
Conference Paper, Published Version

Tzatchkov, V. G.; Alcocer-Yamanaka, V. H.

Risk of Fatigue Failure and Reliability of Intermittent Water Supply Pipelines

---

Verfügbar unter/Available at: https://hdl.handle.net/20.500.11970/109854

Vorgeschlagene Zitierweise/Suggested citation:
Tzatchkov, V. G.; Alcocer-Yamanaka, V. H. (2010): Risk of Fatigue Failure and Reliability of Intermittent Water Supply Pipelines. In: Sundar, V.; Srinivasan, K.; Murali, K.; Sudheer, K.P. (Hg.): ICHE 2010. Proceedings of the 9th International Conference on Hydro-Science & Engineering, August 2-5, 2010, Chennai, India. Chennai: Indian Institute of Technology Madras.

Proceedings of ninth International Conference on Hydro-Science and Engineering (ICHE 2010), IIT Madras, Chennai, India.
2 - 5 August 2010

RISK OF FATIGUE FAILURE AND RELIABILITY OF INTERMITTENT WATER SUPPLY PIPELINES

Tzatchkov V.G.[1] and V.H. Alcocer-Yamanaka[2]

***Abstract**: Intermittent water supply, where pipelines start and stop their operation frequently, is prevalent among developing countries. Even when some intermittently operated pipelines may remain full of water, e.g., pumping pipelines, they are subject to constant hydraulic transients too. Every start and shutdown of pumps, or valve operation in gravity fed pipelines, generate hydraulic transients with pressure variations. Although generally of short duration (during each supply cycle) they may result in infrastructure deterioration and reduce average life of pipes. The progressive gradual damage caused by a large number of repetitive pressure and stress variation cycles above certain levels is known as material fatigue. Under fatigue conditions pipes, valves and other pipeline equipment may fail suddenly, without any warning, under stresses considerably lower compared to their design stress. Current standards for designing water industry pipelines do not consider fatigue. The process is dangerous because the conventional analysis might lead to an assumption of safety that does not exist. Therefore, it is important to assess the possible fatigue, and design accordingly. This paper discusses the phenomenon of material fatigue caused by hydraulic transients in pipelines. Basic concepts from fatigue theory are used to show that steel and ductile iron pipelines designed according to current AWWA practice are fatigue-prone (finite-life ones), under a large number of pressure cycles. Equations for estimation of the number and amplitude of pressure cycles and their application for evaluation of expected life of new steel pipelines are presented.*

***Keywords**: material fatigue; intermittent water supply; pipelines; hydraulic transients.*

INTRODUCTION

Intermittent supply water distribution networks are regularly charged with water and empted, some of them even daily. Every network charging and empting generates hydraulic transients with pressure variations whose magnitude depends largely on local conditions. Although generally of short duration (during each supply cycle) they result in the deterioration of the infrastructure. Intermittent supply surges greatly increase burst frequencies (many times more

---

[1] Senior Research Scientist, Department of Urban Hydraulics, Mexican Institute of Water Technology, Paseo Cuauhnahuac 8532, Jiutepec, Morelos, 62550, Mexico, Email: velitchk@tlaloc.imta.mx

[2] Vice Coordinator, Department of Urban Hydraulics, Mexican Institute of Water Technology, Paseo Cuauhnahuac 8532, Jiutepec, Morelos, 62550, Mexico, Email: yamanaka@tlaloc.imta.mx

than for a continuous supply system). Frequent sudden changes in pressure reduce the average life of pipes. New burst frequencies may be 10 times or more what would be expected for continuous supply at the same average pressure (Lambert (2000). Figure 1 shows the burst frequency of water mains for several countries with continuous and intermittent water supply (World Bank 2006, Pilcher 2005).

