Internal PCCP Force Main Deterioration – Analysis and Rehabilitation

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Abstract

This paper presents a case study of a Prestressed Concrete Cylinder Pipe (PCCP) system that is experiencing deterioration and a failure resulting from internal corrosion. The corrosion mechanism is Sulfuric Acid attack due to Hydrogen Sulfide gas (H_2S) generated from the wastewater. The PCCP pipeline is located in Regina, Saskatchewan, Canada and was constructed in 1979. The nominal inside diameter is 1350 mm (54") and the pipeline was designed as a sewage force main. In 1999, approximately 75 m (246 feet) of the pipe failed and was replaced with HDPE pipe. In 2008, an internal inspection was conducted downstream of the failed section. The inspection was conducted using man entry and by close circuit television (CCTV). The inspection found five (5) pipe sections under severe corrosion attack where the interior concrete surfaces near the crown of the pipe had deteriorated exposing the reinforcing. Another nine (9) sections also showed early signs of H_2S attack.

A post inspection hydraulic analysis indicated the deteriorating pipe section does not flow full, and the hydraulic regime along this section is supercritical transitioning to subcritical resulting in a hydraulic jump forming within the pipe. The wastewater contains high concentration of sulfides. The turbulent flow conditions at the hydraulic jump exacerbate the release of H_2S gas from the aqueous phase to the air phase. The H_2S gas collects near the crown of the pipe and initiates corrosion attack on the concrete surface. A rehabilitation strategy was developed to extend the service life of the PCCP force main.

1. Introduction

A condition assessment was carried out in the 1350 mm (54") PCCP force main used for conveyance of wastewater from a pump station to the wastewater treatment plant. The objective of the condition assessment was to determine the internal condition of a section of PCCP force main that experienced a failure in 1999. The force main was initially installed in 1979. The assessment program consisted of the following phases:

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- Historical review
- Pipe entry and internal inspection
- Hydraulic analysis
- Alternative rehabilitation assessment

Figure 1 shows the profile of the force main system. The total length of the PCCP force main is 1900 m. The assessment program focused on about 200 meters of the force main from Station 0+700 to Station 0+900.

The PCCP force main was manufactured in 1978 in accordance to AWWA C301 (L) Standard in 7.32 m (24') lengths and installed in 1979. In 1991, 78 m (246') of PCCP pipe near a high point was replaced using HDPE pipe. Historical records indicated the top quadrant of the failed pipe collapsed when the failure was discovered. The five (5) sections of collapsed pipes along with other distressed pipes were replaced with HDPE pipe. Plant operation staff expressed a concern that there may be other distressed pipes in the vicinity of the 1991 failure. Therefore, a condition assessment program was undertaken in 2008.

