WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2024.148914
ARCHIVES OF CIVIL ENGINEERING
Vol. LXX ISSUE 1 2024

pp. 325–335

Research paper

Application of the interval approach to determine the exploitation time of pipelines

Iwona Duszyńska[1], Tomasz Krykowski[2],
Paweł Stefanek[3], Joanna Bzówka[4]

Abstract: The fundamental problem from the point of view of pipeline exploitation in KGHM Polska Miedź S.A. is the very high overwearing of the pipes used for the transport of tailings, as well as determining the time of trouble-free operation of pipe system components. Failures involve significant financial outlays, severe restrictions on operation and in some cases even stopping operation. For this reason, it is vital to monitor the condition of the transport systems, as well as to determine the permissible service life of the pipe sections, after which segments at risk should be replaced or turned over in order to extend their further operation. This paper focuses on the application of interval numbers to assess the durability of piping systems. The calculations were made using classical interval numbers by using code written in INTLAB libraries. The correctness of the solutions obtained was verified using the Monte Carlo method, assuming a uniform distribution of random variables.

Keywords: erosion, interval numbers, pipelines, uncertainty

---

[1] MSc., Eng., KGHM Polska Miedź S.A., Oddział Zakład Hydrotechniczny, Lubin, Poland, e-mail: id4723@student.polsl.pl, ORCID: 0000-0002-7983-3114

[2] DSc., PhD., Eng., Silesian University of Technology, Faculty of Civil Engineering, Department of Mechanics and Bridges, Gliwice, Poland, e-mail: tomasz.krykowski@polsl.pl, ORCID: 0000-0002-7294-1788

[3] PhD., Eng., KGHM Polska Miedź S.A., Oddział Zakład Hydrotechniczny, Lubin, Poland, e-mail: pawel.stefanek@kghm.com, ORCID: 0000-0003-3357-0053

[4] Prof., DSc., PhD., Eng., Silesian University of Technology, Faculty of Civil Engineering, Department of Geotechnics and Roads, Gliwice, Poland, e-mail: joanna.bzowka@polsl.pl, ORCID: 0000-0002-1765-7354

1. Introduction

The problems of pipes erosion caused by the transport of material containing flotation waste, a mixture of slit, sand and clay fractions, are a very important issue in the exploitation of mines, copper ore mines and mining plants. The questions of mathematical description of this type of problems, consisting in giving dependencies enabling to determine the rate of pipe degradation for different media, depending on the flow velocity, fluid characteristics and other factors, can be found, among others, in the papers [1–3]. The analytical relationships formulated in these papers allow us to describe degradation caused by the transport of various media according to many factors, such as the grain size of transported fractions, the grain shape or the type transported medium.

With regard to KGHM Polska Miedź S.A., the problem relates to the exploitation of pipelines with a total length exceeding 250 km, which in turn translates into significant financial outlays related to pipeline operating costs and failures.

The fundamental problem from the point of view of pipeline exploitation in KGHM Polska Miedź S.A. is the very high overwearing of the pipes used for the transport of tailings, as well as determining the time of trouble-free operation of pipe system components. Failures involve significant financial outlays, severe restrictions on operation and in some cases even stopping operation. For this reason, it is vital to monitor the condition of the transport systems, as well as to determine the permissible service life of the pipe sections, after which segments at risk should be replaced or turned over in order to extend their further operation.

This work focuses on the application of interval arithmetic to assess the durability of piping systems. Calculations were made applying classical interval models [4–9] using INTLAB libraries [4, 10]. The correctness of the obtained solutions was verified using the Monte Carlo method [11, 12] assuming a uniform distribution of random variables.

2. Problem description

2.1. Introduction

The subject of calculations are pipe defects resulting from the transport of flotation waste (non-cohesive soils with a wide range of grain sizes, from sands to slit). The granulometric and mineralogical composition of the waste depends on the type of processing course during flotation in the individual areas of ZWR Rudna, ZWR Polkowice, and ZWR Lubin facilities. The waste of ZWR Lubin, which contains the largest sand fraction, is deposited at the eastern and partly southern dam of OUOW Żelazny Most reservoir. The waste from ZWR Rudna is transported to the western and northern parts and partly to the eastern and southern parts. The finest waste from ZWR Polkowice is stored inside the OUOW Żelazny Most structure. The properties of the example hydromixtures (transported by pipelines R1 and R2) are summarised in Table 1.

