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HIGH RESOLUTION WATER PRESSURE MONITORING FOR THE ASSESSMENT OF FATIGUE DAMAGE IN WATER DISTRIBUTION PIPES

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Abstract

In the last decade, the increasing use of high frequency water pressure monitoring has shown that water distribution networks can be frequently affected by pressure transients. In some instances, thousands of high amplitude cyclic loadings per year have been exerted on pipes posing a risk of fatigue damage. However, despite this awareness of a possible fatigue risk on pipes, current research has not been able to show the extent of the relevance of this risk. To address this issue, this work analyses and evaluates several months to years of high frequency water pressure data at various locations in operational water distribution networks. We have acquired extensive time series datasets with detailed information of transient events, and utilised this information together with principles and knowledge from fracture mechanics to estimate the extent of fatigue damage on pipes. Results from this research suggest that at some logging locations, and depending on the pipe material and current deterioration state, fatigue damage due to constant cyclic loadings can be a major contributor to pipe breaks.

Keywords: Pressure transients, fatigue failure, high frequency pressure monitoring, cycle counting, pipe breaks, water pressure variations

1 INTRODUCTION

A better understanding of causes for pipe breaks in water distribution networks (WDNs) is of critical importance to optimise capital investment and burst reduction [1]. Over the last decade, several research have been performed in order to better understand and predict pipe deterioration and breaks of pipes [2]. As a result, a corpus of modelling approaches and covariates influencing pipe breaks have been presented in the literature [3]. Nevertheless, although much work have been performed, the relevance of some potential factors causing pipe breaks is not clearly understood. Among these potential factors, hydraulic pressure fluctuations are a topic of current attention [4].

Suggestions that water pressure fluctuations could have a an impact on fatigue failure in WDNs, were made in early investigations utilising high frequency water pressure monitoring. These investigations were initially motivated by the need to localize and understand the propagation of pressure transients for leak localisation and pipe break detection [5], [6]. In addition, high frequency pressure monitoring was also used to understand low and negative pressure transients [7]–[9]. Although the purpose of these investigations was not the structural analysis of pipes, they showed early empirical evidence of the frequency and magnitude of transients in WDNs. In the work of Gullick et al. [7], various examples of pressure monitoring for periods up to 5 days in pumping stations showed several pressure transients (in the order of 5 a day) of cycle range close to 50 mH_2O. Further evidence of cycles were also reported by Fleming et al. [8], were pressure cycles of range between 20 up to 50 mH_2O were measured at two hydrants in a period of 5 days.

The monitoring of water pressure at high frequencies in water distribution networks has presented a challenge that has been investigated and gradually solved over years. Early

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investigation on the use of high frequency monitoring were presented by Stoianov et al. [10]. These investigations were a decade later further expanded to technologies that allow for more extended monitoring of WDNs with various examples such as [11] and [12]. The use of such technology allowed the extension of monitoring periods from days to weeks up to months, from which further research and characterisation of the frequency of pressure transients have been performed. Examples of recent published investigation include the works of [4], [13], [14]. These works have provided characterisation and a better understanding of how pressure transients occur.

Nevertheless, although the literature has reported several cases of pressure fluctuations, these reports have been obtained only over brief periods of pressure monitoring, thus limiting a generalisation of results. In addition, previous analysis in the literature have focused on the description of the pressure fluctuations and transient events, but have lacked a mechanistic evaluation of the relevance of water pressure fluctuations on the propagation of cracks. To address these gaps in research, the present work analyses and mechanistically evaluates time series of water pressure data acquired over several months of high frequency pressure monitoring. In particular, the obtained time series have been processed utilising a cycle counting algorithm in order to extract the magnitude and frequency of cyclic loading at several locations in WDNs. We have assessed optimal sampling rates for the purpose of cycle counting, and, on the basis of the optimal sampling rate, categorised different water pressure profiles according to the frequency and magnitude of measured cycles. We also present some useful characterisation of the obtained water pressure profiles as input parameters for fatigue crack propagation models and provided how to utilise this data for such models. We further present an example for the analysis of a particular material. The main goal of this paper is to provide fundamental understanding of operating cyclic loading conditions in pipes and discuss the impact of their occurrence using fracture mechanics.

Our results show empirical evidence of the magnitude and frequency of cyclic loadings due to water pressure fluctuations. At some logging locations, thousands of cycles over 20 mH_2O were recorded over a one-year-period, and the results were relatively constant between two different years. When analysing the implications of the magnitude and frequency of the measured cyclic loadings from a mechanistic point of view, depending on the material analysed, a reduction of 10 mH_2O can substantially increase the life of an already deteriorated pipe. Therefore, suggesting the importance of reducing pressure transient activity.

2 METHODS

This investigation involved the analysis of high frequency water pressure monitoring data measured from operational WDNs. The analyses were performed to characterise cyclic loading conditions in pipes and assess their implication on the propagation of cracks and eventual fracture of pipes. This section describes the data and fundamental background and methodologies used to perform such analyses.

