Hydraulic Field and Lab Testing of PVC Pipe

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ABSTRACT

Knowing the accurate hydraulic friction factor of a pipe is important to properly understand and design various aspects of a pressure or gravity pipeline project, such as pipe size, flow velocity, and pump size. To aid in determining values that should be used for design of PVC pipe, hydraulic laboratory testing on new PVC pipe has been performed, as well as field C-Factor testing on a 40-year-old PVC water main. This paper will provide the findings of the laboratory and field tests, and it will present how hydraulic factors, such as C-Factors, vary with Reynold's number and pipe age. This paper will also discuss the pros and cons of performing laboratory and field hydraulic tests, along with how these test results coincide with current industry recommended values.

INTRODUCTION

One of the core aspects of designing a water or wastewater pipeline is the hydraulic design. Calculations are performed to determine the appropriate pipe and/or pump size to deliver the required flow capacity. The field of pipe flow hydraulics has been studied and well understood for centuries, which has led to the development of various flow equations (Rennels, 2012). For municipal applications, the most common equations used for pressure pipe flow is the Hazen Williams Equation (Eq. 1), and for gravity flow, it is the Manning Equation (Eq. 2). The Darcy Weisbach Equation (Eq. 3) is seldom used in these applications, except when Eq. 1 & Eq. 2 are not applicable (Jones, 2008). These equations involve the use of a 'friction factor'.

$$h_f = \left[10{,}500\left(\frac{Q}{C}\right)^{1.85}\right]D^{-4.87} \tag{1}$$

$$V = \frac{1.486}{n}R^{2/3}S^{1/2} \tag{2}$$

$$h = f\,\frac{L}{D}\frac{V^2}{2g} \tag{3}$$

where:

h_f = head-loss, feet/100 feet
Q = flow rate, gpm
D = diameter, inch in Eq. 1
V = velocity, fps in Eq. 2
R = hydraulic radius, feet
S = hydraulic slope, feet per foot

h = head-loss, feet
L = length, feet
g = acceleration due to gravity, feet per second squared
C = Hazen-Williams C factor (HW-C), dimensionless
n = Manning's n factor, dimensionless
f = Darcy friction factor, dimensionless

The industry has decades of empirical flow tests to determine friction factors for various pipe materials. Yet, a difficult question still remains for designers and end-users to this day, that is, 'what is an appropriate friction factor to use for this pipeline?'

Traditionally, end-users prefer to specify a conservative friction value in their standards. This is done to account for potential roughening of the pipe wall over time due to depositional buildup or scaling, and to account for minor losses. While this can be good practice, there are issues with being too conservative. Bennett (2011) states that overestimating head-loss by being too conservative can lead to higher discharge flows than anticipated, less efficient operation of pumps, and improper installation of larger pumps, pipes, motors, and equipment than what is actually needed for the required flow rates (Bennett 2011). Additionally, the roughness coefficient of a pipe will always vary with increased flow velocity, so considering a specific intended velocity range is warranted so that an appropriate friction factor can be selected for the design of a project (Kamand 1988).

It is important for designers and end-users to understand where friction factor recommendation comes from, and how the tests were performed. Some pipe manufacturers have performed laboratory tests to develop their recommended values. The benefit of a laboratory test is that all variables are accurately controlled and measured (i.e. flow, pressure differential, etc.). The drawback is that the pipe that is tested is new, since excavating, transporting, and re-assembling used pipe in a laboratory is costly and impractical. Testing new pipe does not give the end user an understanding of how years of service can affect the pipe's hydraulic performance. For in-service pipe, a field flow test can be done. A basic set-up of such a test is shown in Figure 1.

