Monitoring of Pressure Transients in Great Lakes Water Authority Water Transmission System

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Abstract

Great Lakes Water Authority (GLWA) operates one of the largest water systems in the United States and, like most other water utilities, is facing the problem of aging water infrastructure. Internal pressure transient events can be a major contributing factor in the deterioration and failure of aging water pipes. To evaluate the impact of pressure transients on water main deterioration, over three years GLWA has maintained a real-time pressure transient monitoring program within its water transmission system. The Trimble Unity Remote Monitoring suite is used; it includes high speed pressure sensors and data loggers. Approximately 60,000 transient events have been recorded by the 30 transient monitoring sensors installed within the transmission system. A quantitative approach to evaluating the relative impact of pressure transients on the deterioration of water pipes has been used in analyzing the pressure transient events. The approach is based on the frequencies and pressure ranges of transient events. This paper presents the development of the transient monitoring program and analytical results of the pressure transient data. These analytical results, plus the ongoing transient monitoring data, are being used in updating GLWA’s system risk assessment.

1 Introduction

Municipal drinking water infrastructure in the United States is becoming older and thus more prone to failure. Despite increases in infrastructure investment, municipal infrastructure is decaying faster than it is being renewed. According to the 2021 Report Card for America’s Infrastructure, the United States drinking water infrastructure system, made up of 2.2 million miles (3.5 million km) of underground pipes, is aging and underfunded. There is a water main break every 2 minutes and an estimated 6 billion gallons (27 million m³) of treated water are lost each day (American Society of Civil Engineers 2021). Aging water infrastructure is one of the major problems faced by water utilities in the United States, and urgent solutions are required to maintain the integrity of the water supply network.

Generally, failure of water pipes depends on factors such as pipe structural properties, material type, environmental conditions, and internal and external loads. The interactions of individual factors and their impact on pipe failures are extremely complex. While most previous work has focused on pipe material properties and environmental conditions, there is less understanding of internal water pressure loading. Internal water pressure loading can be subdivided into two main categories: steady state pressure (i.e., operational pressure) and transient pressure. Internal water pressure can be quite unpredictable during a transient event and is a major contributing factor to the deterioration and failure of water mains (Rezaei et al. 2015).

For many years, pressure transient modeling has been a major means to determine the effects of pressure transients on water pipe failure. The reliability of any pressure transient hydraulic model depends on how accurately it can predict real world events. Water distribution networks are massive in size and complex in nature. It is quite hard to model an entire network due to excessive model development time and inherent issues with computational aspects (Rathnayaka et al. 2016).

However, conventional pressure measuring instruments are not adequate for assessing the propagation speed of pressure transients that travel at close to the speed of sound. Over the last few years, advances in data logging tools and technologies have allowed a more rigorous approach to the investigation of pressure transients. High speed pressure transducers are being used to measure transient pressures to obtain reliable data for the evaluation of transient effects.

Great Lakes Water Authority (GLWA) operates one of the largest water systems in the nation that serves drinking water to 3.8 million people in southeastern Michigan. Construction of the transmission network started in the middle 1800s. Like most other water utilities, GLWA is facing the problem of aging water infrastructure and is updating its system risk assessment. GLWA is deploying innovative water technologies like sensors and smart
water monitoring to assess system reliability. To evaluate the impact of pressure transients on water main deterioration and failure, GLWA has performed a pressure transient monitoring program for over three years. High speed pressure transducers are installed in the water transmission system to record real-time transient pressures. This paper presents the pressure transient monitoring program and results gained from analyzing the pressure transient records.

2 Water transmission system overview

GLWA provides potable water to approximately 3.8 million people through 88 member partners across 112 communities in southeast Michigan. The average day demand and maximum day water demand for the year 2020 were respectively 417 MGD (21.9 m³/s) and 723 MGD (38.0 m³/s). The system draws its fresh water from Lake Huron and the Detroit River via 3 intake facilities. The water transmission system includes 5 water treatment plants, 19 booster pump stations, 28 water storage reservoirs, and approximately 816 miles (1313 km) of transmission mains. Figure 1 (overleaf) presents a schematic of GLWA’s water transmission network.