The pipelines analysed for post-flotation waste with a diameter DN 1000 mm and DN 800 mm were made of steel S235:

- Pipeline R1, R2 – diameter $D_N = 1000$ mm, length from pumping station region ZWR POLKOWICE and ZWR RUDNA to Chamber RG/PG, approximately $L = 8.6$ km; from Chamber RG/PG to node H, approximately $L = 5.10$ km; from the North Pumping Station, $L = 3.60$ km; to OUOW Żelazny Most, approximately $L = 4.20$ km; pressure from 5 to 12 atmospheres depending on the route and place of waste discharge.
- Pipeline $L2$ – diameter $D_N = 800$ mm, length from pumping station region ZWR Lubin to Chamber LG approximately $L = 8.6$ km; from Chamber LG to junction L, approximately $L = 3.30$ km; to OUOW Żelazny Most, approximately $L = 4$ km; pressure of 5 to 14 atmospheres, depending on the route and place of waste discharge.

Table 1. Properties of the hydromixture of the analysed case from the region of ZWR Polkowice and ZWR Rudna (pipelines R1 and R2)

Material parameter	R1 ZWR Polkowice	R2 ZWR Rudna
Density ρ (kg/m^3)	1138	1139
The content of rock fractions, ρ_s (kg/m^3)	180	180
Percentage content of sand fraction, γ_{sand} (%)	32	51
Percentage content of slit fraction, γ_{slit} (%)	56	41
Percentage content of clay fraction, γ_i (%)	12	8

The pipeline is held on fixed supports every $L_p = 80$ m and sliding supports every $L_{ps} = 20$ m. In the middle of the span between the supports, steel compensators with a diameter were located $D_N = 1000$ mm or $D_N = 800$ mm.

The operating parameters of the pipelines analysed are summarised in Table 2.

Table 2. Parameters of the pipelines analysed in the paper R1, R2 and L2

Parameter	Pipeline R1	Pipeline R2	Pipeline L2
Pipeline diameter, D_n mm	1000	800	800
Range of operating pressure variations on different pipeline sections (Atm)	$\overline{p} = \langle 5, 12\rangle$	$\overline{p} = \langle 5, 12\rangle$	$\overline{p} = \langle 5, 14\rangle$
Initial wall thickness, h_{w0} (mm)	16	16	16

The measurements of annual changes in pipe wall thickness (wall thickness loss velocity v_u) on the perimeter of the analysed pipelines in relation to selected sections of the pipelines are shown in the following figures: a) pipeline R1 in Fig. 1, b) pipeline R2 in Fig. 2, c) pipeline L2 in Fig. 3.

The index K in the descriptions of the pipeline sections under consideration refers to randomly selected pipeline sections located between successive compensators (K_i, K_j).

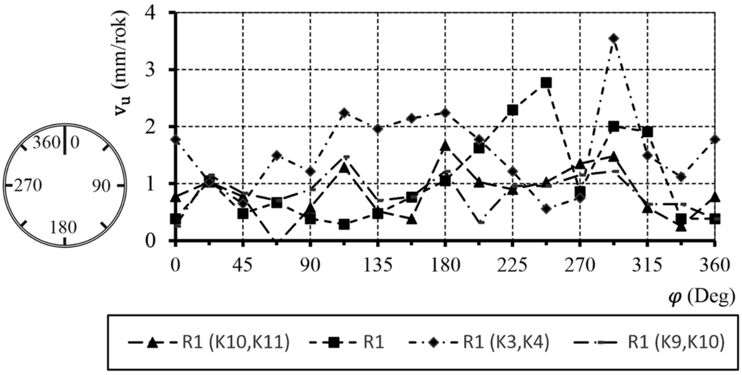

Fig. 1. Rate of wall abrasion v_u of pipeline R1 with a diameter 1000 mm (description in the text)

