DEPOSIT ANALYSIS OF PIPELINES WITH HYDRAULIC GRADE LINES MEASURED BY FREE-FLOATING, IN-LINE TOOLS

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ABSTRACT

This paper demonstrates the methodology for calculating the hydraulic grade line from free-floating, in-line inspection tools and the subsequent deposit analysis of the hydraulic grade line. Neutrally buoyant, in-line inspection tools measure the pressure along the entire pipeline length under regular operating conditions. Deploying multiple tools with a short time delay allows for localized features to be distinguished from changes to the pipeline operation during the deployment. Identified operational changes during the deployment are corrected before calculating the hydraulic grade line using an elevation profile of the pipeline. The resulting hydraulic grade line represents the pressure-head loss due to friction along the pipeline; locations with steeper pressure-head loss indicate restrictions in the pipeline from the build-up of deposits. The gradient of the hydraulic grade line, pipeline specifications, and inspection flow rate are used with the Hazen-Williams equation to calculate the levels of deposits in several segments along the pipeline.

INTRODUCTION

Providing clean drinking water and the removal of wastewater from homes and businesses is a necessity for safe and healthy communities. The United States uses an estimated 39 billion gallons of water per day that must be transported to and from residential, commercial, and industrial locations via a vast network of pipelines (U.S. Geological Survey, 2015). The United States has an estimated 2.2 million miles of pipe carrying drinking water (American Water Works Association, 2019) and over 1.3 million miles of pipe carrying wastewater (U.S. Environmental Protection Agency, 2010) to 16,000 publicly owned wastewater treatment plants (Cybersecurity & Infrastructure Security Agency, 2023). Canada has over 470,000 kilometers of pipe carrying water and wastewater (Statistics Canada, 2022). This water infrastructure is aging with the average age of these drinking and wastewater pipelines in the United States being 45 years old (Tabuchi, 2017) and one-in-five kilometers of water pipelines in Canada being over 50 years old (Statistics Canada, 2022). It is therefore critical that water and wastewater pipelines are monitored to ensure they are in suitable condition and maintain the performance of water and wastewater systems.

Deposit build-up within a pipeline is specifically of concern for pipelines transferring wastewater. Deposits reduce the capacity of a pipeline, can lead to corrosion and wear of the pipe wall, and can cause sanitary systems to overflow. In 2004, the EPA found that 48% of sanitary sewage system overflow events with a known cause in the United States were the results of a partial or complete blockage (U.S. Environmental Protection Agency, 2004). These overflow events pose a risk to public health and pollute the environment.

Deposit build-up within a pipeline will restrict the effective diameter of the pipeline and cause greater frictional pressure losses. Thus, pipeline operators monitor the throughput of pipelines and any available pressure measurements looking for evidence of a restriction. However, these monitoring methods do not indicate the location or size of restriction present. In-line inspection tools that measure the pressure profile along the entire length of a pipeline provide more detailed insight into the performance of a pipeline and facilitates locating and sizing restriction. Locations with steeper frictional pressure losses indicate restrictions in the pipeline from the build-up of deposits or trapped pockets of gas with larger restrictions causing steeper losses. Calculating the hydraulic grade line (HGL) facilitates this analysis by accounting for changes in the hydrostatic pressure along the length of the pipeline.

This paper demonstrates the methodology used to calculate the HGL from free-floating, in-line inspection tools and the subsequent analysis of the HGL to provide information about the level of deposits within a pipeline. First, a technical background details the physical relationships governing flow through a pipeline and the definition of a HGL. The methodology of calculating a HGL is demonstrated including important characteristics of the in-line tool; methods to identify and correct for operational changes during the inspection; and the calculation of a HGL from the measured pressure along the pipeline. Finally, the analysis of a HGL to determine the levels of deposits within the pipeline is detailed.

TECHNICAL BACKGROUND

Steady, incompressible pipe flows are governed by the Bernoulli equation,

$$\left(\frac{p}{\rho g} + z + \frac{v^2}{2g}\right)_{\text{upstream}} = \left(\frac{p}{\rho g} + z + \frac{v^2}{2g}\right)_{\text{downstream}} + h_{\text{friction}},$$

where p is pressure, ρ is fluid density, g is acceleration due to gravity, z is the pipeline elevation, v is fluid velocity, and h_{friction} is the head loss due to friction. This equation can be further simplified because the fluid velocity is constant throughout segments of a pipeline without significant in-flows, out-flows, or changes in diameter. Defining the hydraulic grade line, HGL, as the pressure head plus the pipeline elevation ($HGL = p/(\rho g) + z$), the Bernoulli equation simplifies further to,

$$HGL_{\text{upstream}} = HGL_{\text{downstream}} + h_{\text{friction}}.$$

Thus, changes in the HGL are directly related to the head-loss due to friction, $\Delta HGL = h_{\text{friction}}$.