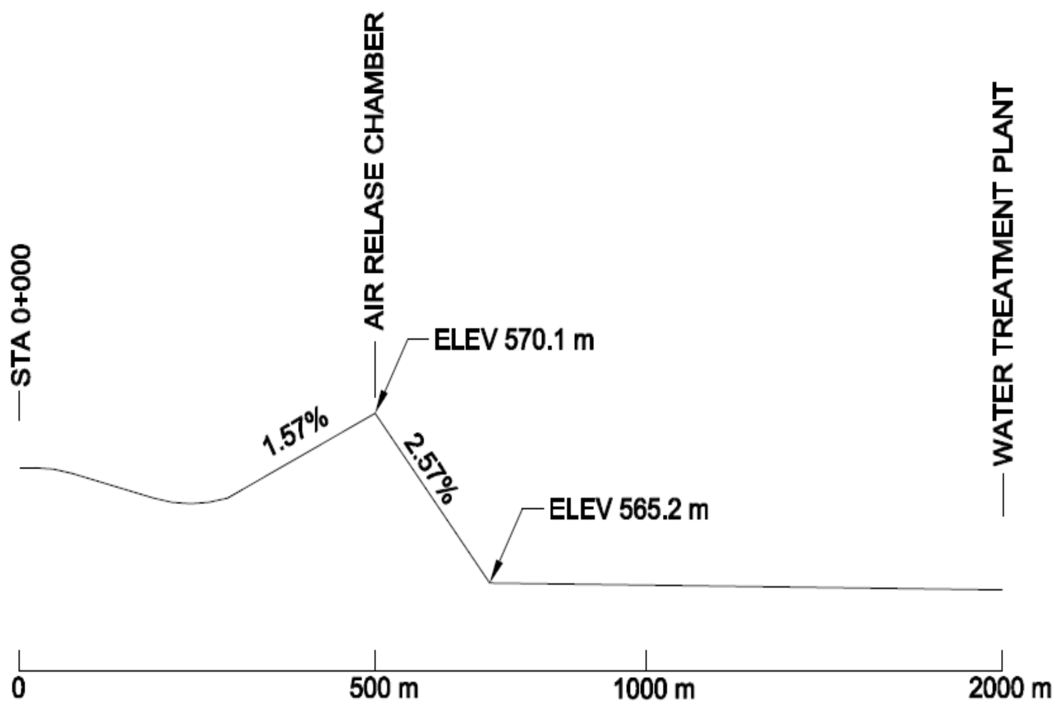

Figure 1. 1350 mm diameter Force main Profile

2. Internal Inspection

Inspection of the interior pipe surface was conducted by CCTV and man entry. Prior to man entry, various safety procedures such as forced air ventilation, safety line, supplied air and self breathing apparatus (SBA) were arranged. The inspection concentrated on 200 meters of pipe downstream of the 1991 failure. A total of twenty (20) pipe sections were manually inspected. Defects were then coded in accordance to the NASSCO's PACP format. The following defects were noted:

- The concrete surfaces along the pipe invert and below the flow line were in good condition. The surfaces were very hard and dense as indicated by the sounding with a hammer.
- Five (5) pipe sections showed surface corrosion of the concrete surface and exposed aggregates. As shown in Figure 2, the corrosion is concentrated along the crown of the pipe between the one o'clock and eleven o'clock positions. At some locations, the steel cylinder is exposed. The joints between these five (5) pipe sections also showed distress. Extensive concrete spalling and corrosion of the exposed steel bell and spigot rings were also observed. This is shown in Figure 3.
- Nine (9) pipe sections showed early signs of corrosion at the crown of the pipe. This is shown in Figure 4.
- There was extensive sand and gravel debris along the pipe invert.
- The remaining pipe sections were in good condition.

The inspection showed one specific section of the force main experiencing severe distress while the remaining pipe section was in relatively good condition, typical of a 30 year old pipe. It was also obvious that the corrosion defects were caused by H_2S/H_2SO_4 corrosion along the crown of the pipe. The corroded areas were above the flow line and the corroded areas got progressively larger in the upstream direction.

Figure 2. Surface Corrosion and exposed aggregates.

Figure 3. Spalling and exposed bell and spigot ring.

Figure 4. Early stages of corrosion at crown of pipe.

3. Hydraulic Analysis

The flow from the pump station to the wastewater treatment plant is dependent on the time of day and the seasons. Historical flow records indicate the following:

- Average dry weather flow during the night – 80 ML/D or .929 m^3/s (32.7 cfs)
- Dry weather flow during the day – 125 ML/D or 1.45 m^3/s or (51.2 cfs)
- Average wet weather flow – 250 ML/D or 2.89 m^3/s (102 cfs)
- Peak wet weather flow – 300 ML/D or 3.47 m^3/s (122 cfs)

The dry weather flow typically occurs between September and May while the wet weather flows occur during the summer season.

As shown in Figure 1, the force main section that is the subject of this assessment is located at about Station 1+000. The pipe was constructed with the following slopes:

- + 1.57%, to air release high point
- - 2.57%, from high point to slope transition
- -0.11%, from slope transition to wastewater treatment plant

Under uniform gravity flow conditions, the theoretical pipe capacities of the 1350 mm (54") diameter pipe flowing full for the 2.57% and 0.11% slopes were determined using the Manning formula with a coefficient (n) of 0.013. Table 1 shows the flow summary.

Table 1.
Uniform Gravity Flow Capacity-1350 mm dia. pipe

Slope (%)	$R^{2/3}$ (ft)	$S^{1/2}$ (%)	Velocity (Ft/s)	Flow – Q (Ft^3/s)	Flow – Q (m^3/s)
2.57	1.082	.163	19.88	316.1	8.95
0.11	1.082	0.331	4.11	65.3	1.85

A comparison of recorded flows and theoretical flows confirmed that some of the time, the force main operates at partial flow conditions. For example, for the case of -2.57% slope at a flow of 250 ML/D, the ratio of actual flow (q) to full capacity (Q_{full}) or q/Q_{full} is 0.32 (2.89 m^3/s /8.93 m^3/s). Using Figure 5, Hydraulic Elements Graph for circular pipe, the following partial full flow ratios are determined:

