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Analyzing SCADA to Understand the Contribution of Hydraulic Pressures to Trunk-Main Failure

G. Williams[a]*, G. Kuczera[a]

[a]*University of Newcastle Australia, University Drive, Callaghan 2308, Australia*

Abstract

Water distribution networks throughout the world are ageing, which increasingly leads to sudden pipe failure. About 108 trunk-main pipe failures in an urban sub-network were investigated using a pipe failure data base and SCADA (Supervisory Control and Data Acquisition) data to understand the contribution of hydraulic pressure to pipe failure using multiple lines of evidence. The forensic investigation revealed a dominant system-wide failure mode which was characterized by predominately off-peak high speed pumping with limited pressure relief from downstream reservoirs. A frequency analysis was conducted for greater understanding of the dominant failure mode.

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Keywords: Pipe failure; SCADA; multiple lines of evidence; mode of failure; pump off peak.

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1. Introduction

Water distribution networks throughout the world are ageing and therefore greater understanding of the factors leading to pipe failure is increasingly useful. Pipe failure can impact customers and incur high maintenance, business, social and environmental costs. In addition the water loss due to pipe failure and pipe leaks is often critical in areas of low rainfall and this problem may worsen with the effects of climate change. Replacing ageing infrastructure is expensive and therefore reducing pipe failure and extending pipe life is highly desirable. It is often difficult to determine the exact cause of pipe failure as there are a number of variables to consider such as the pipe condition (pipe properties, soil conditions and corrosion) and the loading (internal and external pressures and discharge) which together result in a history of failure in the system. Equation 1 notionally describes the critical

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* Corresponding author. Tel.: +61401806791; fax: +61249216991.
E-mail address: gareth.s.williams@uon.edu.au

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resisting stress S_{crit} of a buried pipe, which must be greater than the sum of the applied stresses (failure variables) acting on the pipe, to prevent failure:

$$S_{crit} > S_p + S_s + S_b + S_{res} \tag{1}$$

Where S_p is the pressure-related stress, S_s is the soil stress, S_b is the pipe bending stress and S_{res} is the residual stresses [1]. These stresses act circumferentially and longitudinally on the pipe and should be analyzed separately [1]. For this investigation, the focus was to understand the contribution of hydraulic pressures (S_p) to pipe failure alone. The hoop stress is the circumferential pipe stress which occurs due to hydraulic pressure and is denoted by:

$$S_p = pr/t \tag{2}$$

Where S_p is the hoop stress, p is the internal fluid pressure, r is the radius of the pipe and t is the thickness of the pipe. In general, corrosion pitting reduces the thickness of a pipe, t, which increases the circumferential hoop stress on the pipe [2].

The 'mode of failure' refers to how the pipe fails, for example longitudinal fracturing, circumferential fracturing etc. The most common mode of failure resulting from hydraulic pressure is the longitudinal fracture also known as splits or long splits [3]. Hoop stress due to internal pressure (static and transient), crushing forces, or possibly compressive forces may generate the longitudinal fracture [4, 5]. A longitudinal fracture is commonly developed between the areas of corrosion pitting once the hydraulic pressure reaches the critical stress. The other common mode of failure that is generally indicative of hydraulic pressure contributing to failure is the 'blowout hole.' Blowout holes or 'piece out' modes of failure in cast iron and mild steel pipes generally occur because of localized corrosion pitting which reduces the thickness of the pipe and then internal water pressure 'blows' the weakened piece out [4].

Forensic pipe failure investigations on real water systems have been reported in the literature [6-8]. Ivetic [6] investigated two separate cases of transient pressures causing failure. The objective of both investigations was to assign fault i.e. that something or someone did not perform as expected. One of the cases investigated two damaged valves that both failed during system restart on the Abattemarco pipeline in Italy. Ivetic [6] discovered that the two failed valves had their pressure rating reduced from 40 bar to 25 bar after design, presumably to reduce capital costs. The lower pressure rating seemed sufficient for static conditions, however a pressure rating closer to 40 bars was required to resist transient pressures. One of the failed valves also had an imperfection on its casting (commissioning error) and the other valve had an insufficient support.

Rajani et al [7] investigated a 30" cast iron pipe failure in Cleveland USA that experienced bell-spigot joint failure. The three failure mechanisms explored in the investigation were operational loads, ground movement and bell crack due to rotation followed by fatigue loading. The analysis concluded that the failure likely occurred due to the construction of a concrete vault above the pipe, leading to additional rotational stress on the pipe. This rotational stress possibly induced an initial crack in the bell that grew with repeated loading causing the split. A change in color along the failure surface was evidence of a two-phase split.