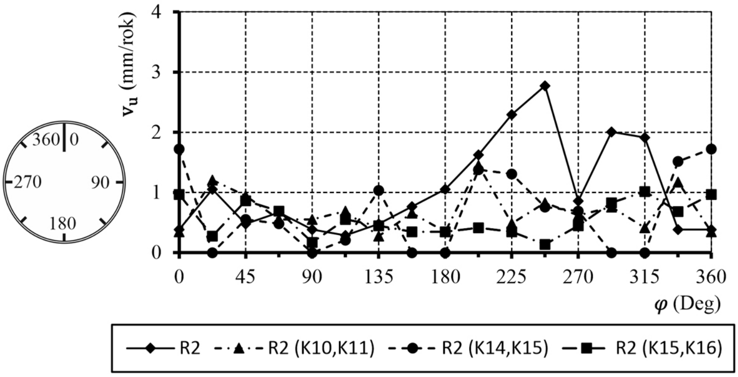

Fig. 2. Rate of wall abrasion v_u of pipeline R2 with a diameter 1000 mm (description in the text)

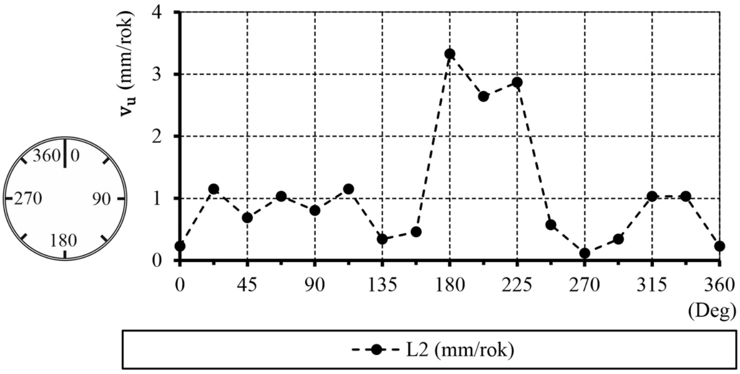

Fig. 3. Rate of wall abrasion v_u of pipeline L2 with a diameter 800 mm (description in the text)

3. Interval approach to model the degradation of pipelines

3.1. Introduction

The method of estimating the service life of pipelines subject to wear and tear as a result of the transport of bulk materials is not of deterministic type. Many parameters describing the process of post-flotation waste transport are uncertain and variable in time. It is also troublesome to describe the problem with the use of probabilistic methods, due to the insufficient amount of computational data. An important aspect is also the need for simplicity to assess the exploitation of pipe sections.

For this reason, the concept of assessing the lifetime of the pipeline using interval numbers was proposed (it was assumed that certain parameters of the pipeline operation are not deterministic). To accept the preliminary estimation of the durability of the pipe in the paper, the assumption was made that the interval quantities would be: pressure $\overline{p}$, density of the transported mixture $\overline{\rho}$ and the rate of pipe wall loss $\overline{v}_u$.

The sought quantity will be the time interval $\overline{t} \in \langle t^-, t^+ \rangle$ in which the pipeline may fail. The concept of evaluating the safe operating time using interval numbers is presented graphically in Fig. 4.

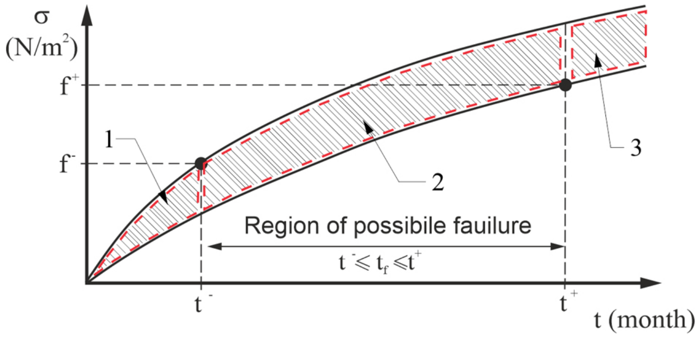

Fig. 4. Concept of estimation of pipeline failure time $t \in \langle t^-, t^+ \rangle$ using interval numbers

The adopted designations define the areas: a) no failures – 1; b) possible failure – 2, c) guaranteed failure – 3.