The head-loss due to friction is dependent on the pipeline geometry, pipe material, and flow rate via the Darcy-Weisbach equation,

$$h_{\text{friction}} = f \frac{8}{\pi^2 g} \frac{\Delta x}{D^5} Q^2,$$

where Δx is the length along the pipe, D is the inside diameter of the pipeline, Q is the flow rate, and f is the Darcy friction factor. The Darcy friction factor depends on the state of the flow (turbulent or laminar) and is a function of the fluid density and viscosity; the pipe inside diameter and hydraulic roughness of the inside surface; and the flow rate. These quantities are traditionally related through the Moody diagram (Moody, 1944) or one of several complex equations including the Colebrook equation (Colebrook, 1939),

$$\frac{1}{f^{\frac{1}{2}}} = -2.0 \log\left(\frac{\epsilon/D}{3.7} + \frac{2.51}{Re\, f^{\frac{1}{2}}}\right),$$

where ϵ is the hydraulic roughness of the inside surface of the pipe which accounts for different pipe materials and $Re = \frac{4\rho Q}{\pi\mu D}$ is the non-dimensional Reynolds number of the flow where μ is the dynamic viscosity of the fluid.

For water at room temperature, the Hazen-Williams relationship exists as a traditional alternative to the Darcy-Weisbach equation. It is a simpler empirical relationship between the flow rate, inside diameter of the pipeline, and a roughness coefficient C, which accounts for the hydraulic roughness of different pipe materials. The Hazen-Williams relationship is (Williams and Hazen, 1905),

$$\Delta HGL = h_{\text{friction}} = \frac{10.67Q^{1.852}}{C^{1.852}D^{4.8704}}\Delta x.$$

A build-up of deposits will restrict the effective pipeline diameter and have an increased roughness compared to a clean pipe; both factors causing increased friction and a steeper decrease in the HGL. Therefore, analyzing the gradient of the HGL at a given flow rate provides indication of the level of deposits within the pipeline. The HGL of a pipeline can be calculated from pressure measurements from a neutrally buoyant, in-line inspection tool.

METHODOLOGY: NEUTRALLY BUOYANT, IN-LINE INSPECTION TOOLS

Traditional inspection methods are restricted to pressure measurements from a small number of locations along the pipeline which do not provide sufficient detail of the pressure profile along the pipeline length. In-line inspection tools have the advantage that they record pressure measurements along the entire length of the pipeline. However, smart-pig, in-line inspection tools rely on the pipeline pressure to propel the pig through the pipeline and therefore do not provide a representative measurement of the pressure under regular operating conditions.

Neutrally buoyant, in-line inspection tools are ideally suited for this application due to their free-floating nature. The neutrally buoyant characteristic of the tool signifies that the tool has the same specific gravity as the fluid and therefore moves with the flow as if it were part of the fluid. This allows neutrally buoyant tools to pass over elevation changes; through valves and diameter changes; and pass closed branches and restrictions as it travels with the flow. Ease of deploying and retrieving the tool allows the inspection to take place under regular operating conditions for a representative measurement of the pipeline pressure.

The neutrally buoyant tools used for the analysis described in this paper are called Pipers®. They are small spherical multi-sensor balls that are less than 3 inches in diameter. Their weight can be adjusted to correspond to the density of the pipeline fluid such that they are neutrally buoyant. The tool carries a multi-sensor array including an inertial measurement unit (tri-axial accelerometer and gyroscope), multiple tri-axial magnetometers, a pressure and temperature sensor, and a passive acoustic sensor. The multi-sensor array allows several aspects of the pipeline condition to be monitored with a single inspection. Advanced data processing techniques (Byington, 2023) paired with the multi-sensor measurements allow accurate measurement localization along the pipeline length without the use of above-ground markers (Kindree, 2022). The tools can be deployed by the pipeline operator under regular operating conditions without modification to the pipeline.

