Tackling Corrosion in the Conveyance System: A Case Study of Advanced Modeling, Testing, and Investigative Techniques to Optimize Control Solutions

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ABSTRACT

The City of Casper, Wyoming operates an extensive wastewater conveyance system that includes the North Platte Sanitary Sewer Interceptor (NPSSI). The NPSSI is a 30-year-old, 47,000-foot-long pipeline ranging in diameter from 24 to 54 inches which is constructed of unlined reinforced concrete pipe. Concerns regarding hydrogen sulfide corrosion prompted the City to undertake a risk-based condition assessment of this interceptor. The primary goal of the investigation was to determine the current extent of hydrogen sulfide corrosion and propose solutions to optimize expenditures for maintaining, rehabilitating and replacing the conveyance infrastructure. The specific objectives were to identify high risk portions of the NPSSI that required rehabilitation; identify portions of the NPSSI which could benefit from a corrosion control technology to extend asset life; and compare corrosion control methods for the portions of the pipeline that did not require immediate rehabilitation.

The investigation began with a video manhole inspection and a preliminary pipeline assessment utilizing a zoom-style, pole-mounted camera. Specific portions of the pipeline that were of highest concern were inspected with closed circuit television (CCTV) cameras. Corrosion modeling was completed to compare several options to curtail corrosion including liquid phase chemical dosing, groundwater injection, and seasonal combinations of these options. Bench-scale chemical testing was completed to screen a number of corrosion prevention chemicals for cost and effectiveness. Full-scale pilot testing was then completed on the two most promising chemicals.

The analysis and testing resulted in a combination of corrosion control strategies including rehabilitation only in segments too corroded to benefit from corrosion curtailment by a combination of liquid phase treatment in the summer and groundwater injection (dilution) in the winter. This optimized approach is estimated to save the City of Casper over 5 million dollars over the next 50 years with expenditures weighted toward the future as illustrated in the figure.
below. Each step in the methodology and findings of this project will be presented culminating in a description the current corrosion prevention program in Casper.

KEYWORDS:
Corrosion, condition assessment, wastewater collection

INTRODUCTION

The City of Casper, Wyoming operates an extensive wastewater conveyance system that includes the North Platte Sanitary Sewer Interceptor (NPSSI). The NPSSI is a 30-year-old, 47,000-foot-long pipeline ranging in diameter from 24 to 54 inches which is constructed of unlined reinforced concrete pipe. The pipe was installed between 1980 and 1983 during a wastewater regionalization project and has been exposed to microbial-induced corrosion (MIC) from hydrogen sulfide (H₂S) and associated sulfuric acid. Corrosion concerns prompted the City to undertake a risk-based condition assessment of this interceptor. The pipeline forms the backbone of the City’s collection system and is a critical asset.

The primary goal of the investigation was to determine the current extent of hydrogen sulfide corrosion and propose solutions for extending the asset life of the NPSSI. The specific objectives were to identify high risk portions of the NPSSI that required rehabilitation; to identify portions of the NPSSI which could benefit from a corrosion control technology; and to compare corrosion control methods for the portions of the pipeline that did not require immediate rehabilitation.

METHODOLOGY

The condition assessment was performed in two phases. Phase I of the assessment was conducted in April through May 2010 by CH2M HILL and focused on manhole and pipeline inspections using a top-side zoom-style video system that was inserted into the manholes to assess existing pipeline conditions. Laboratory tests on scrape samples from inside the manholes were also performed. The results were used to identify evidence of extended corrosion that would require further and more detailed inspections and testing.

The Phase II assessment was conducted in September through October 2011 and involved more detailed closed circuit television (CCTV) inspections of 12,743 LF of specific pipe segments identified during Phase I as needing further investigation. Scouring of the pipe using special high-pressure jetting equipment was performed before CCTV inspections to provide a clear image of the pipe wall condition. Petrographic analysis of select pipe locations was also performed during Phase II to provide more in-depth analysis of the pipe wall composition, extent of corrosion, and condition of the pipe wall exterior.

A corrosion control analysis was performed to determine the feasibility of implementing chemical injection to extend the service life for pipeline segments which did not warrant immediate rehabilitation per the condition assessment. The City has developed a method of
introducing groundwater at the upper reaches of the NPSSI for corrosion control. This process is used during the warmer months of June through October when H2S formation is greatest. Groundwater introduction has resulted in four major benefits: (1) dilution reduced H2S concentration within the waste stream; (2) velocities increased, thereby reducing the release of H2S in the interceptor air spaces because of decreased wastewater detention time; (3) wastewater temperature was lowered, which lessened H2S formation; and (4) H2S formation was reduced because the nitrates in the groundwater decrease the rate of dissolved oxygen depletion resulting in aerobic conditions.