2.1 Pressure monitoring technologies

The data used in this study was acquired utilising high frequency pressure monitoring devices [12] installed in various locations. The sampling rate was 128 S/s (Samples per second), although some of the data was only available for our analysis at 1 S/s. This is because battery operated devices shown in Figure 1b were setup to send 1 S/s sub-sampled data from 128S/s locally stored data. The locations for the installation of the pressure monitoring devices were pressure reducing valves (PRVs), fire hydrants, and telemetry bollards/kiosks. Example illustrations of the installation locations are presented in Figure 1.

a) *b)* *c)*

Figure 1. Installation of a pressure transducer in a) pressure reducing valve (PRV) b) fire hydrant c) telemetry kiosk

2.2 Assessment of the required sampling rate

Some pressure monitoring devices were set to communicate their raw data of 128 S/s, while others only communicated a sub-set of 1 S/s derived from the continuously acquired 128 S/s. Pressure data acquired at 128 S/s have been utilised to localise sources of transients. Pressure transients in WDNs are the consequence of travelling waves [6]. These waves are generated due to sudden changes in flow conditions, and can reach velocities up to 1200 m/s in rigid pipes [13]. The optimal sampling rate for measuring such fast propagating waves depends on the purpose of the analysis. If the intention is to fully characterise the shape of a wave and their exact arrival time in space, then a sampling rate of 128 S/s or more is required to achieve errors of less than 10 m [15]. Nevertheless, if the sole purpose of the analysis is to capture the maximum rising edge of wave in order to count cyclic loadings, then the sampling rate can be reduced without substantial loss of information. Optimising the sampling rate according to the required use is of critical importance because of the large computational resources needed to process and store billions of data points obtained at high resolution. We have assessed the loss of information between counting cyclic loading at data sampled at 128 S/S, 10 S/s and 1 S/s. The three levels separated by one order of magnitude were selected on the basis of practical energy consumption and storage capacity savings. In addition we also evaluated the utilisation of counting cycles after the application of a noise removal algorithm on raw data. (It should be noted that a recent change to the firmware of the utilised InflowSense pressure monitoring devices has included the calculation of the pressure cycles on the devices from the 128 S/s data; e.g. edge processing for the pressure cycles. These pressure cycles are then communicated without the need to communicate raw data).

2.3 Cycle counting

Measuring water pressure at high sampling rates unveil loading conditions in pipes otherwise undetectable at lower frequencies. Figure 2 contrasts the difference between water pressure measured at 1 sample every 15 min for common SCADA systems versus a high speed logger at a rate of 1 S/s. The water pressure profile presented from the high speed logger shows clear pressure variations at different magnitudes. From a mechanistic point of view, a single load of such magnitude does not pose any threat to a pipe. However, it has been experimentally demonstrated that several repetitions of cyclic loadings can propagate cracks up to a point at which the pipe can become vulnerable to normal operating loadings [16], [17]. In order to evaluate such crack propagation due to repeated cyclic loadings, fatigue crack propagation theories from fracture mechanics can be utilised [18].

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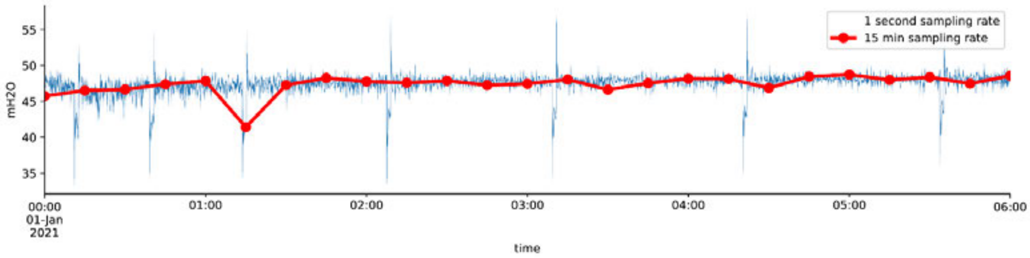

Figure 2. Comparison of pressure profiles obtained by a low and high frequency sampling rates

In order to apply methods from fracture mechanics to assess the propagation of fatigue cracks, it is first necessary to extract the information of the magnitude and number of cyclic loadings presented in the load history. This task is not trivial. In contrast to constant amplitude loadings, where the amplitudes of each cycle are well defined, there is no precise definition of what constitute a cycle under random load histories [19]. In such cases, cycle counting algorithms that perform heuristics to count cycles must be utilised [20]. Several techniques for such cycle counting exits, and the results can vary between one or other technique [20]. In the field of fatigue analysis there is a preference for the rainflow cycle counting technique [21]. The preference of this algorithm relies on its capability to count cycles within cycles, and the possibility to relate its results with stress and strain hysteresis curves [22]. It has been also empirically demonstrated that the use of this algorithm produces satisfactory loadings for prediction of actual fatigue life [23]. Given its preference and general performance acceptability, we have implemented this algorithm in the version of the ASTM E1049-85 [20] for cycle counting of our time series pressure data.

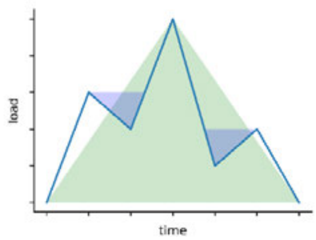

Figure 3. Visualisation of cycle detection by the rainflow cycle counting technique

The outcome of the rainflow cycle counting technique is a distribution or histogram that provides the amplitude of a cyclic load and the number of repetitions for each cycle. This information is, however, not provided in sequence, which means that information of history effects are missing, i.e., the occurrence of high load before a small one. Nevertheless, this information is usually required in detailed fatigue analysis performed "cycle by cycle" where crack closure effects can be considerable at low R ratios [24] (The R ratio is the ratio between minimum and maximum pressure). For the majority of cases where R ratios are high, a simple average of the cycle counts for a specific load history can provide good enough estimates for fatigue analysis [24]. In the results section we present some typical R ratios observed with the measured data.