Concrete, cast iron, and steel pipes constitute approximately 97% of the transmission mains in the GLWA system. The cast iron pipes were installed from the late 1850s to the late 1940s, steel pipes between the 1910s and 1970s, and concrete pipes since the late 1940s. In general, the water system slowly expanded from the 1850s to the mid-1920s with intermittently stagnant growth. Periods of rapid expansion can be identified in the 1920s and 1930s, and the 1950s to 1970. Concrete pipes are mostly 50 y–60 y old pipes, while cast iron pipes are 90 y–110 y old, with some >150 y old. In the past 10 y, an additional 16 miles (25.7 km) of concrete pipes have been installed in the system so that concrete pipe accounts for approximately 62% of the transmission mains. Figure 2 shows the existing water transmission main data by category and age of the pipes.

3 Methodology

Our transient monitoring program uses an integrated suite of remote pressure monitoring hardware and software that includes high speed pressure sensors, locational data loggers, and enterprise support software for data storage and analytics. The Telog Ru-32imA remote monitoring unit, by the Trimble Telog Company, was used in our project to record real-time impulse data during a transient event.

3.1 Using high speed pressure transducers

Conventional pressure transducers are not able to accurately measure the magnitudes of pressure transients; hence high speed pressure transducers were installed in the transmission system to collect transient pressure data. The Ru-32imA unit includes a wireless recording telemetry unit (RTU) and high-speed pressure and flow sensors.

The Ru-32imA RTU, powered by a battery or an AC/DC adaptor, can sample the pressure sensors up to 30 times/s. The Ru-32imA unit recorder stores the waveform of captured pressure impulse waves detected within the water network. The Ru-32imA may be configured to call its server application on a schedule (e.g. once per day; every four hours) and in response to site alarm conditions (e.g. transient event, high or low pressure, or level exceedance).

The Ru-32imA RTU uses wireless communication with a 4G LTE cellular modem, enabling unmanned monitoring of remote sites as well as instant updates and alarm notifications. The Ru-32imA instrument, and different attachment configurations, are shown in Figure 3.

Through the transient monitoring program, 30 transient pressure sensors were installed within the transmission system. Most of them were installed in the 14 large pumping stations located in the suburbs of Detroit due to interest in monitoring real-time pressure transients within the adjacent large diameter prestressed concrete (PC) pipes. Performance of PC pipes has been an item of interest to water utilities for a long time (Romer et al. 2007).

3.2 Deploying Trimble Unity software

In the pressure transient monitoring program, the Ru-32imA instruments were integrated with the Trimble Unity Remote Monitoring software. This approach allowed users to monitor the...
Figure 1  GLWA water transmission system.
real-time performance of the installed pressure sensors. Figure 4 shows a screenshot of the Trimble Unity application.

4 Analysis of pressure transient data

4.1 Summary of pressure transient events

The GLWA pressure transient monitoring program started in 2017. As of 2021-03-01, the program had run for more than three years, and 59342 transient events had been recorded through the 30 monitoring sensors. Most of the sensors are installed in the 14 pumping stations that serve the communities in the suburbs of Detroit. All the transmission pipes being monitored are PC pipes. GLWA prioritizes the assessment of PC pipes because they are typically ≥3 ft (91.4 cm) in diameter, and thus failures have significant impact. Table 1 presents a summary of the transients in PC pipes.

A transient pressure sensor records the minimum and maximum pressure during a transient event. The difference between the maximum and minimum pressure is the transient pressure range. Most of the transient events have a relatively low transient pressure range. The mean range for the 59342 transient events recorded was 26.4 PSI (182 kPa). However, the mean pressure range at some sites is much higher than the system average. For example, the mean ranges for the sites of Imlay Station discharge to Flint and Imlay Station discharge to NSC were respectively 62.6 PSI (432 kPa) and 57.6 PSI (397 kPa). The daily frequency of transient events is calculated for each monitoring site. The frequency for half of the monitored sites is <1 time/d. However, there were 4 sites where transients occurred >10 times/d.