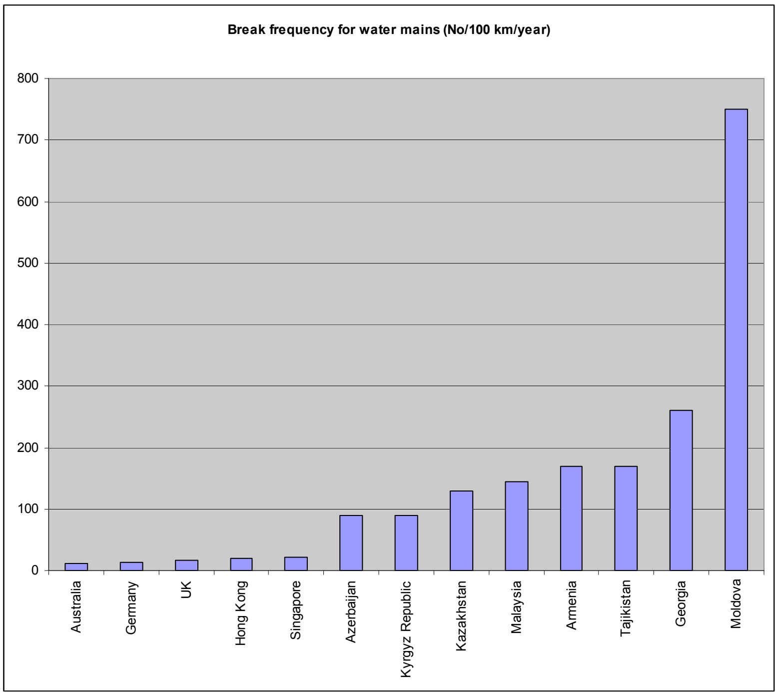

Fig. 1 Burst frequencies from countries with continuous and intermittent water supply (continuous supply - Australia to Singapore, intermittent supply - Azerbaijan to Moldova).

The progressive gradual damage caused by a large number of repetitive pressure or stress cycles above certain levels is known as material fatigue. Under fatigue conditions pipes, valves and other pipeline equipment may fail under a stress considerably lower compared to their design stress. Hydraulic transients following pump starts and shutdowns or valve operations in water supply pipelines are characterized by a certain number of highly variable pressure change cycles. Although fatigue evaluation is mandatory for nuclear and process equipment plant piping (ASME, 2001), the risk of material fatigue is not considered in water and wastewater pipeline design manuals and standards, such as ANSI/AWWA C200-97 (ANSI/AWWA, 1997) and AWWA Manual M11 (AWWA, 2004). Probably it is not considered because present water supply design practice assumes implicitly an almost uninterrupted pipeline operation, and thus a small number of pump starts and shutdowns throughout the pipeline life. Some water conveying pipelines stop and start their operation very frequently, however, for example daily. Reasons for such intermittent operation may be energy saving (avoid to pump during peak hours), insufficient tank capacity, intermittent water supply in general, and others. Because of variable inflow rates pumps in sewage pumping stations may stop and start even several times per hour. This way, the total number of pressure cycles during the expected life of the pipeline may be very large, and

conditions for material fatigue are possible. It is important, therefore, to assess the potential risk of material fatigue in such pipelines, and protect them against it.
Studies related to material fatigue in metal pipes used in water industry are very scarce. Seok et al. (2005) and Park et al. (2006) conducted fatigue tests with standard and non-standard specimens of base and weld metal extracted from a steel pipe used in waterworks, with a 1000 mm diameter 6 m long real pipe subject to external loading. From these results the relation between the S-N diagram of a specimen and that of the pipe was evaluated. Using ex-service pipe specimens Mohebbi et al. (2009) studied the fatigue behavior of cast iron pipes used in United Kingdom, found that it is microstructural dependent, and noted the need of further research. No hydraulic transients were considered in those studies. Up to the knowledge of the writers, Schmitt et al. (2006) are the only authors that studied the influence of pressure transients on fatigue in an operating water pipeline, but their work was directed to corrosion fatigue only.