2.4 Dynamic pressure profile assessment

We have applied the rainflow cycle counting algorithm on several time series of water pressure measured over periods of one year. We then categorised different water pressure profiles within 3 categories of calm, regular and dynamic water pressure profiles according to the magnitude and number of cycle counts within a period of one year. This classification can serve in order to reach targets of pressure reductions according to the implications of the water pressure on specific materials.

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2.5 Fatigue analysis

Once the assessment and characterisation of the water pressure fluctuations are performed, it is necessary to understand the implications of these cyclic loadings from a mechanistic point of view. As it is presented below, the effects that water pressure fluctuations can cause are highly material dependent, and therefore specific analysis must be performed for particular pipe materials. In this section, we present the basic theory of how to perform a general fatigue crack propagation analysis on pipes. To illustrate the proposed analysis, we present its application for a PVC pipe in order to assess the implications of the observed water pressure fluctuations for a particular material.

The assessment of fatigue damage can be performed by three main mechanistic procedures. These are the stress-life approach (S-N), the strain-life approach (ε-N) and the fatigue crack propagation approach [25]. The first two approaches rely on testing an intact component under different cyclic loadings and measuring its life until failure. The first procedure produce S-N curves. In applications where fairly constant amplitude loadings are expected and no cracks in the materials are present, or if the initial conditions of the element to be assessed coincide with the tested specimen, these procedures can be sufficient. However, if the material to be analysed is significantly different from the geometric configuration tested under laboratory conditions, then both methods can become unreliable. The S-N is empirical in nature and provides no insights into the mechanics of fatigue. Meanwhile, the ε-N approach provides insights into the mechanisms that lead to crack initiation [25]. In summary, both approaches provide little understanding into the mechanics of fatigue experienced on propagation of cracks on the tested element, especially in the S-N approach [25].

In contrast to the two previous methods, the fatigue crack propagation approach, which is also based on empirical results, provides direct insight into the mechanics of fatigue through estimating the rate of crack propagation using linear elastic fracture mechanics (LEFM) [18]. The method relies on the observance that the rate of propagation of cracks for a specific material is primarily a function of the amplitude of the stress intensity factor range produced by the applied cyclic loading, and the mean stress, expressed by the ratio between the minimum and maximum stress, as presented in Figure 4a, and in functional form in Equation 1. It is possible to observe from Figure 4 that for every material there is a particular minimum value of stress intensity range below which fatigue crack propagation does not occur.

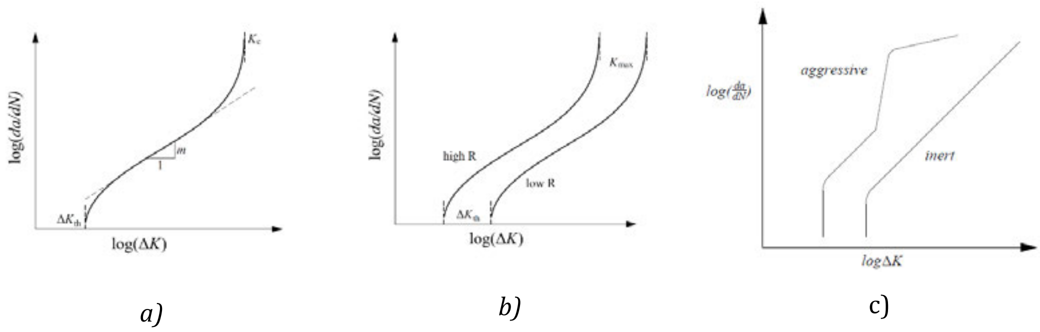

Figure 4. a) empirical crack growth rate curve. b) effect of mean pressure on the crack growth rate curve. C) effect of corrosive environment of fatigue crack propagation on metals (corrosion fatigue)

$$\frac{da}{dN} = f(\Delta K, R, \dots) \quad (1)$$

On the basis of Figure 4a and Figure 4b and the functional form of Equation 1, various "fatigue crack propagation laws" exist that attempt to model this curve. Common equations include the

Paris Law (Equation 2) [17], the Walker equation (Equation 3) [26] and the NASGRO equation (Equation 4) [27], presented below.

$$\frac{da}{dN} = C \cdot \Delta K^m \tag{2}$$

$$\frac{da}{dN} = C_0 \cdot \left[\frac{\Delta K}{(1-R)^{1-\gamma}}\right]^m \tag{3}$$

$$\frac{da}{dN} = \frac{C(1-f)^n \Delta K^n \left(1 - \frac{\Delta K_{th}}{\Delta K}\right)^p}{(1-R)^n \left(1 - \frac{\Delta K}{(1-R)K_c}\right)^q} \tag{4}$$

These equations differ in complexity and their use depends on the material to be analysed. Some materials are insensitive to the mean stress and therefore the R ratio, for which the use of the Paris Law is sufficient [25]. In case of materials that present more complex dependence to the R ratio and more advanced phenomena such as crack closure [28], then the Walker and NASGRO equation are applied. In order to estimate fatigue life, the number of cycles to reach a specific critical crack size can be estimated by integrating any of the above fatigue laws using Equation 5.