Thus, these neutrally buoyant, in-line inspection tools allow the pipeline pressure to be measured with high spatial resolution along the entire pipeline length under regular operating conditions. The pressure measurements from an inspection are used to calculate the HGL of the pipeline and subsequently analyzed.

METHODOLOGY: OPERATIONAL CHANGES DURING DEPLOYMENTS

The free-floating, in-line tool measures a combination of the pressure head along the pipeline and any operational changes to the pipeline during the inspection. Multiple tools can be deployed in the same pipeline with a small time-delay between launches to allow pipeline features to be distinguished from operational changes. Pressure fluctuations measured by both tools at the same location indicate features of the pipeline while pressure fluctuations that are not repeatable between deployments indicate operational changes during the inspection. The top two rows of Figure 1 show the pressure in time measured during an inspection and the bottom two rows show the pressure in distance. The two inspection runs were launched and received about 3 minutes apart (launch times are indicated with green vertical lines and receive times with red vertical lines). Operational changes to the pipeline pressure are highlighted pink and are measured at the same time by both tools which are at different locations within the pipeline at any given time. In contrast, pipeline elevation changes are highlighted yellow and are measured when the tools pass a specific location which occurs at a different time for each tool.

Once identified, operational changes during the inspection can be corrected before calculating the HGL using one of two techniques. In the first technique, auxiliary pressure measurements of the pipeline with sufficient temporal resolution are subtracted from the pressure measured by the in-line tool. The top two rows of Figure 2 show the measured pressure in time from an in-line inspection and auxiliary SCADA pressure measured of the pipeline during the inspection. Changes to the pipeline operation are measured by both the SCADA pressure measurements and the in-line inspection tool at the same time. Therefore, the measured pressure from the in-line inspection tool is corrected for operational changes during the inspection by subtracting the SCADA pressure. The resulting operational corrected pressure is shown in the bottom row of Figure 2 and contains only the pressure head which is used to calculate the HGL.

When possible, both tools are deployed with a short time delay between launches such that they are both in the pipeline at the same time. Thus, both in-line tools will measure the same operational changes at the same time and one set of pressure measurements can be used to correct the operational changes in the second set of pressure measurements. The top two rows of Figure 3 show the measured pressure in time from two inspection runs of a pipeline. The middle row of Figure 3 also shows the detrended pressure from the first inspection run where the decreasing trend has been removed from the measured pressure. Changes to the pipeline operation are measured by both in-line inspection tool at the same time. Therefore, the detrended pressure from the first inspection run is subtracted from the measured pressure of the second inspection run to correct for operational changes during the inspection. The resulting operational corrected pressure is shown in the bottom row of Figure 3 and contains only the pressure head which is used to calculate the HGL.