This paper explains the phenomenon of material fatigue caused by hydraulic transients in steel and ductile iron pipelines, and presents an application of fatigue risk evaluation in the evaluation of expected life of new ones, based on research done by the writers (Tzatchkov et al. 2006, Tzatchkov et al. 2007). Comments on material fatigue in other material pipes are given elsewhere (Tzatchkov et al. 2007). Although the content is focused mainly on pipelines that remain full of water in each supply cycle, it is valid for pipelines that are filled and emptied in each cycle too, provided pressure variation during each cycle is known, obtained by observation or by a model.

BACKGROUND

The most used concept to describe fatigue behavior of some material is its *S-N* (Stress versus Number of cycles) curve, known also as Wöhler diagram of the material. It relates the number of cycles *N* under which the material fails when subject to a given fully alternating stress S_f. Figure 2 shows the aspect of the *S-N* curve for a ferrous metal (such as steel or ductile iron), and a non-ferrous metal (such as aluminum). The horizontal reach in the curve, for a ferrous material, means that the material never fails when the applied alternating stress is below some level, known as endurance limit S_e. For steel, the ratio of the endurance stress to the ultimate tensile strength is equal to approximately 0.50.

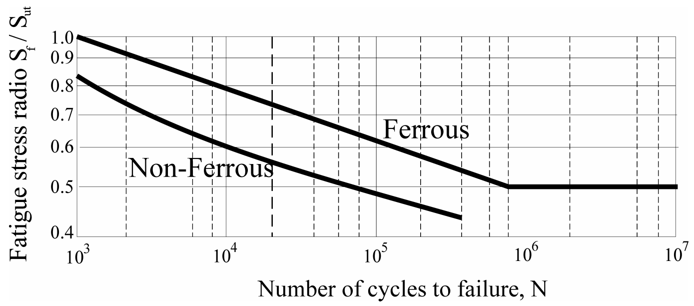

Fig. 2. *S-N* curve (Wohler diagram) for a ferrous and a non-ferrous material.

When plotted on a log-log scale, for steel pipelines the *S-N* curve can be approximated by a straight line as shown in Figure 2, giving rise to the following power law equation, known as the Basquin equation (Basquin 1910):

$$\frac{S_f}{S_{ult}} = CN^b \qquad (1)$$

where b is the slope of the line, sometimes referred to as *Basquin slope* and S_{ult} is the ultimate tensile strength of the material.

S-N curves are obtained experimentally applying a zero mean fully alternating stress to a material specimen, i.e., a stress that varies symmetrically from some positive (tensile) value to a negative (compression) value of the same magnitude. According to present knowledge, the fatigue process is thought to begin at an internal or surface flaw where the stresses are concentrated, and consists initially of shear flow along slip planes. Over a number of cycles, this slip generates intrusions and extrusions that begin to resemble a crack. The crack grows slowly with subsequent stress cycles and may become large enough to satisfy the energy or stress intensity criteria for rapid propagation, producing a fast fracture. Tensile stresses tend to open initial cracks and compression stresses tend to close them. Because of that, fatigue resistance under a non zero mean steady positive (tensile) stress is lower than the fatigue resistance under fully alternating (zero mean) stress. Pressure pipelines are subject to a constant tensile stress, corresponding to their operation pressure. Overpressures and subpressures generated during hydraulic transients produce positive and negative stress variations superimposed on that steady mean stress. Fatigue behavior of a material under non zero mean stresses is characterized by its Goodman diagram, than expresses, for a given number of cycles, the stress under which the material fails for different mean stress. It is a graph with mean stress S_m as the abscissa and applied alternating stress S_{alt} as the ordinate, and a straight "lifeline" drawn from S_e on the axis S_{alt} to the ultimate tensile strength on the S_m. Then for any given mean stress, the endurance limit (the value of alternating stress at which fatigue fracture never occurs)| can be read directly as the ordinate of the lifeline at that value of S_m. Figure 2 shows the Goodman diagram in relative values, i.e., with the ratio of the applied mean stress and the ultimate tensile strength on the horizontal axis, and the ratio of the alternating stress to the endurance limit for fully alternating load on the vertical axis.