- $\frac{d_1}{D_{full}} = 0.40$ and $\frac{v}{V_{full}}$, $= 0.90$
- Partial depth (d_1) = 0.40 x 1350 mm = 540 mm or 0.54 m
- Velocity or v = 0.90 x V_{full} = 0.90 (8.93/1.48) = 5.46 m/s

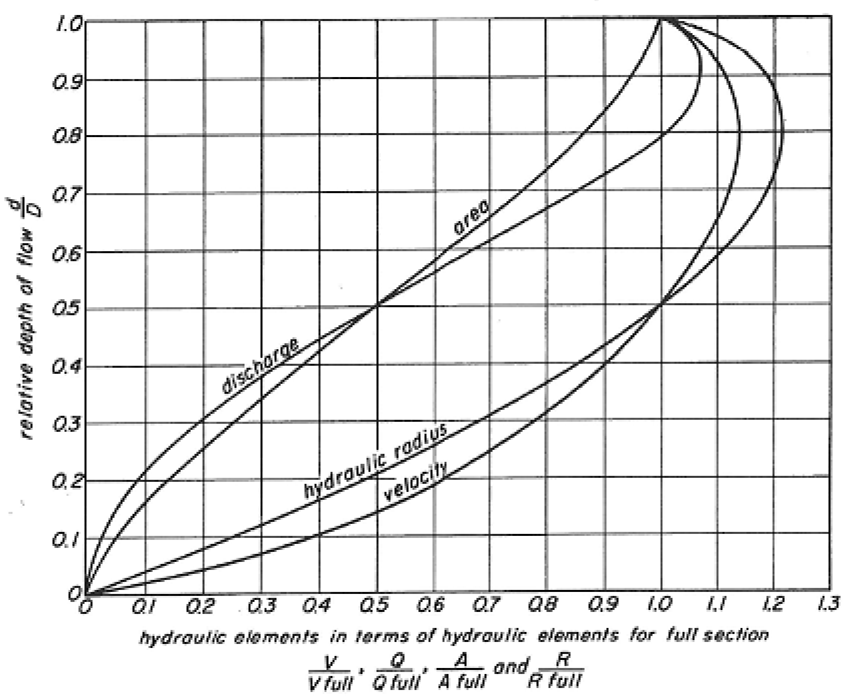

Figure 5. Hydraulic elements-relative flow properties of circular pipe

The corresponding Froude number is $F_1 = V/(gd_m)^{0.5}$,where d_m is the mean hydraulic depth. d_m = area (A)/water surface width (T). Using a ratio of q/Q of 0.4, the following ratios were determined from Chow: T/D = 0.98, a/A =.375 and d_m =A/T = .421 m. The Froude number is 5.46 m/s /(9.81 m^2/s x .421 m)$^{.5}$ = 2.69. This is greater than unity and the flow regime is supercritical. Table 2 is a summary of partial flow conditions for various flow conditions for the -2.57% pipe section.

Table 2.
Partial flow condition for historical flow (slope = 2.57%)

q (m^3/s)	Q (m^3/s)	q/Q	d_1/D	d_1 (m)	V_1/V	v_1 (m/s)	d_m	F Froude #
.926	8.95	.103	.22	.3	.64	3.87	.19	2.8
1.27	8.95	.142	.26	.35	.72	4.36	.21	3.0
1.45	8.95	.162	.27	.36	.75	4.54	.22	2.9
2.89	8.95	.323	.40	.54	.90	5.46	.42	2.7
3.47	8.95	.388	.45	.61	.94	5.7	.47	2.65

The downstream pipe at 0.11% will flow full at 2.89 m^3/s. Therefore a hydraulic jump is formed between the transition from the -2.57% slope section to the -0.11% section.

The Sequent Depth or d_2 of the hydraulic jump on a flat slope can be determined using the approximation Sequent Depth Ratio Y as derived by Hager (1999):

$Y = 1.16\ (F_1\ 0.85) = \frac{d_1}{d^2}$ or $d_2 = d_1\ (1.16)\ (F_1)^{0.85} = 0.54\ \text{m}(1.16)(2.37^{0.85}) = 1.30$ m.

The approximation by Hager for the above equation is +/- 2% for 2< F<10.

The sequent depth will actually be slightly higher due to the effect of the weight component resulting from the sloping pipe.

The critical depth Yc from Hagar's approximation is:

$Yc = (Q/(gD)^{1/2})^{1/2}$ or $= (2.89/(9.81 \text{ x } 1.35)^{1/2})^{½} = 0.89$ m.