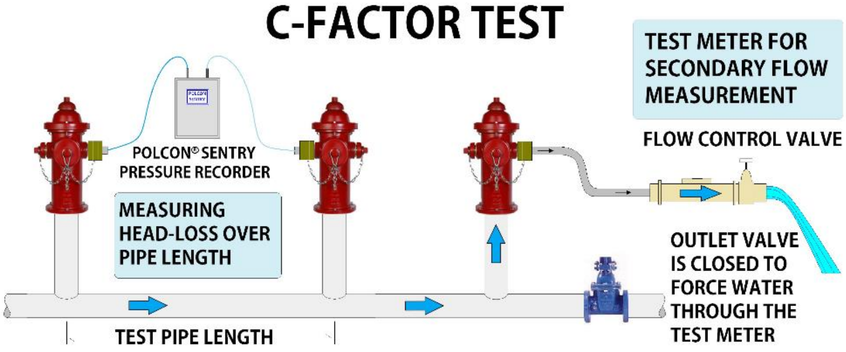

Figure 1. Field Flow Test Set-Up

Some pipe industries utilize averaged results from field flow tests as a recommended friction coefficient. While this type of test provides valuable information on how the pipe is performing, there can be many unknowns with the pipe system being tested, and measurements may not be accurate. This can lead to error in the final friction factor calculation. Some examples include unknown fittings, leaks, actual inside diameters, changes in pipe inside diameter along the pipe length, inaccurate measurements of length and elevations, air pockets in the line, etc. Knowing this, the resulting friction factors from field flow tests may not necessarily be taken as actual values to be used for that pipe material for design of future projects, nor would an average of field flow test results be considered conservative. It can, however, indicate how the pipe material's hydraulics are affected by age. Rather than determining a recommended value for general use, this test is most often used to calibrate hydraulic models or perform asset management activities (Grayman, et. al, 2006). With the pros and cons of either method, it seems that pipe manufacturers could perform both types of tests in order to develop appropriately conservative recommendations for the end-user.

In 2022, the Uni-Bell PVC Pipe Association (PVCPA) decided to undertake flow testing of PVC pipe to better understand its hydraulic performance. The goals of the testing were to measure the pipe roughness coefficient, compare the results to current industry recommendations (HW-C = 150 ; Manning's n = 0.009), and examine how the friction is affected by changes in flow velocity, pipe size, and age. On behalf of Uni-Bell PVCPA, Utah State University performed a laboratory test on new PVC pipe, and M.E. Simpson performed a field flow test on an existing PVC water main.

LABORATORY TESTING

In March 2022, the testing laboratory received 6-inch and 12-inch ASTM D3034 standard PVC gasketed joint pipe segments to use for testing. This bell and spigot pipe was selected due to its ease of setup and because its size represents typical sizes for a distribution water main.

Testing Setup. The gasketed pipe joints were assembled, and each of the test sections used a PVC flange adapter to connect to the lab's steel pipe. The distance between upstream and downstream pressure taps was 220 feet for the 12-inch test setup and 111 feet for the 6-inch test setup.

Each test section included:

- A calibrated magnetic flow meter installed in the upstream piping to accurately measure flow rates for each test run.
- A control valve to adjust flow rates passing through the test pipe.
- A pressure transmitter to make pressure-loss measurements between the upstream and downstream pressure taps, which were installed in the wall of the test pipe. Flexible tubing was used to connect each pressure tap to the high and low sides of the pressure transmitter for measurements of pressure differentials.
- Pressure taps (each consisting of a hole through the wall of the pipe with a brass fitting) to make the tubing connections. After the test pipe was installed in the laboratory flume, wood timbers were used as braces to keep the pipe straight and to hold it in position as the pipe was pressurized. The pipe was also restrained from longitudinal movement using nylon straps and binders.

Test Procedure Water was supplied to the test line from a reservoir near the hydraulics laboratory fed by the Logan River. Flow rate through the pipe and differential pressure along the length of the pipe were measured for each run. Water temperature was also measured. All flow measurements were made using either a 6-inch or a 12-inch Mag 6000® Siemens magnetic flow meter. Both magnetic flow meters were calibrated for accuracy immediately prior to the actual testing. The meter calibrations are traceable to the National Institute of Standards and

Technology and determined that the meters are within +/-0.25% accurate. Discharge was controlled using either a 6-inch or a 12-inch valve downstream of each test section.

Differential pressure measurements were taken from the pressure taps that were installed in each PVC pipe at the upstream and downstream ends of each test pipe section. Test-pipe head-loss differentials were measured using a Rosemount differential transmitter. The transmitter was carefully zeroed at a no-flow condition prior to any data collection and periodically during each test series. Transmitter output was averaged during each individual run using an averaging Fluke volt/amp meter. Appropriate ranges were set on the transmitter to minimize uncertainties as the pipe differentials changed. Measurements were immediately fed into a computer to display deviations in test results before any flow change was made. At least twelve data points were collected during each test series.