The literature described above by Rajani et al [7] and Ivetic [6] investigates one and two failure events respectively. However, this research seeks to understand how the distribution system behaves immediately prior to pipe failure and in particular how hydraulic pressure contributes to failure.

To date, no literature has been found describing the forensic investigation of hundreds of trunk-main failures within a large water distribution system using a pipe failure database and historical SCADA (Supervisory Control and Data Acquisition) data. SCADA controls and monitors pump stations, actuated valves and reservoirs in most modern water networks. A trunk-main is defined in the investigated system as having a nominal diameter of DN250mm or greater.

The primary objective of this study is to develop an approach to forensic SCADA investigation into the hydraulic contribution to trunk-main failure. In particular, the study seeks to use multiple lines of evidence to categorize individual failures into the hydraulic states occurring immediately before failure. The investigation was conducted on a ‘Pilot water system’ that is a real water distribution network within Hunter Water Corporation’s (HWC) lower Hunter catchment near Newcastle, Australia.

Section 2 of the paper describes the methodology for collecting multiple lines of evidence about the hydraulic state of the system at the point of failure. Section 3 describes the Pilot water system that was investigated. Section 4 discusses the results of the investigation, which is followed by conclusions in section 5.

2. Methodology

HWC’s pipe failure and SCADA databases were used to develop multiple lines of evidence in support of a hypothesis that a specific hydraulic situation had contributed to trunk-main failure. HWC’s pipe failure data base recorded 108 trunk-main and joint failures between September 1994 and January 2014 in the investigated water system. HWC’s pipe failure data base recorded the notification time, the pipe properties, the mode of failure and the cause of failure.

The ‘cause’ of pipe failure is noted as corrosion, ground movement, increased water pressure, external load etc., and is recorded by maintenance staff. There is generally low confidence in the ‘cause’ of failure; however the confidence can almost always be improved with a thorough forensic investigation using SCADA data.

SCADA controls and monitors pump stations, actuated valves and reservoirs in HWC’s entire water network. The SCADA user is able to view pump station pressures, reservoir levels and actuated valve position both in real time and for historical data.

The following steps represent the general forensic methodology that was conducted for each of the 108 trunk-main failure events in the investigated water system. In general, the process was iterative; as new information was acquired, the previous failures were revisited:

- Find the trunk-main failure location using HWC’s GIS software. Have failures occurred here before? Record the ground surface elevation at the failure location.
- Assess the trunk-main failure data base. What were the caller's comments? What notes did the maintenance staff record about the failure? Is there any formal reporting regarding the failure?
- Estimate the failure time by interrogating SCADA before the phone call time notifying HWC. A transducer recording a pressure collapse followed by an abnormal drop in reservoir water level is an obvious sign of the failure time. Is there any flow meter data supporting the failure time?
- Analyze SCADA traces to determine the hydraulic state immediately before the failure event e.g. fixed speed pump (transient pressure), high speed off peak pumping etc. Assess the failure situation against normal operation.
- How many pumps upstream of the failure location were discharging at the time of failure? Were the downstream reservoirs in the system providing pressure relief (inflow)?
- What is the confidence rating of the assigned hydraulic state (depending on the number of lines of evidence)?

If the failure time was known, a failure sequence and therefore a hydraulic state for the event could be assigned. In which case, a ‘high’ or ‘medium’ confidence rating was applied to the failure event, depending on the number of lines of evidence. However, if the failure time was unknown then it was mostly difficult to assign a failure situation. For most cases when the failure time was unknown an ‘insufficient evidence’ situation was recorded.

3. The pilot water system

The Pilot water system described in this section was chosen for the forensic investigation because of a high concentration of ‘longitudinal fractures’ and ‘blowout hole’ modes of failure which are generally indicative of hydraulic pressure contributing to failure. The sum of the trunk-main pipe lengths in the pilot water system is approximately 28.1 kilometers. Cast iron cement lined pipes and ductile iron cement lined pipes account for 95% and 4.5% of the trunk-main materials respectively. Mild steel cement lined pipes and concrete pipes represent the remaining trunk-main materials.