In summary, the Froude number is = 2.7 and the Sequent Depth is greater than the critical depth. This clearly indicates a hydraulic jump occurring at the slope transition.

3.1 Hydraulic Jump Flow Characteristics

At a hydraulic jump, the flow is characterized by turbulence and large quantity of air is entrapped at the intersection of the upstream flow and the jump roller. The air is entrained into a free shear layer which is characterized by intensive turbulence production. (Chanson,1994, Wilhelms et al., 2005). The turbulent flow regime creates an ideal condition for natural aeration due to (Mak, 1999):

1. Large water surface areas resulting from mixing/turbulent flow provides a large surface area for gas absorption and release. The ratio of exposed area is very large in comparison to the volume.
2. The liquid film thickness is reduced by constant agitation and internal mixing of the liquid. This will increase the gas transfer coefficient and increase the gas transfer rate.
3. Large quantities of air are trapped due to high level of shear and turbulence. The air is available for absorption to the liquid at the air-water interface.

The turbulence can be characterized by the difference in the upstream and downstream Froude number and the energy loss. For transitional flow up to $F = 1.5$, the jump is undular. For $F>2$, the undulations disappear and the direct hydraulic jump is formed (Hager, 1999).

With respect to gas transfer at the air-water interface, Chanson (1994) conducted laboratory experiments and developed equations to estimate the gas transfer at a hydraulic jump with partially developed inflow.

4. Hydrogen Sulfide Formation and Effects

Hydrogen sulfide gas (H_2S) formation in sewer networks has been extensively studied due to its harmful effects to human health, odour nuisance, and corrosive potential to pipelines. These problems are directly associated with gaseous hydrogen sulfide H_2S (g). When H_2S is in contact with sewer surfaces exposed to the sewer atmosphere, this gas can be absorbed and oxidized to sulfuric acid by aerobic and autotrophic Thiobacillus bacteria. H_2S concentration in a sewer atmosphere varied from 0.2 to 300 ppm (Yongsiri, 2004).

Topography has an effect on the potential for hydrogen sulfide generation. In flat regions, collection systems are designed with flat slopes resulting in an increase in hydrogen sulfide generation due to low velocities, long detention times and solids buildup. The City of Regina is located in the prairie region of Western Canada and its topography is flat. Other parameters that affect hydrogen sulfide and corrosion in wastewater systems are: dissolved sulfides, pH, BOD and temperature, dissolved oxygen, velocity, junctions, force mains, siphons, and ventilation (American Concrete Pipe Association, 1984).

H_2S in the water phase can be transferred to the air phase. H_2S emission from the water phase only plays a role when there is a free surface from which the gas can escape.

The turbulence level in the water phase plays a significant role in the air-water transfer rates of H_2S. Higher turbulence can increase the transfer of H_2S by more rapidly bringing H_2S molecules into contact with the air interface as the transfer processes are controlled by the film in the water phase (i.e. greater transfer resistance in the water film). Increased turbulence can also make the interfacial area larger, thereby giving a higher possibility of H_2S molecules being transferred. This is illustrated in Figure 6 showing a relationship between the overall hydrogen sulfide mass-transfer coefficient (K_La_{H2S}) versus Froude numbers (Yongsiri et al, 2004). The Froude number is a ratio of inertia to gravitational forces and is a reasonable representative for expressing the increase in turbulence level at a hydraulic jump.

Although the data shown in Figure 6 was derived from low Froude Numbers, the laboratory data clearly shows an increasing trend for the overall hydrogen sulfide mass transfer coefficient with increasing Froude Number. This confirms the strong influence of turbulence and release of H_2S from the liquid phase into the air phase.

Figure 7, also from Yongsiri, shows the relationship between the $K_La_{(H2S)}$ and mass transfer coefficient of oxygen, $K_La_{(O2)}$ at different pH levels. It is interesting to note that the H_2S transfer process in water was always slower than that of the re-aeration process at any Froude number investigated.

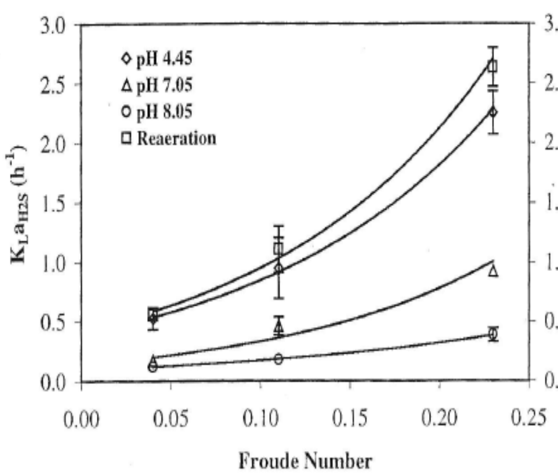

Figure 6. Mass transfer coefficient for H_2S versus Froude numbers at different pH values.