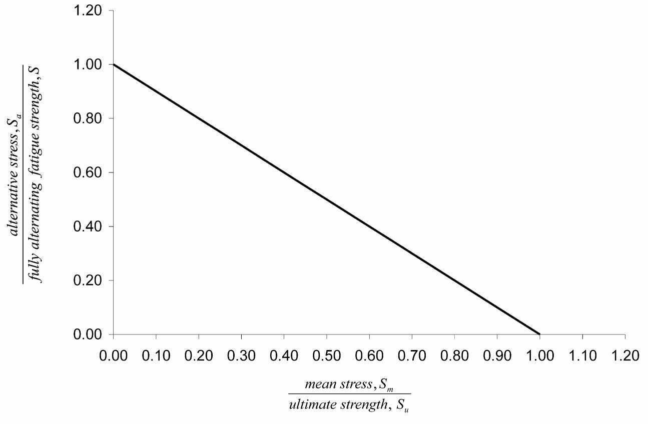

Fig. 3 Goodman diagram.

Pressure cycles and corresponding pipe wall stresses, following pump starts and shutdowns or valve closures, are variable in amplitude. Normally, they start with some maximum value and rapidly attenuate in time. Different amplitude stresses contribute differently to fatigue damage. Assuming a linear and cumulative damage of each pressure variation, the Miner's rule (Miner 1945) (called sometimes also Palmgren-Miner's rule) can be used to take into account that effect. The fatigue lifetime (in cycles), according to Miner's rule, is expressed by the following relation:

$$\sum_i \frac{n_i}{N_i} = 1 \tag{3}$$

where n_i is the number of cycles applied at a load corresponding to a lifetime of N_i .

MATERIAL FATIGUE IN STEEL PIPES

It is easy show that steel pipelines designed following current practice are fatigue-prone, under a large number of pressure cycles. According to the AWWA M11 manual (AWWA 2004), and the standard AWWA C200 (ANSI/AWWA 1997), steel pipe thickness is determined by the conditions to withstand the normal operating pressure with a safety factor of 2 based of the yield strength, and the normal operating pressure plus the transient overpressure with a safety factor of 1.5. This means pipe will be subject to a stress of half its yield strength during normal operation and to a stress of up to 0.75 times its yield strength during transients. Depending on its grade, the yield strength of pipe steel is from 0.54 to 0.84 times its ultimate strength (AWWA 2004). Let consider these two limit values separately. For the first of them the mean stress (corresponding to normal operation) is 0.27 times the ultimate strength. From the Goodman diagram, the corresponding endurance limit should be multiplied by 1-0.27 = 0.73. Since the endurance limit for steel is about half its ultimate strength, the corresponding endurance limit under the given mean stress is 0.365 that strength. Recalling that the yield strength is 0.54 times the ultimate strength, the allowable stress for transients is 0.75 x 0.54 = 0.405 times the ultimate strength. For the second limit value (0.84) the same reasoning gives an endurance limit of 0.29 times the ultimate strength and an allowable transient stress of 0.75 x 0.84 = 0.63 times the ultimate strength.

This means design stress is higher than the endurance limit and thus, with respect to material fatigue, steel pipelines are finite life ones. The point is in the number of pressure (stress) cycles. If it is very high, the pipeline may be subject to fatigue. As shown in the following section, that number may be high enough for that to occur, if the pipeline interrupts its operation frequently.