$$N = \int_{a_i}^{a_f} \frac{1}{f(\Delta K, R, \ldots)} da = \int_{a_i}^{a_f} \left(\frac{dN}{da}\right) da \tag{5}$$

In cases of pipes subjected to corrosive environment, corrosion can also produce an important cause for crack growth. Corrosion can increase a crack by its own and also can increase the rate of crack propagation generating corrosion fatigue, mathematically expressed by Equation 6. Corrosion fatigue has been shown to be of potential relevance in cast iron pipes [29].

$$\left(\frac{da}{dN}\right)_{aggressive} = \phi \left(\frac{da}{dN}\right)_{inert} + \frac{1}{f}\left(\frac{d\bar{a}}{dt}\right)_{EAC} \tag{6}$$

For illustration, we present an example of fatigue crack propagation analysis for a PVC-U pipe in order to show the effects of water pressure fluctuations on fatigue crack growth. The selected pipe configuration was a PVC-U pipe of nominal size 6", (168mm mean outside diameter) according to the BS 3505:1986 [30]. In order to perform the analysis, we have fitted the Paris Law equation to data of fatigue crack propagation (Figure 5) on PVC-U, which was published in [31]. The obtained constants used for the fatigue analysis after fitting the data were C = 1.9318e-6 and m = 3.5578. We estimated the number of cyclic loading at constant amplitude required to increase various crack sizes up to a critical estimated crack of 92mm that would became unstable with the application of a load of 150 mH_2O in the pipe.

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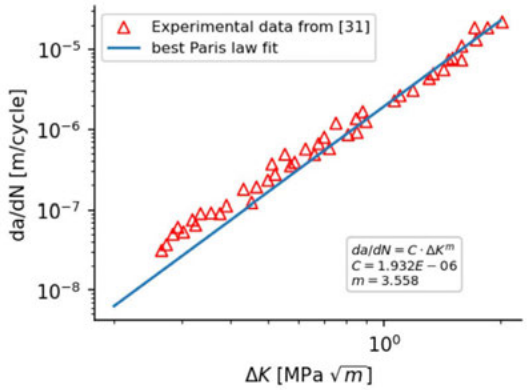

Figure 5) Fatigue crack propagation curve for PVC-U with data from [31]

3 RESULTS

This section presents key results based on the determination of cyclic loadings using the rainflow cycle counting algorithm on time series of high frequency water pressure data. In addition we include an example of the implications of reducing water pressure fluctuations on the fatigue life of a PVC pipe.

3.1 Sampling rate

This work required the utilisation of several months of water pressure monitoring in order to provide sensible results on the fatigue effect of cyclic loadings. Therefore, the trade-off of utilising a sampling rate detailed enough to accurately capture cycles generated by rapidly travelling waves, and a sampling rate that is low enough to allow for savings in computational resources and storage capacity was of critical importance. In order to assess an optimal sampling rate we have compared the difference in cycle counting between sampling data a 128 S/S, 10 S/s and 1 S/s. We have also incorporated the result of counting cycles from the raw data after application of a noise removal algorithm. We have prepared this analysis on data sampled in a single location during 2018 and 2021. The results of this analysis are presented in Table 1 and Table 2. To the best of the authors knowledge, this is the first published evaluation of the ideal sampling rates for purposes of cycle counting of water pressure fluctuations.

The pressure at the measured location had moderate pressure fluctuations. As Table 1 shows, most cycles are in a range below 2 m, with more than 86% of the presented data. This number can reach almost 99% in case of also counting cycles below 1 m. However, these cycles were not included as they were considered noise. It is observed that the application of a lower sampling rate resolution of 10 S/s can achieve better results closer to the counting of raw data. When applying the lowest sampling rate of 1 S/s, the errors increase considerably for lower cycle ranges. Nevertheless, the errors become acceptable when dealing with cycles over 5 m. Depending on the material, these could be a limitation of the 1 S/s sampling rate. Nevertheless for materials that possess higher stress intensity threshold, a sampling rate of 1 S/s seems to be adequate. The results over the two analysed years are consistent.

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Table 1. Cycle counting comparison at different time resolutions, 1 year of data 2018

Stoke Lane	01/01/2018 count	19/12/2018					
range	128 S/s	1 m noise removal	relative error	10 S/s	relative error	1 S/s	relative error
(0.999, 2.0]	584769	440229	25%	485298	17%	226982	61%
(2.0, 3.0]	40527	31988	21%	32162	21%	19484	52%
(3.0, 4.0]	5179	4563	12%	4493	13%	3468	33%
(4.0, 5.0]	1748	1790	2%	1666	5%	1429	18%
(5.0, 10.0]	1537	1241	19%	1456	5%	1292	16%
(10.0, 20.0]	430	421	2%	413	4%	399	7%
(20.0, 40.0]	179	178	1%	150	16%	146	18%
(40.0, 60.0]	5	5	0%	2	60%	1	80%
cycles over 5 m	2151	1845	14%	2021	6%	1838	15%
cycles over 10 m	614	604	2%	565	8%	546	11%

Table 2. Cycle counting comparison at different time resolutions, 1 year of data 2021