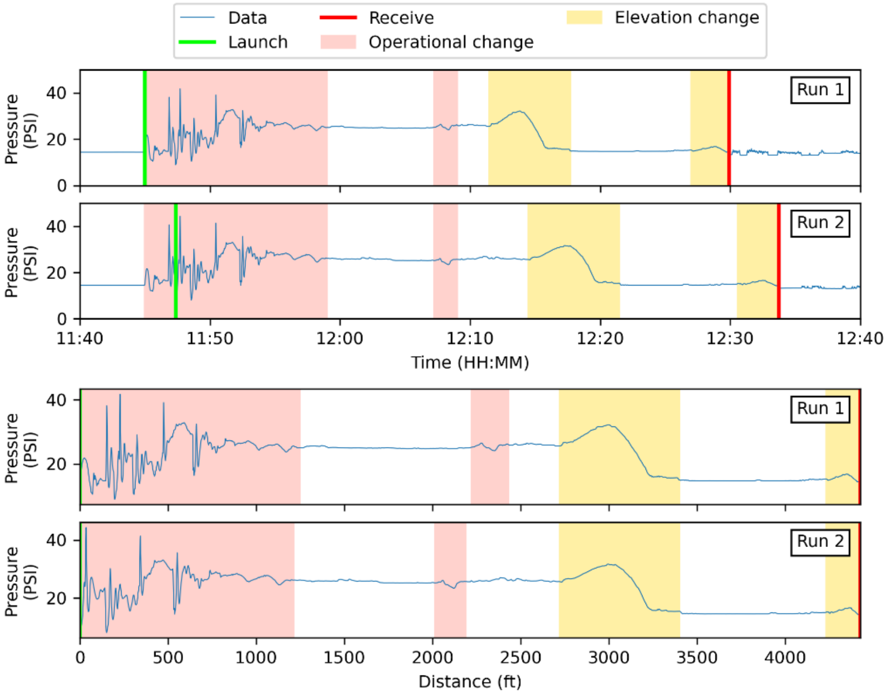

Figure 1: Pressure measurements from two inspection runs of a pipeline with a small time-delay between the tool launches. The top two rows show the measured pressure in time and the bottom two rows show the measured pressure in distance. Operational changes during the inspection are highlighted pink and elevation changes along the pipeline are highlighted yellow.

METHODOLOGY: THE HYDRAULIC GRADE LINE

After correcting for operational changes during the survey, the HGL can be calculated by adding the pressure head to an elevation profile of the pipeline. Elevation profiles are often available from design or as-built drawings of the pipeline. However, if drawings are not available, the above-ground elevation profile can be obtained from services such as Google Earth with only a GIS map of the pipeline and used for the HGL calculation (this assumes the pipeline is buried to a constant depth along the length of the pipeline). Figure 4 shows the measured pressure along the pipeline from an in-line inspection, the elevation profile of the pipeline, and the resulting HGL. Note that the measured pressure (top row of Figure 4) and the elevation profile (middle row of Figure 4) have an inverse relationship (i.e. pressure increases caused by the pipeline descending and pressure decreases caused by the pipeline ascending).

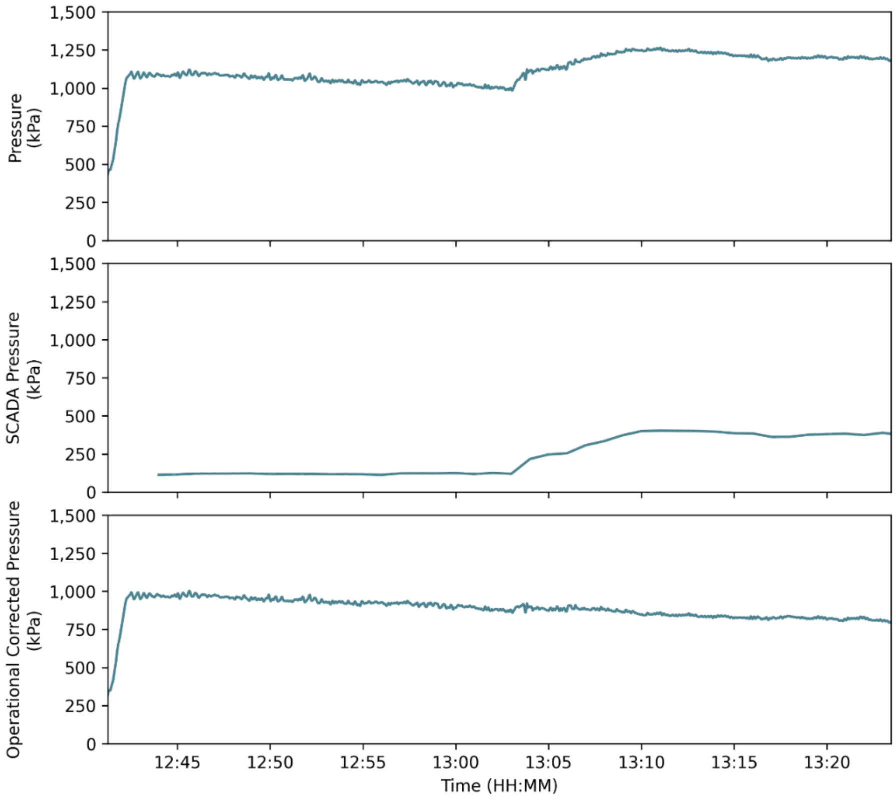

Figure 2: From top to bottom: measured pressure in time from an in-line inspection, auxiliary SCADA pressure measured of the pipeline, and the measured in-line inspection pressure corrected for operational changes during the inspection (i.e. measured pressure minus SCADA pressure).