Ductile iron pipes designed following current practice are somewhat more fatigue resistant, although finite life ones too. The yield and ultimate strength of ductile iron is 42,000 psi (289.6 MPa) and 60,000 psi (413.7 MPa) respectively, with an endurance ratio of 28,000 psi (193.1 Mpa). According to the AWWA manual M 41 (AWWA 2003), ductile iron pressure pipes are designed by the condition to withstand the normal operating pressure plus the transient overpressure with a safety factor of 2 based of the yield strength. This gives a maximum design stress of 21,000 psi (144.8 MPa), lower than its endurance ratio, so that under zero steady mean stress ductile iron pipe is infinite life one. Considering the mean stress, however, it turns to be finite life one for mean stresses above 0.25 times its ultimate strength, as can be shown by the following reasoning. From the Goodman diagram, a mean stress of 0.25 times the ultimate strength corresponds to a endurance limit of 0.75 times the endurance limit under fully alternating stress, which for ductile iron is equal to 0.75 x 28,000 = 21,000 psi (144.8 MPa).

NUMBER OF PRESSURE (STRESS) C CLES

In order to evaluate the fatigue risk, the number of pump starts and shutdowns or valve operation needs to be estimated, along with the number of the pressure change cycles and the magnitude of those changes in each cycle. The number of the pressure change cycles and their magnitude can be obtained, in principle, by direct observation of the transient pressure (in existing pipelines), by a transient flow numerical model, or by approximate models. In the last case, Brunone's or alike methods could be employed (Brunone et al. 1995). Given the approximate nature of the fatigue risk evaluation, the last of these 3 kinds of methods may be considered as sufficient, at least for single pipelines with no column separation during transients. Normally, pipe shutdowns and valve closings produce much more transient pressure cycles, compared to pipe starts and valve openings. According to Brunone et al. (1995) for a pipeline that remains full with water the transient overpressure (under pressure) attenuation in a single pipeline is given by the following equation:

$$\frac{\Delta H_i}{\Delta H_{i-1}} = \left(\frac{1}{1+k}\right)^2 \tag{3}$$

where k is between 0.03 and 0.10. Later, Pezzinga (2000) generalized the concept and presented graphs for k in function of a characteristic parameter of the pipeline, the initial Reynolds number and the relative roughness. In those graphs the value of k reads from approximately 0.003 to 0.06. Other authors, cited by Pezzinga (2000), found values for k from 0.00827 to 0.15. Figure 4 shows the observed pressure variation in a real pipeline during a shutdown and subsequent startup of the pumps at one of its pumping stations (Tzatchkov et al. 2007), and Figure 5 its approximation for the initial (immediately after shutdown) part of the transient with k=0.015.

With respect to the initial overpressure (underpressure) ΔH_o Eq (3) can be written as

$$\frac{\Delta H_i}{\Delta H_0} = \left(\frac{1}{1+k}\right)^{2i} \tag{4}$$

Figure 6 shows the pressure variation represented by Eq (4) for 3 values of k: the minimum one obtained by Pezzinga (2000), the maximum one obtained by other authors, and an intermediate value. Even when the smallest value k = 0.003 (and the related largest number of pressure cycles) might be taken with some reserve, as being too small compared by the value of k from other authors, Figure 6 shows an important number of pressure cycles during a transient for most pipelines. Now, let the number of pressure cycles per transient be 100. If the pipeline stops daily, for one year the number of pressure cycles will be 36,500, and for 10 years it will be 365,000. According to ASME Boiler and Pressure Vessel Code, Section III (ASME, 2001), fatigue analysis is mandatory when the number of pressure cycles is greater than 1,000. Since water pipelines operate with mean stresses above the endurance limit, as explained in the previous section, all pipe stress variations during those pressure cycles are in fact fatigue generating.