CH2M HILL’s proprietary pipeline corrosion modeling software, INTERCEPTOR, was used to characterize the physical, chemical, and biochemical processes bearing on corrosion within the NPSSI. The corrosion control analysis was performed during early 2012. The INTERCEPTOR model was developed using a mass balance approach and uses a simultaneous solution of liquid and gas-phase steady-state mass balances to represent several important reactions/processes, including the following:

- Liquid-phase generation of sulfides
- Temperature and biochemical oxygen demand (BOD) effects on sulfide generation
- Liquid-phase bulk transport of sulfides
- Liquid-phase natural oxidation of sulfides
- pH-dependent sulfide species distribution (i.e., H2S, HS−, and S2−)
- Liquid–vapor mass transfer of H2S
- Liquid drag induced natural ventilation rates
- Vapor-phase bulk transport of H2S
- Liquid phase chemical removal of sulfide
- Reinforced concrete pipe corrosion

The model was used to compare three different alternatives: year-round liquid phase chemical treatment; year-round vapor phase treatment; and summer liquid-phase chemical treatment and winter groundwater injection. The corrosion model was used to determine the predicted cost effectiveness of various corrosion inhibitors that could delay capital outlays for rehabilitation of portions of the interceptor. A capital improvements plan was developed based on asset management recommendations for rehabilitation and operations and maintenance from the Phase I and II study results.

Following the corrosion modeling, bench-scale testing was completed in the summer of 2012 to determine the cost and effectiveness of several liquid phase treatment technologies for removal of sulfide in the NPSSI wastewater. Bench-scale testing was recommended to narrow the cost range and eliminate the least cost-competitive options before proceeding with more costly assessment techniques such as pilot testing.

Four chemicals were tested for sulfide control on a wastewater sample from the downstream end of the NPSSI. Each chemical was tested at several doses to establish a dose/response curve for each chemical on the wastewater sample. The dose response curves were then used to determine the optimum dose rate for each chemical and to compare the cost effectiveness of chemicals for removing sulfide.

Following the bench-scale testing, the most promising of the tested liquid chemicals (ferrous chloride) was used in a two-week, full-scale pilot test on the NPSSI during the summer of 2013.
In addition, calcium nitrate (Bioxide) was also used in a separate two-week, full-scale trial. Nitrate products such as Bioxide cannot be bench-scale tested since they act at a microbial level and need to be tested in situ. The pilot testing methodology was designed to achieve two goals: 1) Determine the effective dose rate to suppress sulfide using both Bioxide and ferrous chloride and 2) Determine an optimized dose rate that controls sulfide effectively without excessive overdosing. The results would then permit the City to choose the most cost effective chemical for implementation of permanent liquid phase treatment, and to provide initial guidance on the dosing regimen including estimated cost.

Four thousand gallons each of Bioxide (37% NO$_3^-$) and ferrous chloride solution (38% FeCl$_2$) were delivered by tanker truck to the dosing site. A 6,500 gallon polyethylene tank was used for the duration of the pilot. The tank was fitted with a PVC fill-pipe assembly terminating in a cam-lock fitting compatible with the tanker truck hose. A manhole on top of the tank provided access for cleaning between and after chemical dosing. Two valves at the bottom of the tank provided a tap for chemical feeding. An HDPE liner supported by staked wire fencing was set up to provide secondary containment in the event of a spill or leak. Figure 1 shows a photo of the tank being placed.

**Figure 1 - Placing Temporary Chemical Tank**

Because hydrogen sulfide in the sewer headspace causes corrosion, vapor phase hydrogen sulfide concentration was the key parameter assessed as part of the pilot testing. Detection Instruments Odalogs were installed under the manhole cover at the 13$^{th}$ Ave. and K Street locations for the duration of the pilot test (however, the Odalog was not installed at K Street until the start of Bioxide dosing). The Odalogs were set to measure concentration at 1-minute intervals and store measurements in an internal memory chip. Data was periodically uploaded via a remote access cell phone connection. In this way, data could be monitored without removing the Odalogs. The 13$^{th}$ Avenue Odalog was replaced with a fresh Odalog midway through the pilot test.
Continuous monitoring of hydrogen sulfide concentrations provided the ability to observe diurnal changes in hydrogen sulfide loading during baseline conditions and the response of hydrogen sulfide to changes in chemical dose during testing. Odalogs have an accuracy of ± 1 ppmv at the low end of their range.