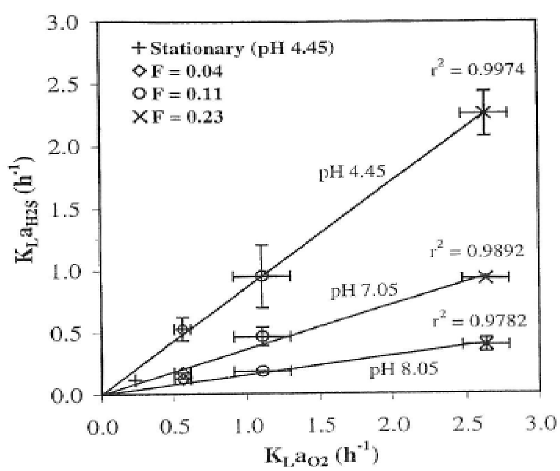

Figure 7. Relationship between H_2S and O_2 mass transfer coefficients.

Experiments by Yongsiri et. al. also showed an approximate linear relationship between the ratio of $K_La_{(H2S)}$ and $K_La_{(O2)}$. The following empirical equation can be use for practical application in wastewater engineering:

$$K_La_{(H2S)} = (1.736 - 0.196\ pH)\ K_La_{(O2)} \qquad (4.5 \le pH \le 8.0)$$

Jensen (1995) refined a semi-empirical model to predict re-aeration in sewer:

$$K_La_{(O2)} = 0.86\ (1+0.2F^2)\ (S_L\text{-}v)^{3/8}\ d_m^{-1}\ \theta_r^{\ (T-20)}$$

Where:

F = Froude number = $\frac{V}{(g\, d_m)^{0.5}}$

S_L = Slope of sewer (m/m);
V = Mean flow velocity (m/s);
d_m = Mean hydraulic depth (water cross-sectional area divided by the width of the water surface) (m)
θ_r = Temperature coefficient for re-aeration = 1.024;
T = Temperature (degree C)

5. Alternative Rehabilitation Assessment

The man entry and CCTV inspection confirmed some pipe sections are under H_2S/H_2SO_4 corrosion attack. H_2S gas is released from solution and accumules along the crown of the pipe. The mixing and turbulent flow associated hydraulic jump exacerbate the release of H_2S gas and resultant corrosion attack. Where the pipe is flowing full or at sub-critical flow condition, there were minimal signs of corrosion.

Various remedial options were analyzed to address the defects. The options include:

- Pipe replacement
- Internal spray barrier coating
- Internal structural lining

The selection of remedial methods considered the duration of the force main shut down since stopping flow affects the wastewater treatment plant operation. The condition assessment determined that five pipe (5) sections and associated joints are in need of immediate repair or replacement. Another nine (9) pipe sections are in the early stage of surface deterioration along the crown of the pipe. Based on factors such as risk of failure, environmental factors, economic consideration, disruption to plant service, availability of material local labour, the final remedial plan includes:

- Replacement of eight (8) PCCP pipe sections with HDPE pipe material
- Cleaning and removal of debris downstream of the pipe replacement section
- Installation of a barrier coating on the crown of the pipe between one o'clock and eleven o'clock position on nine (9) sections of pipe.

The proposed remedial work was completed in 2010 over a 13-day period.

6 Summary and Conclusion

A man entry and CCTV condition assessment of a 1350 mm (54") diameter concrete force main showed deterioration of the interior surfaces near the crown of the pipe. The deterioration is the result of hydrogen sulfide/sulfuric acid corrosion. One section of the force main containing about five (5) pipes and associated joints experienced severe deterioration. The remaining pipe sections were in relatively good condition.

Hydraulic analysis showed the pipe section with severe deterioration is flowing partially full and located upstream of a hydraulic jump where the flow regime is supercritical. The existence of the hydraulic jump created intense mixing and turbulence within the pipe. The hydraulic jump in turn increased the release of dissolved hydrogen sulfide gas from the aqueous solution into the air space and accelerated the corrosion attack on the crown of the pipe. Remedial measures were developed to repair the pipe and extend the service life.

Acknowledgment

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