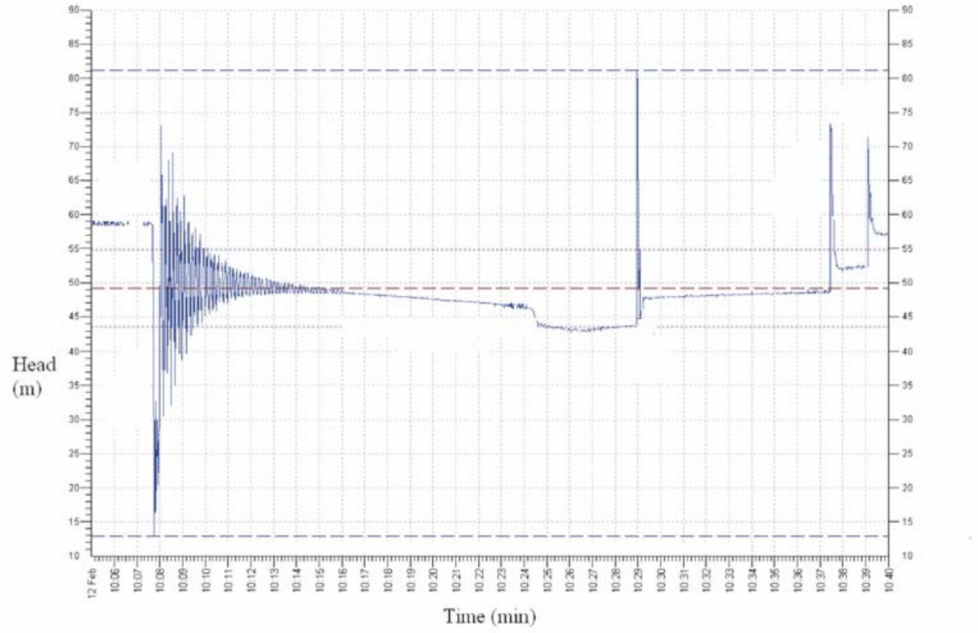

Fig. 4 Observed pressure variation in a pipeline in Mexico during a shutdown and subsequent startup of the pumps.

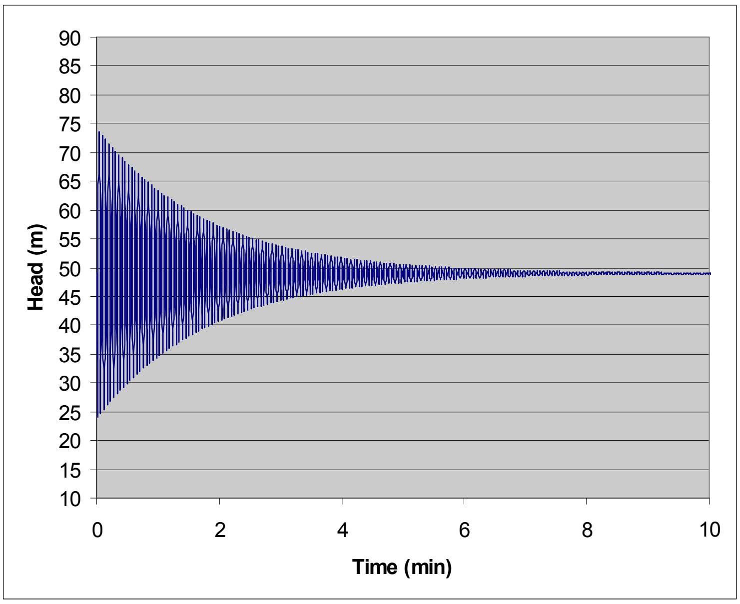

Fig. 5 Approximation of initial part of the observed pressure variation from Figure 4 for *k* . 15.

APPLICATIONS

Using the above principles, in another paper (Tzatchkov et al. 2007) applications for fatigue-safe design of new pipelines and evaluation of the remaining life of existing ones are proposed. An analytical determination of the expected life of new steel pipelines is presented here.

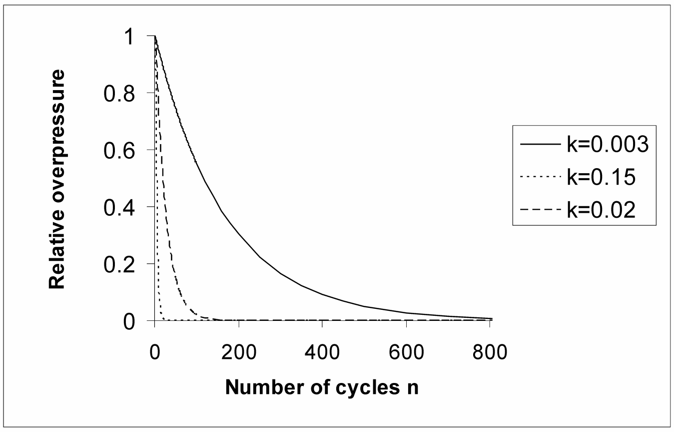

Fig. 6 Relative over (under) pressure variation versus number of cycles during a transient.