Throughout each test, constant flow was maintained through the pipe section during the run period. Each averaging period took between 3 and 5 minutes, which was long enough to:

- Allow the flow rate and differential pressure to stabilize
- Record the actual flow rate through the master magnetic flow-meter
- Record the average pressure differential.

Results. Test results are shown in Table 1 for the 6-inch PVC pipe and in Table 2 for the 12-inch pipe. The velocities range between 2 fps – 18fps. In each table, results are provided for Darcy "f," Manning's "n," and Hazen-Williams "C" coefficients. The results for these tests vary with increasing Reynolds number, which is consistent with the Moody Diagram and with other theoretical calculations. The variables that influence the resulting friction factors are:

- Fluid properties
- Fluid velocity
- Pipe inside diameter
- Relative roughness of the interior wall of the pipe

Figures 2 & 3 below illustrates the variance of the HW-C for both pipe sizes with Reynolds number. While there is a slight increase in HW-C with higher Reynolds number for a given diameter (in other words, increase in flow velocity), all HW-C values are greater than 150.

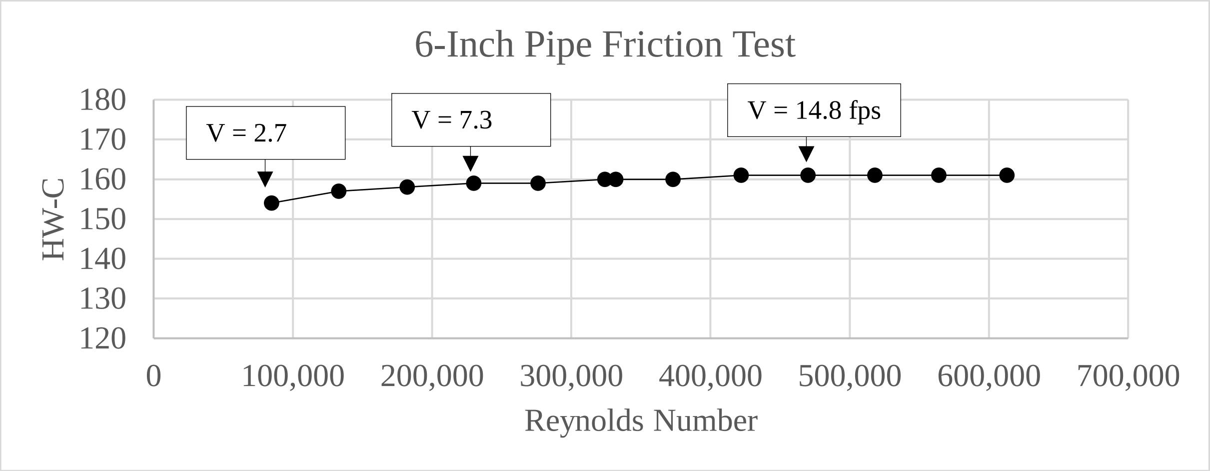

Figure 2. Laboratory HW-C Test for 6" Pipe

Table 1. Test Results for 6-Inch PVC Pipe

Run No.	Flow Volume (cfs)	Flow Velocity (fps)	Inlet Reynolds Number	Friction Loss (ft of H2O)	Friction Loss (psi)	Hydraulic Slope (ft/100 ft)	Darcy "f"	Hazen-Williams "C"	Manning's "n"
1	0.5	2.7	84,600	0.42	0.18	0.38	0.017	154	0.0085
2	0.8	4.2	133,000	0.95	0.41	0.85	0.015	157	0.0081
3	1.1	5.7	182,000	1.67	0.72	1.50	0.014	158	0.0078
4	1.4	7.3	230,000	2.54	1.10	2.29	0.014	159	0.0077
5	1.6	8.7	276,000	3.55	1.54	3.20	0.013	159	0.0075
6	1.9	10.2	324,000	4.75	2.06	4.28	0.013	160	0.0074
7	2.2	11.8	373,000	6.15	2.67	5.54	0.013	160	0.0073
8	2.5	13.3	422,000	7.67	3.33	6.91	0.013	161	0.0072
9	2.8	14.8	470,000	9.33	4.04	8.40	0.012	161	0.0072
10	3.1	16.4	518,000	11.20	4.85	10.09	0.012	161	0.0071
11	3.3	17.8	564,000	13.10	5.68	11.80	0.012	161	0.0071
12	3.6	19.3	613,000	15.20	6.60	13.69	0.012	161	0.0070
13	2.0	10.5	332,000	4.98	2.16	4.48	0.013	160	0.0074