As an example, the profile of transient events recorded at the site of Franklin Station discharge from January 2018 to January 2021 is shown in Figure 5. A total of 559 events were recorded during the period of three years. The average pressure range was 32.7 PSI (225 kPa) and the average duration of transient events was 28.3 s. There were 9 transient events that had a pressure range >100 PSI (689 kPa). The longest duration of a transient event was 100 s, and average duration was <30 s.
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Table 1  Summation of transient events by pressure sensor.

| Location of Sensor          | Pipe Size (in.) | Number of Transient Events | Average Impulse Duration (s) | Average Pressure Range (PSI) |
|-----------------------------|-----------------|----------------------------|------------------------------|-----------------------------|
| Adams Road Discharge        | 54              | 62                         | 26.76                        | 25.60                       |
| Adams Road Suction          | 54              | 86                         | 34.97                        | 27.80                       |
| Ford Road Discharge         | 48              | 166                        | 27.98                        | 25.50                       |
| Ford Road Suction           | 48              | 211                        | 44.75                        | 21.71                       |
| Franklin Road Discharge     | 60              | 559                        | 32.67                        | 28.32                       |
| Franklin Road Suction       | 60              | 9764                       | 42.68                        | 17.14                       |
| Haggerty Discharge          | 42              | 314                        | 20.42                        | 24.46                       |
| Haggerty Suction            | 42              | 453                        | 21.41                        | 27.91                       |
| Imlay Discharge to Flint    | 60              | 41                         | 27.81                        | 62.62                       |
| Imlay Discharge to NSC      | 84              | 59                         | 23.22                        | 57.64                       |
| Joy Road Discharge          | 48              | 1172                       | 20.72                        | 23.28                       |
| Joy Road Suction            | 48              | 4111                       | 31.12                        | 19.12                       |
| Michigan Ave Discharge      | 24              | 68                         | 20.29                        | 26.73                       |
| Michigan Ave Suction        | 24              | 357                        | 25.46                        | 27.92                       |
| NSC Discharge               | 84              | 554                        | 29.29                        | 27.46                       |
| NSC Suction                 | 72              | 1265                       | 93.86                        | 25.94                       |
| Newburgh Discharge          | 42              | 1158                       | 23.31                        | 23.66                       |
| Newburgh Suction            | 42              | 2106                       | 23.58                        | 23.43                       |
| Rochester Discharge         | 42              | 9048                       | 8.53                         | 17.29                       |
| Rochester Suction           | 42              | 1045                       | 8.15                         | 16.57                       |
| Schoolcraft Discharge       | 36              | 1700                       | 26.59                        | 25.02                       |
| Schoolcraft Suction         | 36              | 295                        | 27.12                        | 29.59                       |
| Wick Road Discharge         | 36              | 2705                       | 23.70                        | 26.46                       |
| Wick Road Suction           | 36              | 2816                       | 24.11                        | 21.76                       |
| WSC Suction                 | 60              | 12455                      | 36.91                        | 18.94                       |
| WSC Discharge High          | 54              | 331                        | 42.59                        | 22.83                       |
| WSC Discharge Int.          | 54              | 4793                       | 30.58                        | 20.28                       |
| Ypsilanti Discharge         | 48              | 451                        | 24.48                        | 35.75                       |
| Ypsilanti Suction           | 42              | 1167                       | 36.30                        | 21.64                       |
| Dequindre 54-inch Main      | 54              | 30                         | 19.84                        | 18.46                       |

4.2 Assessment of impact of transient on pipe fatigue life

The internal loading in a water pipe includes two parts: transient pressure and steady state pressure (i.e., the operating pressure). For the steady state pressure in a pipe, the focus is the values of water pressure. The higher a pressure value is, the more stress a pipe endures. For transient pressure, the emphasis is on sudden pressure changes caused by short term events (i.e., cyclic pressure ranges).

Transient pressures produce cyclic stress in a pipe and result in pipe fatigue. The fatigue life of a pipe is defined by the number of loading cycles for the pipe to fail. Usually for a given material, the Wöhler curve is developed to reflect the relation between the amplitude of cyclic load or stress (S) and pipe fatigue life (N). Figure 6 shows the typical shape of a Wöhler curve.