Stoke Lane	01/01/2021 count	31/12/2021					
Range	128 S/s	1 m noise removal	relative error	10 S/s	relative error	1 S/s	relative error
(0.999, 2.0]	604109	324631	46%	473317	22%	281498	53%
(2.0, 3.0]	84528	48762	42%	65497	23%	38827	54%
(3.0, 4.0]	11406	7139	37%	8844	22%	5368	53%
(4.0, 5.0]	2270	1726	24%	1955	14%	1450	36%
(5.0, 10.0]	1580	1267	20%	1383	12%	1122	29%
(10.0, 20.0]	417	407	2%	392	6%	371	11%
(20.0, 40.0]	45	39	13%	37	18%	33	27%
(40.0, 60.0]	3	3	0%	3	0%	3	0%
Cycles > 5 m	2045	1716	16%	1815	11%	1529	25%
Cycles > 10 m	465	449	3%	432	7%	407	12%

A point of consideration is that the cycle count presented in the table only shows the count of full cycles. However, there are also residual half cycles. Especially for very large, isolated cycles, it is possible that at lower resolutions, only half of a large cycle might be counted. Nevertheless, as it can be seen, these isolated events are unlikely to generate large changes in the overall estimations for fatigue in a fracture mechanics analysis. Unless these events are very large in order to reach the fracture toughness of the material, or if these events are capable of proving retardation or acceleration events, they should not pose a source of large errors.

On the basis of the presented calculations, it is clear that a minimum sampling rate of 10 S/s is closest to the original sampling rate. An important consideration is that in the analysed profiles, it can be seen that sampling at a rate of 1 S/s can be accurately enough for cycles above 5 m. For lower cycle magnitude, it seems that there could be a proportional loss of information that could be accounted when estimating cyclic loadings.

As it is presented below, depending on the material to be analysed, it might be required only to assess cycles above 5 m, for which a sampling rate of 1 S/s is sufficient in operational WDNs. Nevertheless, materials with very low stress intensity threshold such as asbestos cements might

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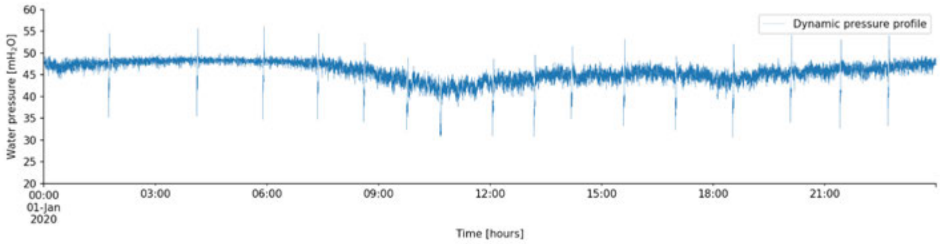
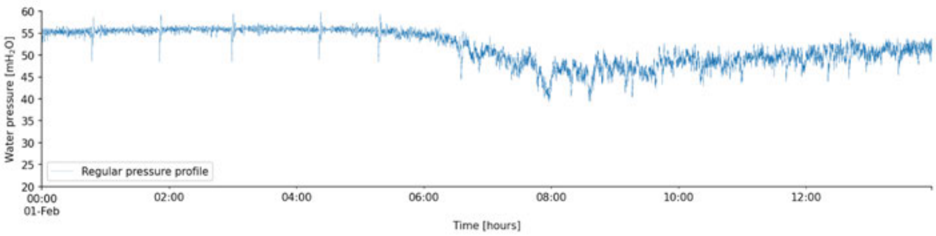
require a higher precision in counting cycles. Because of computational complexity and efficiency, the rest of the analyses are being performed on data sampled at 1 S/s. However, for further work, depending on the stress intensity threshold of the material analysed, it might be desirable to utilise the cycles calculated at the edge from the 128 S/s data, which has been recently implemented.

3.2 Dynamic vs calm profiles

Several time series of one year of water pressure monitoring were investigated. Given the size of the accumulated data over a period of 1 year, and computational processing time, the pressure profiles were analysed using a sampling rate of 1 S/s. From the analysed profiles, three categories based on the cycle counting results were generated. These categories are illustrated with the example pressure profiles of Figure 6 and the cycle counting summary of Figure 7.



a)



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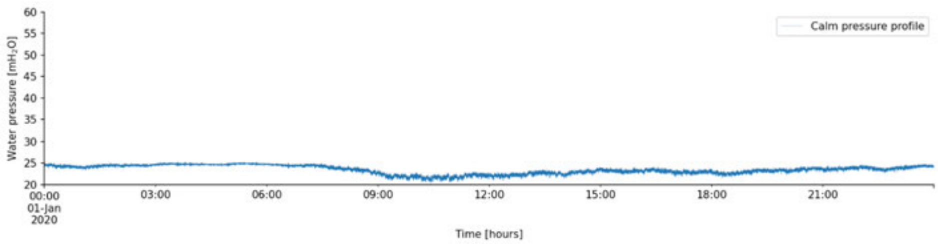

c)

Figure 6) Measured water pressure profiles in operational water distribution networks, example of a regular day, a) Dynamic, b) regular, c) calm

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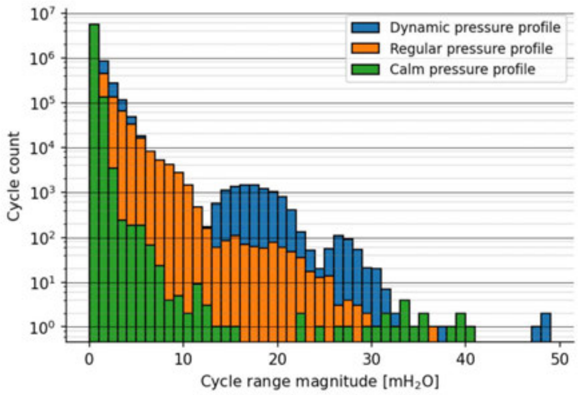