Expected life of new steel pipelines

For steel pipes (and in fact for other pipe materials with linear S-N diagram) the Basquin equation (1) can be combined with Eq (4) for the number of pressure cycles and the Palmgen-Miner rule to obtain analytically the expected life. Since for a pipe stress is linearly proportional to pressure, from Eq (4):

$$S_f = S_o\left(\frac{1}{1+k}\right)^{2i} \tag{5}$$

where S_o is the initial stress. The fatigue life N corresponding to S_f can be then obtained from the Basquin equation (1) as

$$N_i = \left(\frac{S_o}{CS_{ult}}\right)^{\frac{1}{b}}\left(\frac{1}{1+k}\right)^{\frac{2i}{b}} \tag{6}$$

According to the Palmgren-Miner rule, the total fatigue damage due to all pressure cycles i in a transient event is then equal to:

$$\sum_{i=0}^{\infty}\left(\frac{1}{\left(\frac{S_o}{CS_{ult}}\right)^{\frac{1}{b}}\left(\frac{1}{1+k}\right)^{\frac{2i}{b}}}\right)=\frac{1}{\left(\frac{S_o}{CS_{ult}}\right)^{\frac{1}{b}}\left[(1+k)^{\frac{2}{b}}-1\right]} \qquad (7)$$

Finally, assuming all transient events are the same from Eq (7) the expected life L of the pipeline, expressed in number of transient events it can withstand, is

$$L=\left(\frac{S_o}{CS_{ult}}\right)^{\frac{1}{b}}\left[(1+k)^{\frac{2}{b}}-1\right] \qquad (8)$$

Typical values for C and b are 1.62 and -0.085 (corresponding, as in Figure 1, to S_{1000} at N=1,000 equal to 0.9 S_{ult} and S_e at N=1,000,000 equal to 0.5 S_{ult}). If the pipeline is designed exactly according to AWWA M11, then the initial overpressure stress S_o is equal to 0.75 times the yield stress, i.e., 0.405 to 0.63 times S_{ult}, as explained previously in this paper. For S_o/S_{ult}=0.63, k=0.003, C=1.62 and b=-0.085 Eq (8) gives L=4,555 transient events. Thus, if the pipeline stops its operation every day, its life will be some 12 years. If it stops and starts operation two times a day, its life would be 6 years. The value of L obtained from Eq (8) is very sensitive to the value of k, however. For k=0.15 and the same other data, the expected life would be 177 years. It should be noted also that startup transients are neglected in this analysis, so that considering them the expected life will be somewhat shorter.

CONCLUSIONS

Pipelines that stop and start their operation frequently may be subject to material fatigue, due to the cyclic pressure variation during hydraulic transients. Fatigue is possible when the number of cycles is large. Examples are intermittently operating water supply pipelines and sewage force mains. Under fatigue, pipelines may fail under a stress far below their design stress. Current standards for designing water industry pipelines do not consider fatigue. The process is dangerous because the conventional analysis might lead to an assumption of safety that does not exist. Therefore, it is important to assess the possible fatigue, and design accordingly. It is shown in this paper that current design practice for steel and ductile iron pipelines leads to stresses above the endurance limit and thus steel and ductile iron pipes are finite life ones, and are fatigue-prone.

On this basis, using simple concepts from fatigue theory, a procedure is presented for assessing the expected life of new intermittently operated steel pipelines. The procedure includes an estimation of the number of pressure cycles the pipeline is subject to, and the pressure variation within them. It is important to consider the mean steady stress, since it reduces considerable the endurance limit. Finally, fatigue can be largely prevented, or pipeline life can be made longer, by suitable designed surge control devices that reduce the number of pressure cycles and the amplitude of the pressure variations.