A schematic of the Pilot water system is shown in Fig. 1. Water enters the Pilot system via PSA (Pump Station

A), where pumping is governed by the water level in reservoirs 1 and 2. If PSA is discharging, then the pressure from PSA is the dominant system pressure distributing flows throughout the network. However, if PSA shuts-off flows are distributed by gravity throughout the network by reservoirs 1 and 2. In low demand periods, PSA is able to discharge to the seven downstream reservoirs. However, when demand increases, pumping from PSD and PSF is required to discharge to reservoirs 7 and 6 respectively. PSA was converted to variable speed pumping in October 2012.

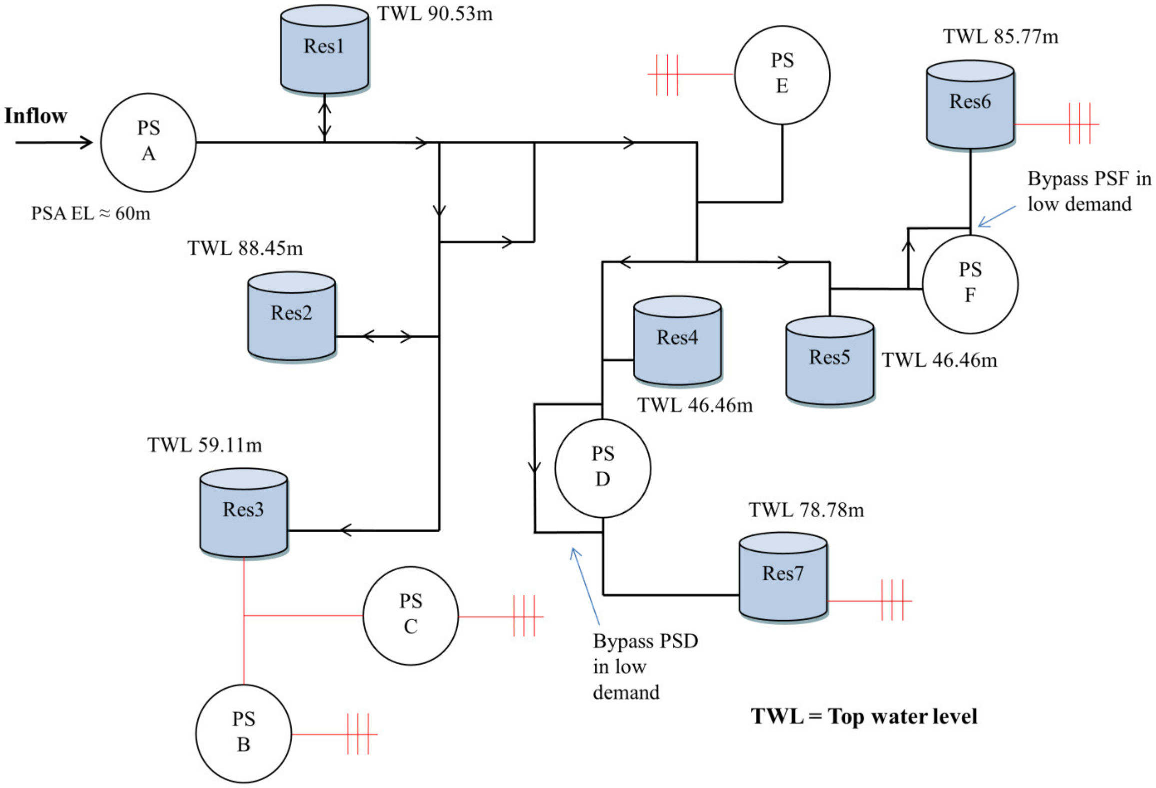

Fig. 1. Schematic of the Pilot water system.

In Fig.1 the bold thick lines represent the trunk-mains. There are additional sub-systems with red, ‘thinner’ lines downstream of Res3, Res6, Res7 and PSE. Pipe failures within these sub-systems were not assessed. Therefore, the hydraulic boundaries for the trunk-main investigation were between PSA and the seven downstream reservoirs and PSE. Any reference to pumping in the next section is from PSA unless noted otherwise.

4. Results and discussion

A summary of the hydraulic states contributing to failure in the Pilot water system is shown below in Fig. 2. The most common failure situation was ‘pump off peak’ (POP) which was characterized by high speed, predominately off peak pumping, with limited pressure relief from downstream reservoirs. The dominance of the POP hydraulic state became obvious through the iterative investigative process.