Figure 7) Cycle count histogram comparison of dynamic vs calm profiles over one year of pressure monitoring

Based on the application of the cycle counting algorithm on several datasets, we categorised the observed pressure profiles as shown in Figure 7. Our categorisation is based on the shape of the distribution of cycle count for the measure water pressure. This categorisation updates the one provided by Rezaei [32], which was based on the shape of the water pressure profiles and the visible apparent number of pressure fluctuations and magnitude. The utilisation of the shape of the cycle counting histogram provides better insight into the possible damage that a cyclic loading can generate, and it is easy to visually evaluate the number of cycles that occur over one-year-period.

The presented histogram is in a log scale, which shows an indication of the orders of magnitude of difference between the pressure profiles. We have observed these profiles as a summary of several location of the investigated WDN, nevertheless it is also possible to encounter larger profiles at transmission mains. For the largest measured pressure profile, more than 1700 cycles with a minimum magnitude of 20 m were counted. This number increase to more than 8000 cycles with a minimum magnitude of 10 m. Over a period of 50 years this can reach up to 400,000 cycles over 10 m. Depending on the material evaluated and the stress intensity factor generated by the combination of the stress and crack length, this level of cyclic loading can produce an accelerated deterioration of a pipe, as it is estimated in the next section.

Figure 8 shows a rainflow matrix, which presents the distribution of the cycles that occur from one initial magnitude until its peak. Cycles that spread over a diagonal from left to right show little damage, while cycles that spread over the perpendicular diagonal are of consideration. It is worth observing that although the loading conditions can be random in nature, most pressure profiles showed a symmetric shape as the one presented in Figure 8. The shape of the rainflow matrix can be an indication of the source of the pressure fluctuations. A symmetric shape for example, might be the result of a pump operation. An ideal shape of rainflow matrix showing little pressure fluctuations is indicated in Figure 8a.

The data presented in this section shows different levels of cyclic loading conditions that can be observed in water distribution networks. Our results show a more damaging water pressure cycles and in larger quantity that the one assumed in the study of Rajani and Kleiner [33] for example. These results reinforce the importance of continuously measuring pressure at high-sampling rates (above 1 S/s). However, the acquired high frequency data has little value if these data are not analysed by taking into consideration material properties and a fatigue crack propagation analysis. For example, what can be a highly damaging pressure fluctuation over time for a material can produce no damage for other material. The next section illustrates the effects of different water pressure fluctuations from a fracture mechanics perspective.

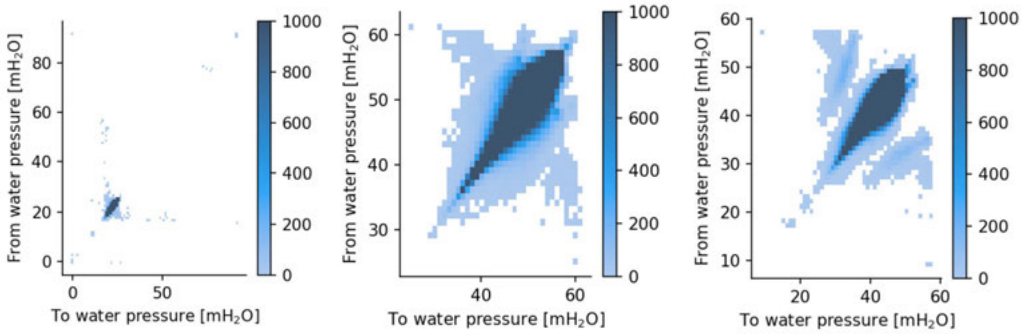

Figure 8) Rainflow matrix on water pressure profiles a) calm water pressure, b) regular water pressure c) dynamic water pressure

3.3 Fracture mechanics and fatigue implications from water pressure

As indicated, cycle counting data by itself provides little insight into the deterioration and fracture of a pipe if these data are not assessed in combination with knowledge from fracture mechanics and material properties of the pipe. As an starting point to perform a fatigue crack propagation analysis, Figure 9 shows the relation between the measured cycle ranges and their corresponding R values. As explained in the methods, larger R values can shift the crack growth curve of fatigue crack propagation of a material to the left, which indicates that lower values of stress intensity factor can cause fatigue. From the observed results it appears reasonable to utilise fracture mechanics curves obtained from testing at R ratios of 0.5 or more in case of lack of data for an specific material.

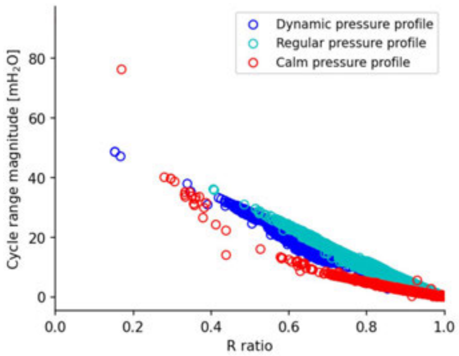

Figure 9) Cycle range and R ratio distribution

Material properties play an important role for fatigue crack propagation. The most important material properties include the stress intensity threshold and constants for the material fatigue crack propagation law. These values can largely differ for specific materials. For example, for cast iron it is common to observe fatigue thresholds in the order of 2-8 MPa√m [33], [34], while this number can be reduced almost an order of magnitude for PVC pipes up to 0.3 MPa√m and even further for asbestos cement pipes. The value of stress intensity threshold is the minimum value of stress intensity factor that a pipe must experience in order to be affected by fatigue crack propagation.