REFERENCES

ANSI/AWWA, 1997. *Steel Water Pipe 6 In. (150 mm) and Larger*, *ANSI/AWWA C200-97*: American Water Works Association, Denver, CO.

ASME, 2001. *ASME Boiler and Pressure Vessel Code, Section III*. New York.

AWWA, 2004. *Steel Water Pipe: A Guide for Design and Installation*, *AWWA M11*, Fourth Edition, American Water Works Association, Denver, CO.

AWWA, 2003. *Ductile-Iron Pipe and Fittings, Second Edition, AWWA M41*, American Water Works Association, Denver, CO.

Basquin, O. H. 1910. The exponential law of endurance tests.*Proc. Am. Soc. Test. Mat.*, 10, 625-630.

Brunone, B., Golia, U. M., and Greco, M. 1995. Effects of two-dimensionality on pipe transients modeling. *J. Hydraulic Engrg*., ASCE, 121(12), 906–912.

Lambert A. 2000. What do we know about Pressure: Leakage Relationships in Distribution Systems? *IWA Conference on System Approach to Leakage Control and Water Distribution Systems Management*, Brno

Miner, M. A. 1945. Cumulative Damage in Fatigue.*J. Applied Mechanics*, 12, Trans. ASME, 67, A159-164.

Mohebbi, H, Jesson, D. A., Mulheron, M. J. and Smith, P.A. 2009. Characterisation of the fatigue properties of cast irons used in the water industry and the effect on pipe strength and performance" *Journal of Physics: Conference Series 181: 7th International Conference on Modern Practice in Stress and Vibration Analysis*, 1-8.

Pezzinga, G. 2000. Evaluation of unsteady flow resistances by quasi-2D or 1D models, *J. Hydraulic Eng*., 126 (10), 778–785.

Park, J.S., Seok, C.-S. and Choi, J. H. Fatigue life characteristics of waterworks pipe welds. *International Journal of Modern Physics B: Condensed Matter Physics; Statistical Physics; Applied Physics*, 20 Issue 25-27, 3969-3974.

Pilcher, R. 2005. A Practical Approach to Developing a Sustainable Water Loss Reduction Strategy in Sandakan, Sabah, Malaysia *, IWA Specialised Conference Leakage 2005", Halifax, Nova Scotia, Canada*, 1-10.

Schmitt, C., Pluvinage, G., Hadj-Taieb, E. and Akid, R. 2006. Water pipeline failure due to water hammer effects, *Fatigue Fract Engng Mater Struct*, 29, 1075–1082.

Chang Sung Seok, Jae Sil Park, Hyung Ick Kim, Young Min Lee, Won Hak Cho and Weon Keun Song. 2005. Evaluation of Fatigue Characteristic of a Real Waterworks Pipe, *Key Engineering Materials* (Volumes 297 - 300), Volume Advances in Fracture and Strength , 2471-2476.

Tzatchkov, V., Alcocer-Yamanaka, V. H. and Bourguett-Ortiz, V. J. 2006. Diseño de Acueductos Seguro Contra Fatiga del Material en los Transitorios Hidráulicos,*Proceedings VI Seminario Iberoamericano, Planificación, Proyecto y Operación de Redes de Abastecimiento de Agua (SEREA)*, *Joao Pasoa, Brazil, June 5-7, 2006* (in Spanish).

Tzatchkov, V., Alcocer-Yamanaka, V. H. and Bourguett-Ortiz, V. J. Material fatigue due to hydraulic transients in pipelines,*Water Management Challenges in Global Change,* Taylor & Francis/Balkema, London et al., 31-38.

World Bank. 2006. *Infrastructure in Europe and Central Asia Region. Approaches to Sustainable Services*, World Bank, Europe and Central Asia Region, Infrastructure Department.