The resulting HGL provides insight into the performance of the pipeline under normal operating conditions. The HGL can be analyzed in several ways:

- Since friction can only cause the HGL to decrease, locations where both in-line tools measure an *increase* in the HGL must be caused by an additional decrease in the pipeline elevation not accurately captured by the elevation profile. Conversely, locations where both in-line tools measure a *decrease* in the HGL may be caused by either increased friction (from a restriction to the flow) or by an additional increase in the pipeline elevation not accurately captured by the elevation profile. With this information, a more accurate understanding of the pipeline elevation is achieved.
- The HGL can be used as input, refinement, or validation of more complex engineering simulations of the pipeline system, thus providing a more accurate and detailed knowledge of the pipeline system dynamics. The HGL can also be validated against any auxiliary pressure measurements of the pipeline and provide insight into what the auxiliary measurements may indicate for the remainder of the pipeline.
- The HGL decreases along the length of the pipeline due to flow friction with steeper segments indicating increased frictional head-loss. Thus, segments of the HGL with steeper gradients may indicate a larger build-up of deposits relative to the remainder of the pipeline. The frictional head-loss is related to the effective inside diameter and hydraulic roughness of the pipeline via the Hazen-Williams equation (or the Darcy-Weisbach equation). Therefore, gradients of the HGL are measured and used with the Hazen-

Williams equation to provide quantitative measures of the level of deposits present in segments along the pipeline.

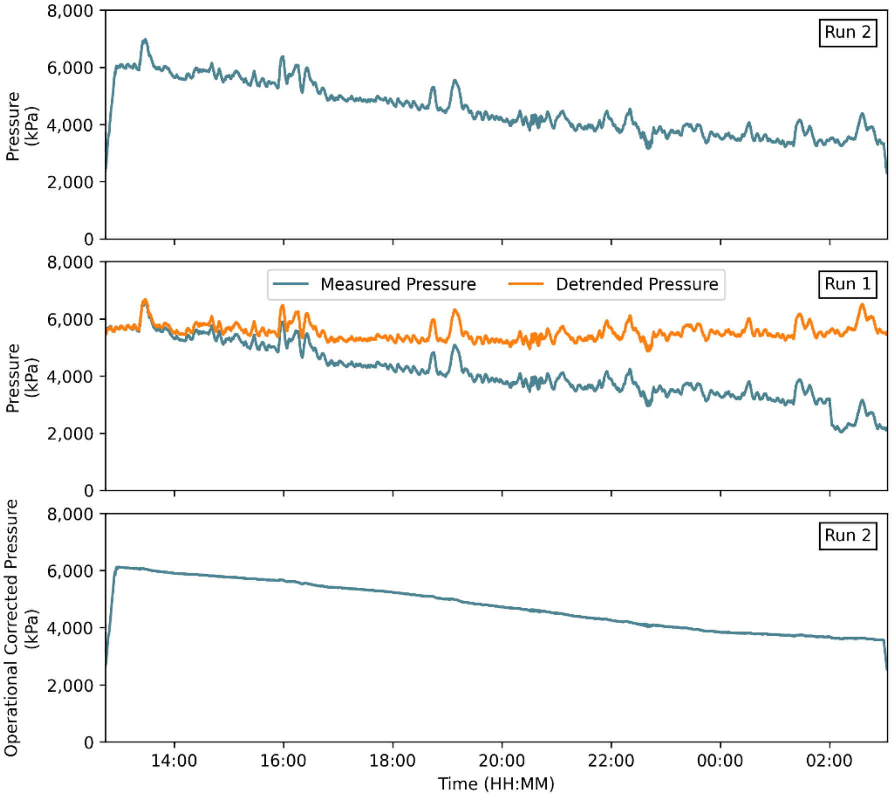

Figure 3: From top to bottom: the measured pressure of the second inspection run of a pipeline, measured pressure and detrended pressure of the first inspection run of a pipeline, and the measured pressure from the second inspection run corrected for operational changes during the inspection (i.e. measured pressure of the second inspection run minus the detrended pressure from the first inspection run).

METHODOLOGY: DEPOSIT ANALYSIS

The HGL is divided into segments with similar gradients and a line is fit to each segment with a least-squares method. The least-squares method reduces the impact of any remaining small fluctuations in the HGL caused by either small operational changes during the deployment or small discrepancies between the provided elevation profile and the actual pipeline elevation. Figure 5 shows the HGL from the in-line inspection of a 18-inch DIP force main shown in the bottom of Figure 4 with lines-of-best-fit overlaid. The above-ground elevation profile obtained from Google Earth and the pipeline elevation profile are also included for reference.

