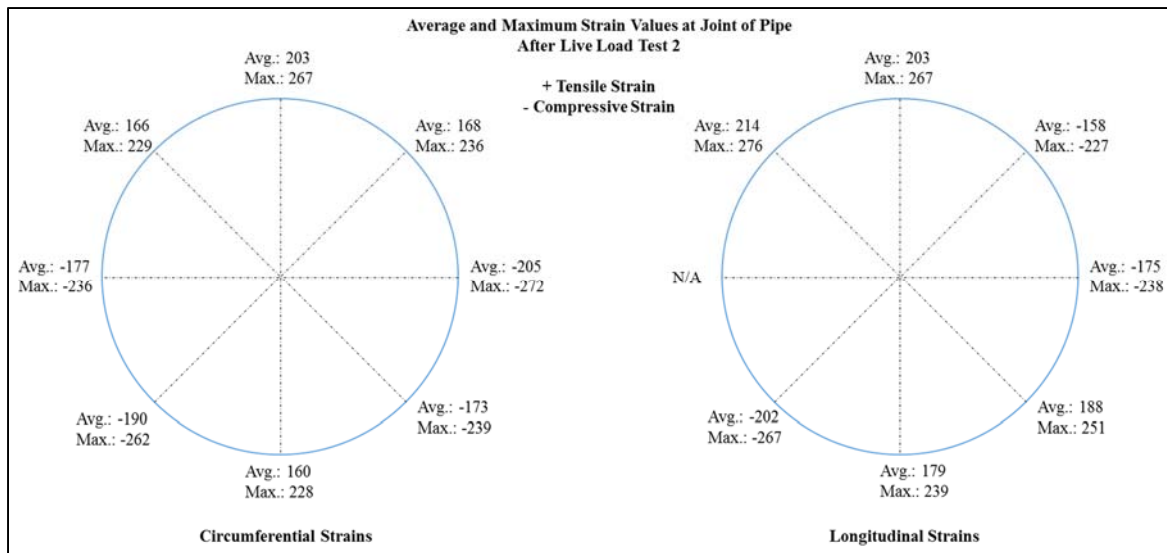


Figure B.13 Average and maximum strain at joint of pipe after live load test 2 (units in psi)