Liquid phase sampling required manholes to be opened and a wastewater sample collected each time a grab sample was made. Liquid phase dissolved sulfide was measured in the field using Gastec colorimetric tubes which have a range of zero to 20 mg/L and an accuracy of ± 0.5 mg/L. Nitrate concentration was measured using AquaCheck nitrate test strips. Ferrous iron was measured using a ferrous Iron Color Disc Test Kit, Model IR-18C.

FINDINGS

The results of the INTERCEPTOR corrosion model demonstrated that, without intervention, the pipes with remaining concrete cover over the rebar may not last the remaining 20 years of the design life (assuming a 50-year service life). Figure 2 presents the results for summer dissolved sulfide and corrosion rate. The model-predicted results are presented as continuous curves progressing from upstream to downstream (left to right). Measured values are presented as individual data points.

Figure 2 – Corrosion Modeling Results
Groundwater injection has made a positive impact in terms of sulfide reduction, as evidenced in the above figure by the drop in measured liquid phase sulfide at approximately 9,000 feet downstream. However, it is not sufficient during the warm season because the hydrogen sulfide generation and associated corrosion rate is above what is recommended for maximizing pipeline asset life. During the winter, groundwater injection may sufficiently slow corrosion, provided liquid-phase chemical treatment is implemented in the summer.

The decision of which chemical to use was further examined during the bench-scale testing to refine the cost effectiveness. The effectiveness of liquid phase treatment chemicals can vary in some cases over an order of magnitude and depends on the constituents specific to the wastewater in question. For this reason, bench-scale testing was needed to narrow the cost range and eliminate the least cost-competitive options before proceeding with more costly assessment techniques such as pilot testing.

Four chemicals were tested for sulfide control on a wastewater sample from the downstream end of the NPSSI. Each chemical was tested at several doses to establish a dose/response curve for each chemical on the wastewater sample. The dose response curves were then used to determine the optimum dose rate for each chemical and to compare the cost effectiveness of chemicals for removing sulfide.

Liquid-phase treatment chemicals may or may not be capable of removing sulfide down to non-detectable concentrations. Therefore, a non-zero benchmark was selected of 0.5 mg/L of dissolved sulfide. This dose target was used to compare the cost/effectiveness of each chemical. The dose target is also relevant as a goal for acceptable corrosion control. Figure 3 shows an example chemical dose response for hydrogen peroxide for removing dissolved inorganic sulfide in the City of Casper wastewater. These results indicate that peroxide was efficient for removing dissolved sulfide from the wastewater sample. The target was achieved at a dose of less than 1.6 g H₂O₂/g sulfide, as compared to the stoichiometric dose of 1.0 g H₂O₂/g sulfide. This analysis was performed for all four of the tested chemicals.
For the tested chemical oxidants and sulfide precipitants, the bench-scale testing results were used to calculate the cost for removing sulfide in terms of \$/lb sulfide removed, as shown in Table 1.

**Table 1. Chemical Cost per Mass of Sulfide Removed – Oxidizers and Sulfur Precipitants**

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Bulk Delivered Cost ($/gal)</th>
<th>Chemical Concentration (weight fraction)</th>
<th>Chemical Density (lb/gal)</th>
<th>Dose to Achieve Target (lb/lb sulfide)</th>
<th>Chemical Cost ($/lb sulfide)</th>
<th>Cost @ 2.5 mg/L sulfide ($/yr/mgd)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaOCl</td>
<td>$1.12</td>
<td>12.5%</td>
<td>10.00</td>
<td>3.5</td>
<td>$3.14</td>
<td>$23,800</td>
</tr>
<tr>
<td>H$_2$O$_2$</td>
<td>$6.00</td>
<td>50.0%</td>
<td>10.00</td>
<td>1.6</td>
<td>$1.92</td>
<td>$14,600</td>
</tr>
<tr>
<td>FeCl$_2$</td>
<td>$1.89</td>
<td>30.0%</td>
<td>11.00</td>
<td>3.8</td>
<td>$2.18</td>
<td>$16,500</td>
</tr>
<tr>
<td>FeCl$_3$</td>
<td>$2.02</td>
<td>40.0%</td>
<td>12.00</td>
<td>10.0</td>
<td>$4.21</td>
<td>$32,000</td>
</tr>
</tbody>
</table>