The fatigue life decreases with amplitude of cyclic load for a pipe. Contrastingly, transient damage to pipe increases with amplitude of cyclic load. The transient damage to pipe is defined as the reciprocal of pipe fatigue life (1/N) multiplied by a constant. The relation is not linear. When both the cyclic load and damage to pipe are displayed on logarithmic scales, a linear relation can be established. Figure 7 shows the relation between transient damage to the pipe and cyclic load plotted as linear vs. linear and logarithmic vs. logarithmic.

For any site in GLWA’s transient monitoring program, many transient events have been recorded. The pressure ranges for...
these transient events vary at different times. The transient time records of a monitoring site are used to evaluate the impact of pressure transients at the site. To do so, the transient records are categorized into levels based on the amplitude of the pressure range. Table 2 shows the defined transient load levels.

Table 2 Levels of transient pressure range.

| Cyclic Load Level | Lower Range (PSI) | Upper Range (PSI) | Note |
|-------------------|------------------|------------------|------|
| 1                 | 15               | 25               | 1    |
| 2                 | 25               | 35               |      |
| 3                 | 35               | 45               |      |
| 4                 | 45               | 55               |      |
| 5                 | 55               | 65               |      |
| 6                 | 65               | 75               |      |
| 7                 | 75               | 85               |      |
| 8                 | 85               | 95               |      |
| 9                 | 95               | 105              |      |
| 10                | 105              | 115              |      |
| 11                | 115              | 125              |      |
| 12                | 125              | 135              |      |
| 13                | 135              | 145              |      |
| 14                | 145              | 155              |      |
| 15                | 155              | 165              |      |
| 16                | 165              | 175              |      |
| 17                | 175              | 185              |      |
| 18                | 185              | 195              |      |
| 19                | 195              | 205              |      |
| …                |                  |                  |      |
| 38                | 485              | 495              |      |
| 39                | 495              | 500              | 2    |

Notes:
1. A transient event recording is triggered when pressure change exceeds 15 PSI or more in 3 s.
2. A transient pressure sensor can record a pressure up to 500 PSI.

For prestressed concrete pipes, which consist of multiple layers of different materials such as concrete, steel wire or steel cylinder, no quantitative relation has been determined for cyclic load vs pipe fatigue life or cyclic load vs impact of transient on pipe. For the purposes of this study, similar to Wöhler curves for other materials of pipes, an exponent relation between transient pressure range and impact on fatigue life was assumed for prestressed concrete pipes. To quantify the effect of a transient under a given load level, the impact of the transient is defined as the product of transient frequency and exponent function of corresponding transient load level, which is:

\[ Si = f \cdot \exp(i) \]  

where:
- \( Si \) = impact on fatigue life under cyclic load level \( i \);
- \( f \) = daily frequency of transient at level \( i \);
- \( \exp \) = exponential function with base the natural logarithm \( e \); and

\( i \) = cyclic load level based on amplitude of pressure range (as shown in Table 2).

There are different levels of cyclic load in the transient time records for a site. The cumulative impact of transients at the site is defined as the sum of impacts from all cyclic load levels. An index of transient impact at a site is defined as the logarithmic scale of the cumulative impact. The logarithmic scale makes a linear or quasi-linear relation between the index and transient impact.

\[ I = \log[\sum(Si)] \]  

where:
- \( I \) = index of cumulative transient impact at the site, and
- \( \sum \) = sum of transient impacts for all levels of the transient occurrences at the site.

The calculations of \( I \) for the Franklin Discharge monitoring site are presented in Table 3 as an illustration of using Equations 1 and 2.