Table 2. Test Results for 12-Inch PVC Pipe

Run No.	Flow Volume (cfs)	Flow Velocity (fps)	Inlet Reynolds Number	Friction Loss (ft of H2O)	Friction Loss (psi)	Hydraulic Slope (ft/100 ft)	Darcy "f"	Hazen-Williams "C"	Manning's "n"
1	1.5	2.0	126,000	0.23	0.10	0.10	0.017	150	0.0094
2	2.5	3.4	217,000	0.59	0.26	0.27	0.015	153	0.0089
3	3.5	4.8	304,000	1.10	0.48	0.50	0.014	154	0.0086
4	4.5	6.1	393,000	1.75	0.76	0.79	0.013	155	0.0084
5	5.7	7.7	493,000	2.66	1.15	1.21	0.013	155	0.0082
6	6.7	9.1	581,000	3.57	1.55	1.62	0.012	156	0.0081
7	7.9	10.6	679,000	4.74	2.06	2.15	0.012	156	0.0080
8	8.8	11.9	761,000	5.83	2.53	2.65	0.012	157	0.0079
9	10.0	13.5	861,000	7.30	3.16	3.31	0.012	157	0.0078
10	10.9	14.7	943,000	8.64	3.75	3.92	0.011	157	0.0078
11	12.0	16.3	1,040,000	10.40	4.49	4.72	0.011	157	0.0078
12	13.5	18.2	1,170,000	12.80	5.55	5.81	0.011	157	0.0077

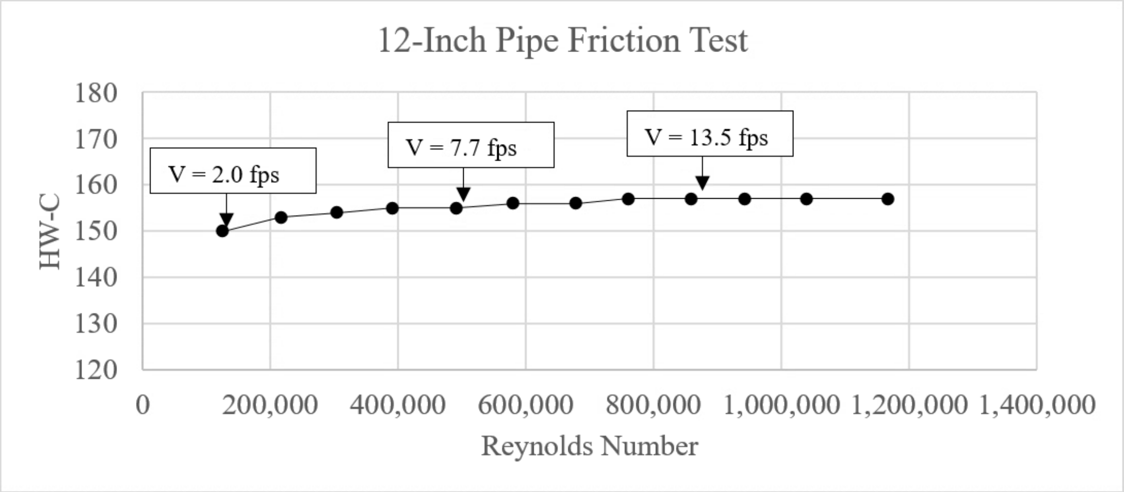

Figure 3. Laboratory HW-C Test for 12” Pipe

FIELD TESTING

Uni-Bell PVCPA partnered with Granger-Hunter Improvement District (GHID) in West Valley City, UT to perform flow tests on an existing PVC pipe water main. Various water main segments were reviewed as potential test sites, and ultimately a section that was a straight run with no appurtenances was selected.

The main that was selected was an 8-inch DR 18 AWWA C900 PVC pipe that was installed in 1976, which means it had been in service for 46 years. It should be noted that the AWWA C900 standard was created in 1975. This main is shown in Figure 4 as the lower horizontal blue line. The section that was tested is between the 2 blue arrows on the left, which had a length of approximately 278 ft. The hydrant that was opened for the flow is the blue arrow on the right. The appropriate valves were closed in order to isolate this section and ensure flow was coming from one direction. The utility indicated that the only maintenance activity done on this main while it has been in service was routine exercising of valves and hydrants.