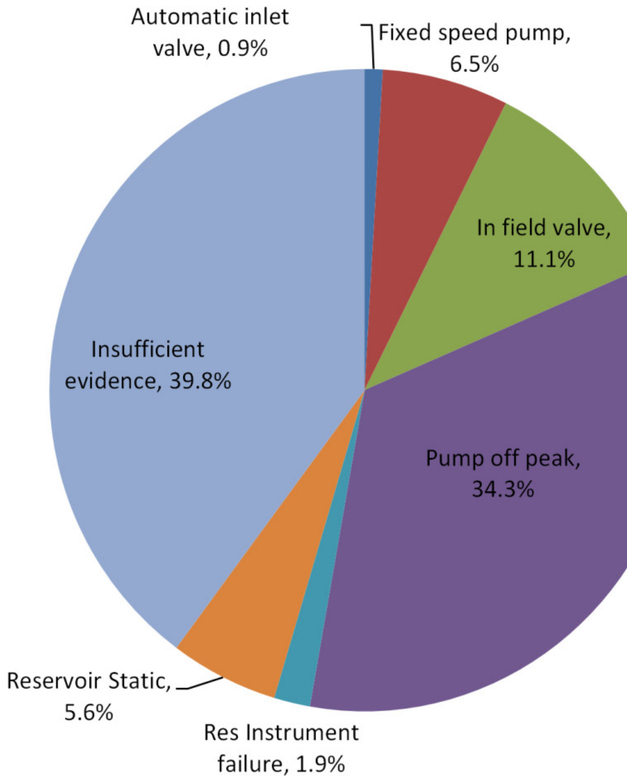

Fig. 2. Hydraulic states contributing to trunk-main failures in the Pilot water system

The following points describe each of the hydraulic states that were assigned to individual failures.

- Reservoir static: When the trunk-main failed there was no upstream pumping from PSA. The pressure in the system at the time of failure was provided by reservoirs 1 and 2. Generally for this failure situation comments from the maintenance staff suggested the trunk-main was in poor condition due to corrosion.
- Reservoir instrument failure: There were two failure events where reservoir 7's sensor that records the water level, was incorrectly recording a low reservoir water level. This error caused reservoir 7's automatic inlet valve (AIV) to open and close continuously. The upstream PSD (fixed speed) was also turning on and off continuously. Transient noise was recorded at pressure transducers located at PSD, PSE and PSF before a trunk-main failure occurred in the Pilot water system.
- Pump off peak (POP): POP was characterized by high speed pumping, predominately during low demand periods with limited pressure relief from downstream reservoirs. Approximately 75% of the failures occurred between 9:00pm and 6:00 am. However, approximately 25% of POP failures occurred when there were one or multiple pumps discharging during the medium-high demand period with limited pressure relief from downstream reservoirs.
- In-field valve: This failure situation arises when maintenance staff open or close valves inducing transient pressures which contribute to failure.
- Fixed speed pump: This event occurred when PSA had a rapid start-up or shut-off which induced a transient pressure and caused a subsequent break.
- Automatic inlet valve (AIV): There was one failure event where the AIV at reservoir 1 closed quickly inducing a transient pressure to cause a subsequent break. And so on

Approximately 40% of the failure events had insufficient evidence to assign a hydraulic state. These events were generally for trunk-main failures occurring before the year 2001 when there was limited SCADA data. Other insufficient evidence cases were for events when the failure time was unknown because of small break flow or because of a high demand period.

Confidence levels were assigned to failure situations based on the number of lines of evidence. There were 33 'high' confidence POP events and 4 'medium' confidence POP events. The key difference between these events was that the failure time was unknown for 'medium' confidence events due to limited SCADA data. However, despite the unknown failure time there were still lines of evidence supporting the POP hypotheses - for example the phone call notification time, extended pumping duration before the notification time and the mode of failure etc.

4.1. Pump off peak pressure relief

The seven reservoirs downstream of PSA can be viewed as surge tanks providing pressure relief to the system. If there was inflow to the reservoir immediately before the failure occurred, it was deemed that the reservoir was providing some pressure relief to the system. Fig. displays the pressure relief state for 33 high confidence POP failures.