Table 3 Calculations for index of transient impact \( I \) at Franklin Discharge site.

| Cyclic Load Level (i) | Average Range (PSI) | Count of Events | Daily Frequency of Impulse (f) | Impact on Pipe Life | Accumulative Impact \( \Sigma(Si) \) | Index of Impact \( \log[\sum(Si)] \) |
|----------------------|---------------------|----------------|-------------------------------|---------------------|-----------------------------------|----------------------------------|
| 1                    | 18.98               | 349            | 0.3167                        | 0.8609              | 8499.40                           | 3.93                             |
| 2                    | 29.95               | 99             | 0.0898                        | 0.6638              |                                   |                                  |
| 3                    | 39.37               | 51             | 0.0463                        | 0.9295              |                                   |                                  |
| 4                    | 49.58               | 20             | 0.0181                        | 0.9909              |                                   |                                  |
| 5                    | 60.24               | 11             | 0.0100                        | 1.4814              |                                   |                                  |
| 6                    | 68.30               | 16             | 0.0145                        | 5.8574              |                                   |                                  |
| 7                    | 75.13               | 1              | 0.0009                        | 0.9951              |                                   |                                  |
| 8                    | 86.53               | 1              | 0.0009                        | 2.7050              |                                   |                                  |
| 9                    | N.A.                | 0              | 0.0000                        | 0.0000              |                                   |                                  |
| 10                   | N.A.                | 0              | 0.0000                        | 0.0000              |                                   |                                  |
| 11                   | 121.96              | 2              | 0.0018                        | 108.6645            | 8499.40                           | 3.93                             |
| 12                   | 134.83              | 1              | 0.0009                        | 147.6904            |                                   |                                  |
| 13                   | 138.96              | 3              | 0.0027                        | 1204.3922           |                                   |                                  |
| 14                   | 154.20              | 1              | 0.0009                        | 1091.2925           |                                   |                                  |
| 15                   | 159.51              | 2              | 0.0018                        | 5932.8809           |                                   |                                  |
| 16                   | N.A.                | 0              | 0.0000                        | 0.0000              |                                   |                                  |
| 17                   | N.A.                | 0              | 0.0000                        | 0.0000              |                                   |                                  |
| 18                   | N.A.                | 0              | 0.0000                        | 0.0000              |                                   |                                  |
| 19                   | N.A.                | 0              | 0.0000                        | 0.0000              |                                   |                                  |
| 20                   | N.A.                | 0              | 0.0000                        | 0.0000              |                                   |                                  |
| 21                   | N.A.                | 0              | 0.0000                        | 0.0000              |                                   |                                  |

The evaluation results for the transient impact index for all 30 monitoring sites are shown in Table 4. There were 15 sites where the index of transient impact was low (\( I < 2.0 \)). These sites have either a low frequency of transient events or are events associated with a small amplitude of pressure range (i.e., <25 PSI, 172 kPa). The sites with relatively high indexes of transient impact include Schoolcraft Suction, Franklin Discharge, Joy Road Discharge and Haggerty Suction, each of which had several transient events.
occurrences with a pressure range >130 PSI (90 kPa). The transient events with a high pressure range can make significant contribution to the index of impact at each of these sites because these transients are those that have significant impact on fatigue life of a pipe and sometime cause failure of the impacted pipe. The pipes with high index of transient impact were then prioritized for subsequent additional monitoring and assessment by GLWA’s asset management division.

Table 4  Transient frequency and index of transient impact by site.