Figure 4. Schematic of 8” AWWA C900 Water Main for Field Test

Two tests were conducted, one with a lower flow rate measured through a calibrated Sensus® test meter, and the other at a higher flow rate measured through a Hose-Monster®

hydrant flow diffuser. This hose assembly was calibrated for accuracy at the Utah Water Research Laboratory.

To accurately calculate the C-Factor of the pipe from the field measurements of head-loss and flow rate, the inside diameter of the buried pipe was also needed. Since a nearby valve on the field test pipe needed to be replaced, GHID removed a section of the test pipe during the valve replacement and provided a short section of pipe. The inside diameter of the samples were measured.

Figure 5. Excavated Samples of 8” AWWA C900 Water Main for Dimension Measurement

Procedure. To establish the “C” values for the selected water main, it was necessary to measure the flow rate, head-loss, and linear distance along the pipe between the upstream and downstream pressure monitoring locations. Redundant **Polcon® Sentry** Pressure Recorders were used to measure the head-loss through the pipe section being tested, and the results were averaged together, with the difference between each being less than 0.3% of the total measurement. They were connected to pressure taps at pre-selected upstream and downstream sites and the head-loss was recorded concurrently with the measured velocity. By using differential pressure recorders at a single location, the pressure difference due to elevation was eliminated. The linear distance along the length of the pipe was measured twice using a standard measuring wheel.

Results. Table 3 below provides the results of the two flow tests performed.

Table 3. Field Test Results for 46-year old PVC Water Main

Run No.	Flow Volume (gpm)	Flow Velocity (fps)	Friction Loss (ft of H2O)	Friction Loss (ft H2O / ft)	Hazen-Williams “C”
1	606	3.86	1.30	0.005	164.2
2	1,370	8.73	5.93	0.021	163.3
				Average	163.8

DISCUSSION OF RESULTS

The results of both the laboratory and field tests indicate that PVC pipe is very smooth, especially when compared to other pipe materials. Typical friction values used for common pipe materials, such as cement-lined metallic pipe or plastic pipe (including PVC), range from HW-C = 135-150 and Manning's n = 0.009-0.013 (Walski, 2002). Additionally, the laboratory test results indicate that for velocities greater than 2 fps, the PVC roughness coefficients are smoother than the PVC industry's recommendations (HW-C = 150; Manning's n = 0.009). Thus, these industry recommendations can be considered conservative for municipal applications.

An interesting finding is that the PVC pipe with almost 50 years of service was calculated to have a HW-C of 164. It should be noted that it is difficult to ascertain an actual C-factor of the pipe when performing field flow tests, regardless of the pipe material, as mentioned earlier. Some error could be introduced, such as measurements of length between hydrants, or fully closing valves to ensure isolating the test section. There may also be unknowns with the pipe in the ground that are not reflected in the utility's records. While the authors are not able to quantify any potential error for this test, it is believed that the actual HW-C of this main is likely to be in the range that was found for new pipe in the laboratory testing. This indicates that long use of water main service has an insignificant effect on the hydraulics of PVC pipe.

These test results coincide with historical testing on PVC pipe from which the industry's recommendations were derived. Neal and Price performed laboratory flow tests on 8" and 12" PVC pipe. The HW-C ranged from 153-158 with an average of 155 (Neal, 1964). Lamont published a popular table of C factors for various materials, based on over 300 test records (Lamont, 1981). Smooth PVC pipe is shown to have a HW-C of 149 for 6-inch, and 153 for 48-inch sizes. For sewer pipe, Bishop took 25 field measurements of existing PVC sewer mains in service up to 5 years old, where some samples were noted to have "slime buildup" (Bishop, 1978). The average Manning's n = 0.009, with a standard deviation 0.0012.

CONCLUSION

To answer the question that was presented earlier in this paper, 'what is an appropriate friction factor to use for this pipeline?', it is useful to have comprehensive tests that account for variables such as flow rate, pipe size, and age. The combination of laboratory and field tests provides this information and can help determine a friction factor value that is appropriately conservative. As a contrast, some pipe manufacturers may recommend a value that is an average of only field test data, or the value from a single laboratory flow test. Use of either of these methods alone may not lead to an appropriately conservative design, as demonstrated in this paper.

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