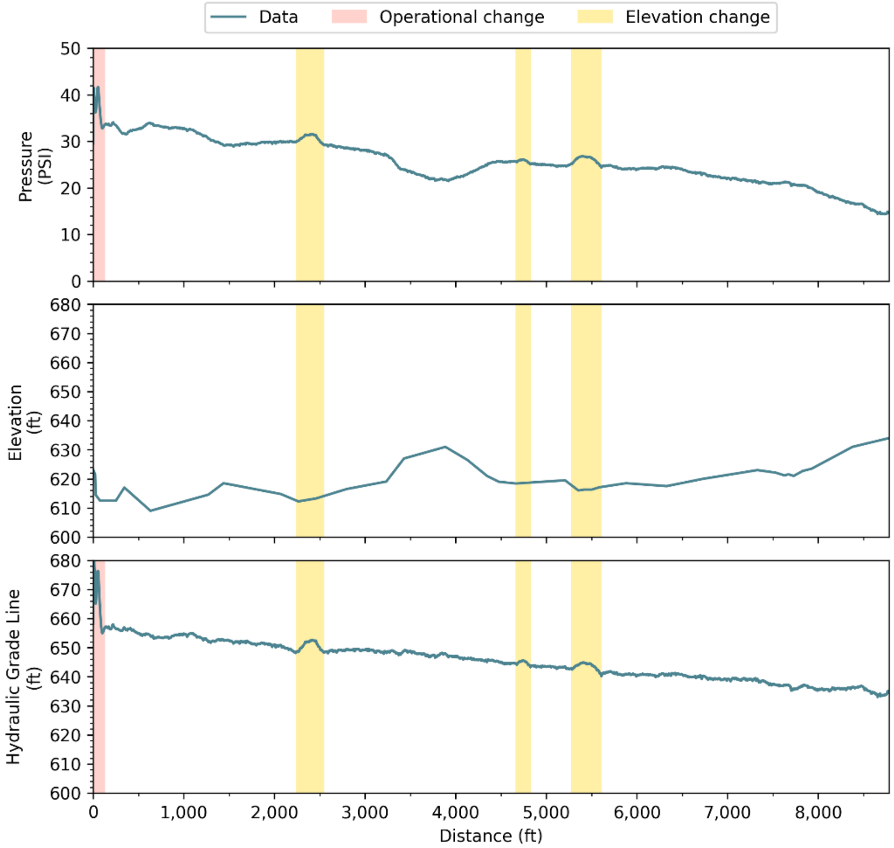

Figure 4: From top to bottom: measured pressure along the pipeline, elevation profile, and hydraulic grade line (i.e., pressure head plus pipeline elevation). Elevation changes along the pipeline that are not accurately captured by the elevation profile are highlighted yellow.

The gradients of the HGL; pipeline geometry and material; and the flow rate of the inspection are used with the Hazen-Williams equation (or the Darcy-Weisbach equation) to provided quantitative values for three scenarios:

- Differences between the gradient of the HGL and the gradient expected for a clean pipeline may be caused by discrepancies between the elevation profile and the actual pipeline elevation (ie. the pipeline elevation may have a different slope across a segment of the pipeline than indicated in the elevation profile). The maximum additional elevation change across each segment of the pipeline is calculated which would cause the observed difference in the gradient of the HGL.
- The inner surface of the pipe may be rougher due to a build-up of deposits or ageing of the pipe causing a steeper gradient of the HGL. The minimum roughness coefficient that would cause the steeper gradient of the HGL is calculated using the Hazen-Williams equation. The resulting roughness coefficient can be compared to values of aged pipe or values for pipe in good-to-poor condition for an indication of the pipe condition.
- The effective diameter of the pipeline may be restricted due to a build-up of deposits causing a steeper gradient of the HGL. The effective diameter that would cause the steeper gradient of the HGL is calculated using the Hazen-Williams equation. The resulting effective diameter is subtracted from the diameter of a clean pipe to determine the level of deposits present in each segment of the pipeline.