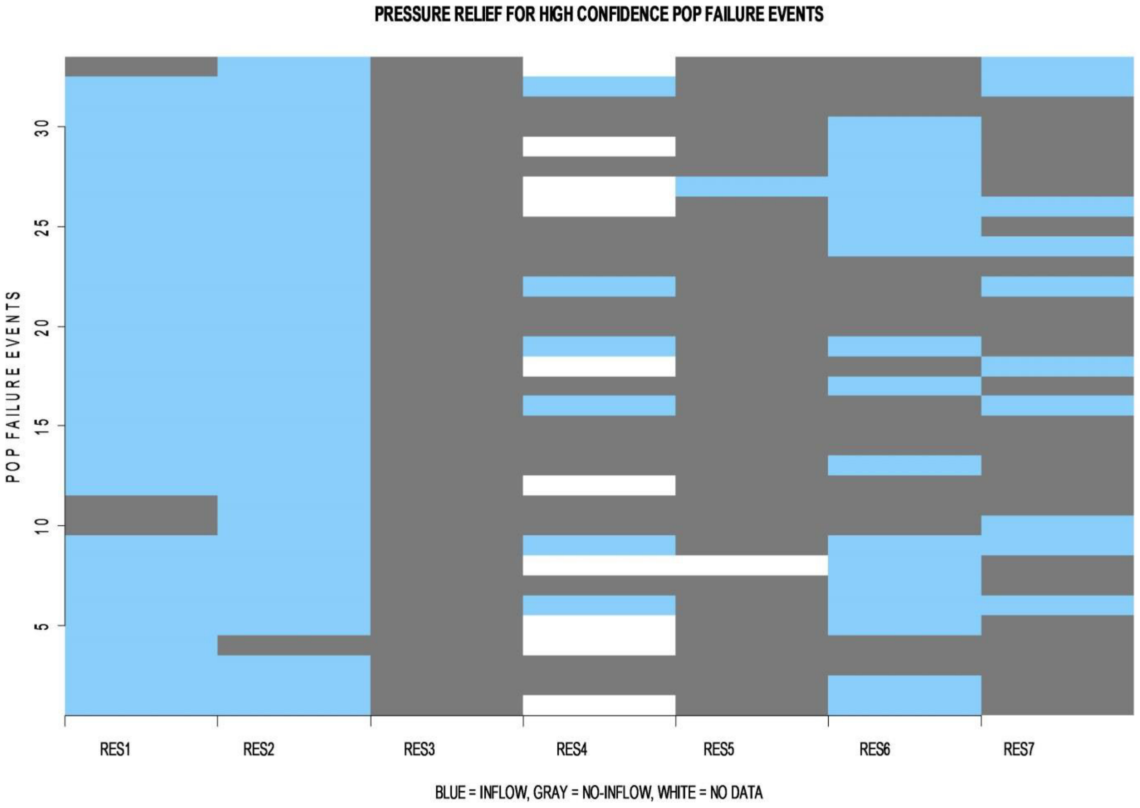

Fig. 3. Pressure relief situations for high confidence POP events.

Fig. shows that for the majority of high confidence POP failures there was pressure relief from reservoirs 1 and 2. This is because POP failures only occur if reservoirs 1 or 2 'call' PSA because they are low. Reservoirs 4 and 5 were generally closed during the POP events. The TWL (top water level) of reservoirs 4 and 5 was approximately

45 meters below reservoir 1's TWL and therefore they filled quickly. Reservoir 6 (TWL = 85.8m) and reservoir 7 (TWL = 78.8m) provided pressure relief immediately before failure approximately 50% and 33% of the time respectively. Reservoir 3 was closed for all 33 of the high confidence POP failure events. It was common for failures to occur approximately 20 minutes after reservoir 3 AIV closed. This result initiated the critical operating state frequency analysis below.

4.2. Critical operating state frequency analysis

The pressure relief analysis in the previous section revealed a critical operating state (COS) characterized by POP hydraulic conditions and reservoir 3 AIV being closed. Analysis was conducted to determine the frequency of the COS contributing to failure. The frequency analysis started in January 2002 and finished in October 2012 because at this time PSA was converted to variable speed pumping. The analysis was conducted for off peak pumping between 11:00 pm and 6:00 am alone. Fig. shows a sample of the COS frequency analysis.