Table 1 shows that, at $1.92/lb of sulfide removed, hydrogen peroxide was the most cost-effective chemical for removing sulfide. However, peroxide alone would not be feasible for dosing to the NPSSI because it only has a residual effectiveness of between 30 and 60 minutes. In other words, it reacts indiscriminately for 30 to 60 minutes and thereafter has no ability to remove sulfide. Since the NPSSI has an average detention time of approximately 8 hours, a successful peroxide dosing program would require at least four dosing stations, the sites for
which, are not available. The second most cost-effective chemical was ferrous chloride at $2.18/lb of sulfide removed. Ferrous would have sufficient residual effectiveness and would remain available in solution to react with sulfide as it is formed. Thus, ferrous chloride would be the most practical and economical choice.

Full-scale pilot testing of ferrous chloride and calcium nitrate was performed to provide further insight into the cost effectiveness and operability of liquid chemical treatment. A chronological overview of the results is presented in Figure 4. As shown, baseline hydrogen sulfide vapor phase concentrations are fairly consistent for the midpoint 13th Avenue location when chemicals were not being fed (i.e. between chemical dosing trials) and range between approximately 5 and 30 ppmv. Vapor phase hydrogen sulfide and liquid phase dissolved sulfide were significantly suppressed at both locations during both Bioxide and ferrous chloride dosing.

Figure 4 – Pilot Test Overview with Vapor Phase Continuous Hydrogen Sulfide and Liquid Phase Dissolved Sulfide Concentrations

The pilot test demonstrated that both chemicals were capable of suppressing sulfide. However, ferrous was far more cost effective at 250 gallons per day, times $2.10 per gallon, as compared with Bioxide at 500 gallons per day, times $3.39 per gallon. These dose rates are for the warmest part of the year during dry weather when the testing occurred.

A flow rate of 250 gallons per day of 38% ferrous chloride solution to remove 4.53 mg/L (the downstream baseline concentration during the pilot) of sulfide from 4 mgd (approximately half
of the average wastewater treatment plant influent flow) equates to a dose effectiveness of 6.8 grams FeCl$_2$ per gram sulfide. This is significantly higher than the laboratory measurement which was near stoichiometric at 3.8 grams per gram, though much lower than the typical high field dose of 12 grams per gram. This result demonstrates the value of pilot testing to take into account actual field conditions.

Assuming that the sulfide concentration varies by a factor of two over the 6 warm months, (2.37 to 4.53 mg/L), the chemical cost at $2.10 per gallon is estimated to be $70,000 per year to dose during the six warm months. This assumes the dosing protocol would be adjusted in response to seasonal changes in sulfide loading over the warm months, based on hydrogen sulfide monitoring data, with a flat diurnal dosing profile. Savings could potentially be achieved by implementing a variable diurnal dosing schedule such as was tested during the second week of the ferrous pilot test. Therefore $70,000 per year should be considered a reasonably conservative estimate for chemical costs.

COST-EFFECT ANALYSIS

The cost effectiveness of the status quo of summer groundwater injection (Option A) versus implementing a 6-month summer liquid phase corrosion control program with a 6-month winter groundwater injection period (Option B) was compared over a 50-year period. The comparison included operations costs for corrosion control and capital costs for trenchless rehabilitation at predicted appropriate times, based on the respective corrosion rate and failure thresholds for reinforced concrete pipe sewers. Figure 5 shows the comparison of cumulative costs over 50 years.

**Figure 5 – Cumulative Costs for Rehabilitation and Corrosion Control Options**
Both options have nearly identical costs for the first five years and both assume rehabilitation of the portions of the pipeline that are in need of immediate rehabilitation. Option B is slightly more expensive in the first five years due to the costs for implementing chemical addition for corrosion control. However, the cost comparison shows that significantly deferred rehabilitation costs, and long-term cost savings of approximately $5 Million over the 50-year forecasted period would result from implementing the liquid phase treatment in the summer and groundwater injection in the winter (Option B). Overall, the additional cost of the liquid phase treatment is offset by the delayed rehabilitation costs that result from the slower corrosion rate. Thus the recommended set of corrosion control options represents significant cost optimization and savings for the City.

REFERENCES


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