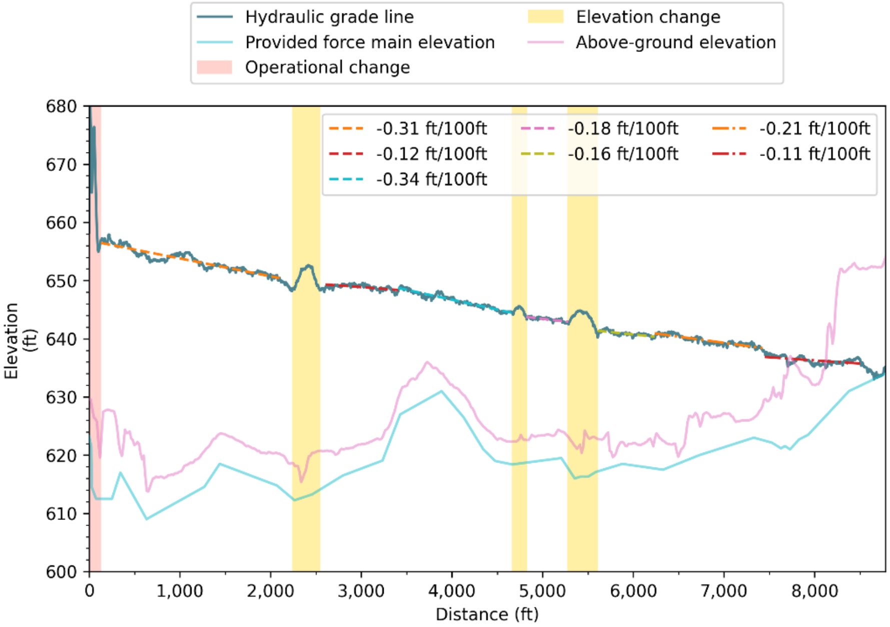

Figure 5: HGL with lines-of-best-fit overlaid, the provided force main elevation, and the above-ground elevation obtained from Google Earth. Elevation changes along the pipeline that are not accurately captured by the elevation profile are highlighted yellow.

Ultimately, segments of the pipeline with a steeper gradient of the HGL are likely caused by a combination of factors since the elevation profile may not be completely accurate and a build-up of deposits will both restrict the diameter and increase the hydraulic roughness of the pipeline. The maximum values of the three scenarios are calculated for each segment of the pipeline. Table 1 lists the results of these calculations for the HGL shown in Figure 5 for an 18-inch DIP force main.

Table 1: Measured and expected gradients of the HGL and the corresponding maximum diameter restriction, maximum elevation discrepancy, and minimum roughness coefficient for each segment of the pipeline.

Pipe segment (ft)	Provided flow rate (GPM)	Measured HGL gradient (ft/100ft)	Expected HGL gradient (ft/100ft)	Max. diameter restriction (inch)	Max. elevation discrepancy (ft)	Min. roughness coefficient
130 - 2,100	2,450	-0.31	-0.13	3.0	3.4	89
2,605 - 3,405		-0.12		N/A	-0.1	N/A
3,405 - 4,670		-0.34		3.3	2.6	84
4,820 - 5,285		-0.18		1.1	0.2	119
5,605 - 6,235		-0.16		0.8	0.2	125
6,235 - 7,425		-0.21		1.8	1.0	108
7,450 - 8,530		-0.11		N/A	-0.3	N/A

CONCLUSION

A methodology for calculating the HGL from free-floating, in-line inspection tools was presented in this paper along with the subsequent analysis of the HGL to provide insight into the location and level of deposits within a pipeline. The ease of deploying and retrieving the neutrally buoyant, in-line tools allows the inspection to take place under regular operating conditions for a representative measurement of the pipeline pressure. The method of calculating the HGL is robust such that operational changes during an inspection are identified and corrected using different techniques depending on the available information. The resulting HGL illustrates the overall performance of the pipeline and can form the basis of further engineering analysis. The deposit analysis of the HGL indicates segments of the pipeline with a larger build-up of deposits in addition to indicating the maximum level of diameter restriction caused by the deposit build-up. This information helps pipeline operators target and plan cleaning programs. In demonstrating the method, several examples of the high-resolution pressure and HGL profiles were presented.

The ease of deployment allows this approach to be used on a frequent basis for continuous monitoring of the pipeline condition. Comparing the HGL from inspections before and after a cleaning program can measure the efficiency of the cleaning. Additionally, comparing the HGL from inspections after extended periods of normal operation can indicate how the deposits in the pipeline have grown or shrunk. Thus, comparison of the HGL from separate inspections is currently being validated.

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