| Location of Sensor          | Transient Event Frequency (/d) | Average Range of Top 20 Transient Events | Index of Impact on Fatigue Life |
|----------------------------|-------------------------------|------------------------------------------|-------------------------------|
| Adams Road Discharge        | 0.42                          | 37.66                                    | 3.48                          |
| Adams Road Suction          | 0.62                          | 27.80                                    | 0.41                          |
| Ford Road Discharge         | 0.94                          | 34.55                                    | 1.33                          |
| Ford Road Suction           | 1.18                          | 28.10                                    | 0.56                          |
| Franklin Road Discharge     | 0.51                          | 98.21                                    | 3.93                          |
| Franklin Road Suction       | 8.84                          | 62.66                                    | 1.71                          |
| Haggerty Discharge          | 0.30                          | 27.58                                    | 1.19                          |
| Haggerty Suction            | 0.43                          | 85.17                                    | 3.59                          |
| Imlay Discharge to Flint    | 0.06                          | 85.64                                    | 2.47                          |
| Imlay Discharge to NSC      | 0.08                          | 85.92                                    | 2.20                          |
| Joy Road Discharge          | 1.19                          | 51.51                                    | 3.66                          |
| Joy Road Suction            | 4.13                          | 53.95                                    | 1.27                          |
| Michigan Ave Discharge      | 0.11                          | 39.16                                    | 0.84                          |
| Michigan Ave Suction        | 0.45                          | 47.63                                    | 0.62                          |
| NSC Discharge               | 0.61                          | 58.15                                    | 2.75                          |
| NSC Suction                 | 1.81                          | 42.43                                    | 1.06                          |
| Newburgh Discharge          | 1.07                          | 78.87                                    | 2.80                          |
| Newburgh Suction            | 1.94                          | 55.15                                    | 1.28                          |
| Rochester Discharge         | 113.10                        | 28.64                                    | 2.65                          |
| Rochester Suction           | 12.90                         | 21.35                                    | 2.11                          |
| Schoolcraft Discharge       | 1.51                          | 66.14                                    | 1.46                          |
| Schoolcraft Suction         | 0.42                          | 74.51                                    | 4.97                          |
| Wick Road Discharge         | 2.25                          | 56.56                                    | 1.65                          |
| Wick Road Suction           | 2.62                          | 50.30                                    | 1.01                          |
| WSC Suction                 | 11.82                         | 66.21                                    | 2.11                          |
| WSC Discharge High          | 3.32                          | 16.09                                    | 2.79                          |
| WSC Discharge Int.          | 12.49                         | 53.73                                    | 2.37                          |
| Ypsilanti Discharge         | 0.43                          | 87.28                                    | 2.36                          |
| Ypsilanti Suction           | 1.74                          | 55.06                                    | 1.22                          |
| Dequindre 54-inch Main      | 0.08                          | 19.59                                    | 0.01                          |

A map showing the geographical distribution of monitoring sites with different impact levels is presented in Figure 8 (overleaf). The impact levels for each of the affected transmission pipes were estimated. The estimation was based on the corresponding impact levels of the monitoring points near an affected pipe. The estimation results are also presented in Figure 8.

Note the clear geographical clustering of impacted pipes shown in Figure 8. Geographical clustering is expected because transients are generated by local events such as pump activations and valve operations. Our approach was to demonstrate a method of measuring pipe pressure transients, map the spatial variation of occurrence, and ultimately develop a prioritization of pipe assets for subsequent asset management, monitoring and assessment.

5 Conclusions

Our approach enabled us to assess and prioritize the condition of water main pipes by monitoring and assessing pressure transients. Internal pressure during a transient event can be a major contributing factor in the failure of aging water pipes. Based on the analysis described in this paper, the impact of water transient events on water pipe deterioration, and thus overall condition assessment, can be estimated by integrating transient amplitude with frequency.

The assessment of pressure transient effects in the GLWA transmission system, which uses the proposed quantitative approach to evaluate the transient impact on pipe fatigue life, was presented. Transient impact on pipe deterioration is exponential with an increase of transient pressure range. The assessment results showed the approach is useful to evaluating relative impact levels of transient events to the pipes located near a transient monitoring location. It is planned to perform transient monitoring for the entire transmission system. A conceptual design solution could be made for the locations where the transients have a significant impact when the transient monitoring and impact assessment are performed for the entire transmission system.

GLWA has a predictive model to evaluate the conditions and forecast future rehabilitation or replacement needs of the water transmission pipes. The prediction is based on water pipe reliability functions. The current pipe reliability functions majorly depend on pipe material and age. Because the complete historical breaks were not available for verification, the amplitude and frequency of transient loading affect the pipe fatigue life and would be used to revise the pipe reliability functions.

The GLWA water transmission system contains the longest length of prestressed concrete pipe in the nation and GLWA has put its transient monitoring priority on the pipes of this type of material. GLWA is extending its program to monitor transient events in the pipes of other materials (cast iron and steel). This program informs our prioritization of pipe assets for subsequent asset management efforts, such as expanded inspections and assessment methods.
Figure 8  Results of transient monitoring data assessment showing impact level by site.
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