The stress intensity factor in a pipe is a function of the applied stress, pipe geometry and the size of the crack. For reference, Figure 10 illustrates how the stress intensity factor changes in different groups of cast iron pipes when these are being affected by different constant amplitude cyclic loadings at different crack sizes. As it can be observed, as a crack increases, the value of the stress intensity factor increases and more cycles start to affect the fatigue life of a pipe. In order to generate fatigue for a cast iron pipe with a stress intensity threshold of 2 MPa√m2, a minimum cycle range of 20 mH_2O for a crack of around 60 mm is required. This value substantially decreases for a PVC or asbestos cement pipes. Further work is currently conducted by the authors

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to gather evidence and analyse fatigue crack propagation for specific pipe materials, and the stochastic nature of pipe failures.

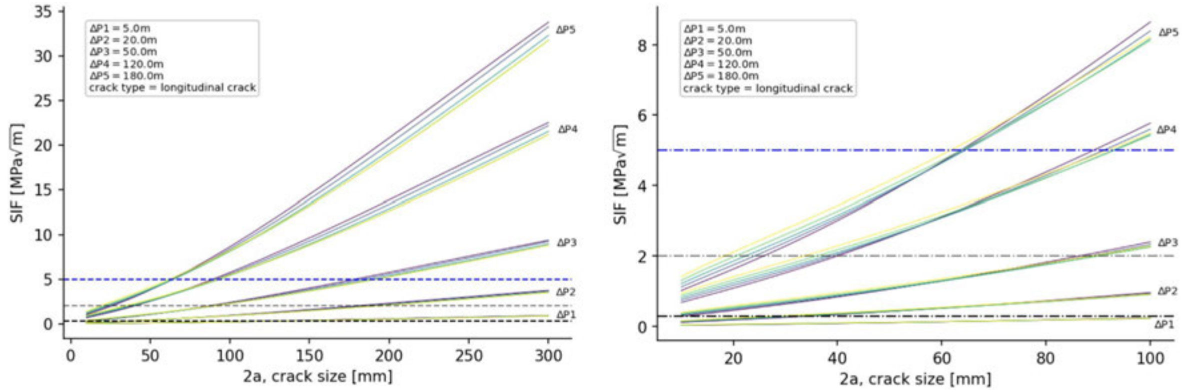

Figure 10) Stress intensity factor estimations from different water pressure magnitudes and crack length

Figure 11 shows an example of fatigue crack propagation analysis for a PVC pipe with OD 168 of mm. As it can be seen, the size of an existing crack plays an important role in the life of a pipe. However, the magnitude of the applied pressure fluctuations can significantly determine the life of a pipe. We can observe that the number of cycles required to fail the pipe can increase by an order of magnitude just by reducing the magnitude of pressure fluctuations from 30 mH_2O to 20 mH_2O, and even further for 10 mH_2O. In the previous section, we estimated a large presence of over 2000 cycles over 20 mH_2O. This number of cycles can be approximately translated to a remaining life of approximately 40 years for a pipe with a highly developed 70 mm crack without introducing safety factors. This life could be largely increased just by reducing the water pressure fluctuations.

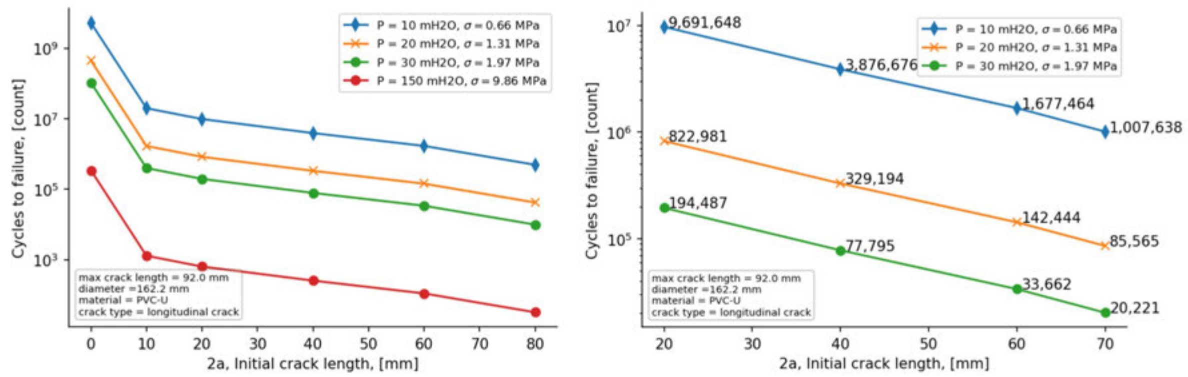

Figure 11) Fatigue life prediction for a PVC-U pipe under different constant cyclic loading conditions and initial crack sizes. a) full plot. b) Detailed view.