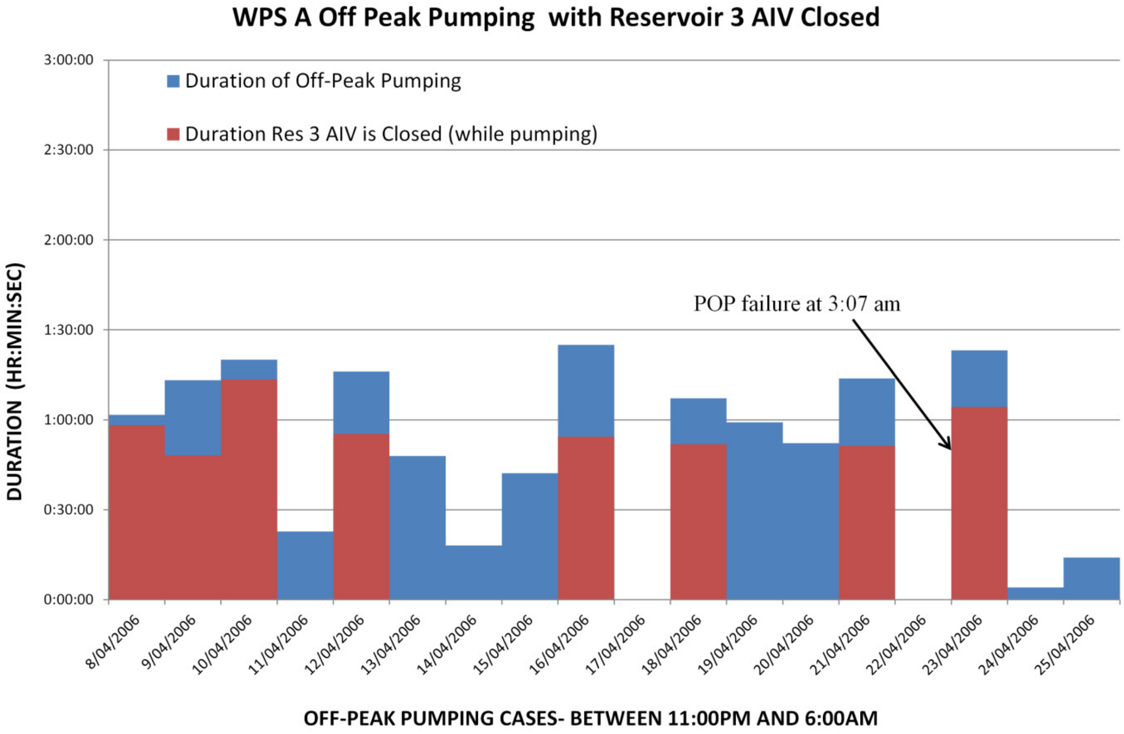

Fig. 4. Sample of the frequency analysis for off peak pumping while reservoir 3 AIV is closed

The COS frequency analysis revealed a POP failure occurred on average 1 in 77 critical operating states. The results may be useful to HWC in the failure mitigation space and for trunk-main replacement planning.

A critical operating state for the POP events was that reservoir 3 AIV was closed for all of the 33 high confidence POP events. Reservoir 3 has a top water level approximately 45 meters lower than reservoir 1 and therefore fills quickly. However, there is potential to optimize reservoir 3's AIV to allow a longer duration of (partial) pressure relief. Similarly, reservoirs 4 and 5 may also be optimized to allow greater surge protection from 'dead end' reservoirs.

Variable speed pumping was enabled at PSA in October 2012. Since this operational change, there were five trunk-main failures downstream of PSA, of which 3 failures were ‘high confidence’ POP failures. Two of these POP events had two pumps discharging at high speed while the other POP event had one pump discharging at high speed. The three POP failures also had a ‘longitudinal fracture’ mode of failure. In light of the failures occurring since variable speed pumping was enabled, there is potential to optimize pumping to reduce the likelihood of POP failures.

5. Conclusion

Multiple lines of evidence revealed a dominant hydraulic state contributing to failure in the Pilot water system. This hydraulic state was called ‘pump off peak’ (POP) which was characterized by high speed pumping with limited pressure relief from downstream reservoirs. Approximately 75% of the POP failures occurred during low demand periods between 9:00pm and 6:00am. However, POP failures also occurred in medium and high demand periods, when 1 or multiple pumps were discharging with limited pressure relief from downstream reservoirs. Generally the POP failures occurred after reservoir 3’s automatic inlet valve had recently closed and the system pressure was increasing, until a weak point was exploited. These weak points were often due to external corrosion pitting that was noted by maintenance staff and in some cases photographed.

The forensic investigation systematically analyzed SCADA data associated with trunk-main failure observations recorded in HWC’s pipe failure data base. The SCADA analysis spanned the state of the surrounding Pilot water system at the time of trunk-main failure. This forensic method proved insightful as the previously unknown ‘POP’ failure trend was revealed.

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