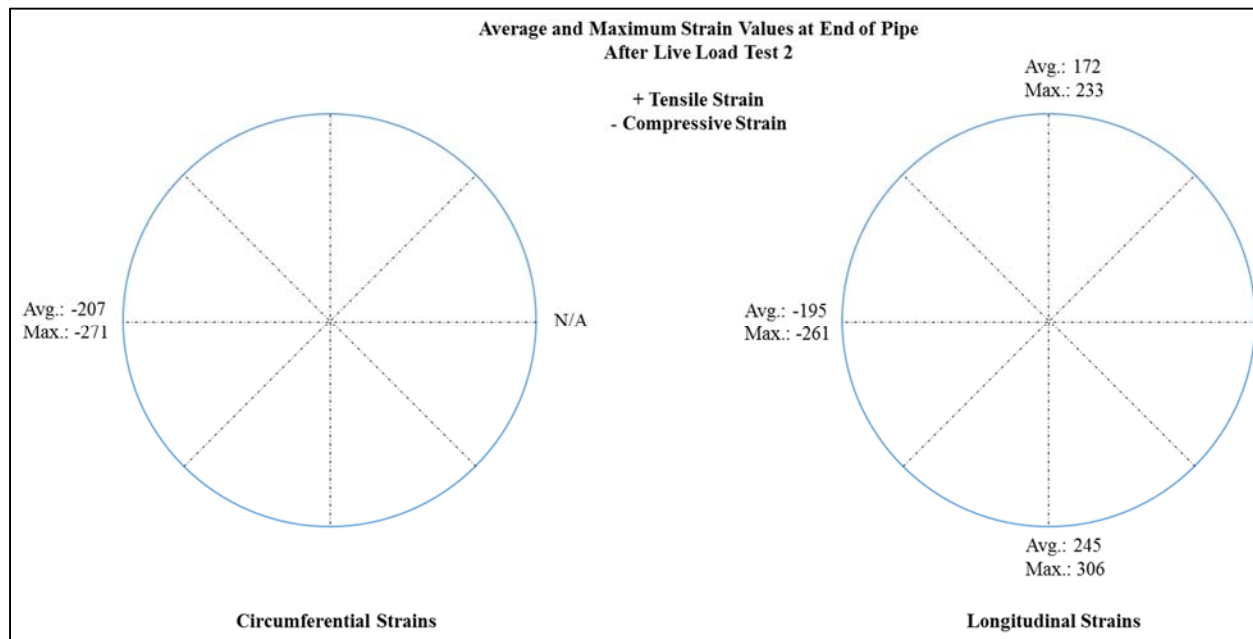


Figure B.14 Average and maximum strain at end of pipe after live load test 2 (units in psi)

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ABBREVIATIONS

AC – Asbestos-Cement Pipe
ACE – Annual Conference and Exposition by AWWA
ANSI – American National Standards Institute
ASCE – American Society of Civil Engineers
ASME – American Society of Mechanical Engineers
ASTM – American Society for Testing and Materials
AW – American Water
AWWA – American Water Works Association
AwwaRF – American Water Works Association Research Foundation

B.C. – Before Christ
BRS – Bulldog Restrained Joint System
BWP – Bar-wrapped Steel-cylinder Concrete Pipe

CDS – Cable-extension Displacement Sensor
CIP – Cast Iron Pipe
CISPI – Cast Iron Soil Pipe and Fittings Handbook
CLSM – Controlled Low Strength Material
CPVC – Chlorinated Polyvinyl Chloride Pipe
CUIRE – Center for Underground Infrastructure Research and Education

D – Mean Diameter (of pipe, which equals the average between the OD and the ID)
DIP – Ductile Iron Pipe
DIPRA – Ductile Iron Pipe Research Association
DR – Dimension Ratio
DS – Displacement Sensor

EPC – Earth Pressure Cell

FEA – Finite Element analyses
FEM – Finite Element Model
FHWA – Federal Highway Administration

GRP – Glass Reinforced Pipe

HDB – Hydrostatic Design Basis
HDD – Horizontal Directional Drilling
HDPE – High Density Polyethylene Pipe
HDS – Hydrostatic Design Stress
HS – High Strength Wire

ID – Inside Diameter
iPVC pipe – Structurally enhanced/ Innovative PVC Pipe

JSWA – Japanese Sewage Works Association

LPT – Linear-Position Transducer

LTHS – Long-Term Hydrostatic Strength

LVDT – Linear Variable Differential Transformer

MDPE – Medium Density Polyethylene Pipe

MOAW – Missouri American Water

NASTT – North American Society for Trenchless Technology

NRCC – National Research Council of Canada

OD – Outside Diameter

PA1 – Polyamide 1

PA2 – Polyamide 2

PC – Pressure Class

PCCP – Prestressed Concrete Cylinder Pipe

PE – Polyethylene Pipe

PPI – Plastics Pipe Institute

PPII – Pyungwha Pipe Industry Inc. (Manufacturer of iPVC pipe)

PS – Pipe Stiffness

PVC/ PVC-U – Un-plasticized (regular) Polyvinyl Chloride Pipe

PVC-M – Modified Polyvinyl Chloride Pipe

PVC-O – Oriented Polyvinyl Chloride Pipe

RCP – Rapid Crack Propagation

RCP – Reinforced Concrete Pipe

RTP – Reinforced Thermoplastic Pipe

SEM – Scanning Electron Microscope

SF – Stiffness Factor

SG – Strain Gauge

SL – Side Load

SP – Steel Pipe

SRHDPE – Steel Reinforced High Density Polyethylene

Std. Dev. – Standard Deviation

STR – Short Term Rating

U.S. – United States

UTA – University of Texas at Arlington

UV – Ultraviolet

VCM – Vinyl Chloride Monomer

VCP – Vitrified Clay Pipe

VL – Vertical load

WRF – The Water Research Foundation

Y/T – Yield to Tensile Ratio



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