4 DISCUSSION

To our knowledge, the study reported here is the first study that analyses and characterises water pressure cycles over large periods using high frequency monitoring at fixed locations in a WDN. We have also quantitatively presented the implications of water pressure fluctuations in terms of fatigue crack propagation and the need to analyse their reduction with emphasis on specific materials. We evaluated the optimal sampling rate at which water pressure should be measured in order to accurately count cycles at an individual site, concluding that a sampling rate of 10 S/s and even 1 S/s can be sufficient for cycle counting. Three categories of water pressure time series were observed, our categorisation has been based on histograms for cycle counting generated by

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applying the rainflow cycle counting algorithm, updating the categorisation provided by Rezaei [32].

The proposed fracture mechanics assessment shows guidance on the magnitude of the stress intensity factor that can be generated on pipes for different crack sizes. The chart provided in Figure 10 serves as a basic tool for the understanding of the stress intensity factor applied to a pipe given its current crack length and an estimated level of water pressure cycle loading. This value of stress intensity factor can be compared to the minimum stress intensity threshold for a specific material in order to assess a preliminary estimation if a pipe can be affected by fatigue.

From the measurements and categorisations of pressure profiles obtained in the analysed WDN, it seems that pipes with high stress intensity threshold above 5 MPa√m might not suffer from pure fatigue failure. This claim must be further investigated and validated, since corrosion in cast iron can dramatically reduce the required minimum value of water pressure fluctuations to produce corrosion fatigue. Example of a reported case of a most likely failure due to corrosion fatigue was reported in [29]. In addition, previous studies that have correlated the effect of water pressure daily range as a proxy for water pressure fluctuations have shown positive correlations for reducing pressure range and reduction of pipe breaks, including pipes of high stress intensity threshold such as cast iron pipes [35], [36].

On the other hand, for pipes with lower stress intensity factor, the measured water pressure fluctuations can be significant, depending on the level of crack propagation that the pipes could have in any section of their length. Figure 11 provides an example calculation of fatigue crack propagation life for a 168 mm PVC-U pipe. This figure clearly remarks the importance of reducing water pressure fluctuations for an extended fatigue life. A highly deteriorated pipe could stop its fatigue crack growth by reducing the level of pressure fluctuations in 10 mH_2O. Thus, the importance of the application of pressure control techniques and also methodologies for pressure surge reduction as the ones indicated in [37] .

The literature has offered some estimations for fatigue crack propagation assessment of pipes such as in [33]. However, only rough estimations for cyclic loading were utilised. This study shows that water pressure fluctuations up to 20 mH_2O, can be generated constantly over a period of one year, reaching almost 2000, or in the order of 5 to 6 daily fluctuations. This number can be used as a reference for the regular pressure fluctuations observed in a network. Nevertheless, this study was limited to the characteristics of the analysed sector of the WDN, and it might be highly possible to encounter higher pressure profiles. An investigation in due course is being proposed to investigate the magnitude and propagation of water pressure fluctuations in close proximity to transmission mains connected to pump stations.

The methodology for the assessment of fatigue in this work relies on the presence of cracks in pipes, this is a limitation in the level of certainty of the results. A number of reasons can produce cracks in a underground pipe depending on the material. For cast iron pipes, corrosion is a concern for crack initiation and propagation which can be exacerbated by corrosion fatigue. For the case of plastic pipes such as PVC and PE pipes, poor installation conditions, and the presence of rocks and roots can produce initiation of cracks. More statistical understanding of the presence of cracks in pipes would allow the use of fracture mechanics together with risk analysis methodologies to provide results with confidence intervals in order to utilise this information in pipe assessment and rehabilitation programmes. This study has provided an initial overview of the effect of cycling loading on pipes from a mechanistic view. However, this study must be followed by detailed studies on specific materials in order to provide case specific guidelines for pipe failure prevention.

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5 CONCLUSIONS

This paper has provided an analysis of time series of water pressure obtained from high speed pressure transducers over periods of one year at different locations in a water distribution network. We performed analyses in order to understand the potential effects of water pressure fluctuations on fatigue failure on pipes and how to utilise data from high speed pressure transducers for such purposes. Our analysis show that a sampling rate of 10 S/s is an optimal rate for the sole purpose of counting cycles of water pressure. Nevertheless, 1 S/s can be enough for applications in which cycles over 5 m are of interest. We have observed different categories of water pressure profiles an proposed a categorisation based on the histograms for cycle counting generated in water pressure profiles over one year of monitoring. The results of the number of cycles observed at the worst locations in this study when compared to fracture mechanics fatigue crack propagation analysis for an example PVC pipe have shown that fatigue crack propagation is a potential concern in pipes with low stress intensity threshold, and we have presented results that indicate that reduction of 10 m of water pressure can potentially increase in one order of magnitude the fatigue life of a pipe. Therefore confirming the importance of fatigue failure and the analysis of high speed data for materials with low stress intensity threshold.

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7 APPENDIX

7.1 Stress intensity factors in pipes

The stress intensity factor is a concept of LEFM, which basically provides an indication of the stress intensification that is produced in a material near the tip of a crack. This value can be expressed as a function of the applied load in the material, the geometry of the material, the type of crack, and the crack length as follows:

$$K = Y \cdot \sigma \cdot \sqrt{\pi \cdot a}$$

Where Y is a geometric function that accounts for the geometry of the material and the crack configuration, σ is the applied stress on the material and a is half the crack length $(2a)$.

There exists several expressions for estimating the stress intensity factor according to the geometry of the body surrounding a crack and the crack configuration. In this research we have calculated the stress intensity factor utilising the empirical solution for a longitudinal through crack in a cylinder presented in [38].

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