In order to evaluate the degradation time of the pipeline, an analytical model based on the theoretical analysis of the strength of the vessel loaded with its own weight and pressure was adopted. The analytical formulation of the deterministic model is presented in the paper [13] that is generalised to the case of a pipe that erodes around the entire circumference. Estimating the degradation time around the perimeter involved iterative checking of the load capacity of the element for subsequent interval data sets with the wall thickness values changing as a function of time.

3.2. Interval computational model

Calculations in the scope of the impact of the uncertainty were made using libraries available in the INTLAB package, applying classical arithmetic for interval numbers $\overline{X}$ [4, 14],

$$\overline{X} = \left[X^-, X^+\right], X^- < X^+, X^- = \inf\left(\overline{X}\right), X^+ = \sup\left(\overline{X}\right) \tag{3.1}$$

where: X^- is the lower limit of an interval number, X^+ is the upper limit of an interval number.

The basic operations to which interval numbers are subject are presented, among others, in [4, 14],

$$\overline{X} \pm \overline{Y} = \left[X^- \pm Y^-, X^+ \pm Y^+\right] \tag{3.2}$$

$$\overline{X} \cdot \overline{Y} = \left[\min\left(X^-Y^-, X^-Y^+, X^+Y^-, X^+Y^+, \max\left(X^-Y^-, X^-Y^+, X^+Y^-, X^+Y^+\right)\right]\right. \tag{3.3}$$

$$\overline{X}/\overline{Y} = [X^-Y^+] \cdot [1/Y^+, 1/Y^-] \tag{3.4}$$

The application of interval methods to evaluate the durability of pipelines can be presented using a schematic drawing in Fig. 5.

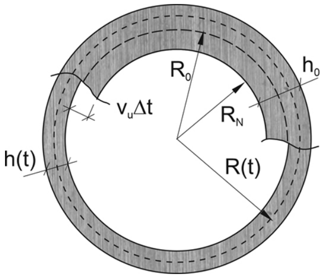

Fig. 5. Calculation model of the eroded pipe

It will be assumed that the parameter that determines the rate of degradation of the pipeline, that is the rate of loss of wall thickness $\overline{v}_u = \left[v_u^-, v_u^+\right]$, is of interval type, same as the material density $\overline{\rho}$ of the media and the pressure $\overline{p}_0$. Consequently, the wall thickness of the pipe $\overline{h}_w = \left[h_w^-, h_w^+\right]$ after time from the initiation time of exploitation of the pipeline is also the interval (uncertain) value. Subsequently, the interval and uncertain quantities will be the radius of the pipe $\overline{R} = [R^-, R^+]$ and reduced stress $\overline{\sigma}_{\text{red}} = \left[\sigma_{\text{red}}^-, \sigma_{\text{red}}^+\right]$.

The calculations assumed an analysis involving the reduction of the cross-sectional area of the pipe. In the case of the analytical model, the moment of reaching the limit stress in the pipe wall was analysed by using the method of successive approximations.

Reduced stress in the case of a thin-walled circular vessel loaded from the inside by pressure and own weight, in which the radius $\overline{R} = \overline{R}(t)$ and $\overline{h} = \overline{h}(t)$ are time-dependent quantities can be described by the relationships:

$$\inf\left(\overline{\sigma}_{\text{red}}\right) \leq f_y \tag{3.5}$$

$$\sup\left(\overline{\sigma}_{\text{red}}\right) \leq f_y \tag{3.6}$$

$$\overline{\sigma}_{\mathrm{red}} = \frac{g\overline{\rho}\overline{R}\,(t)^2}{\overline{h}(t)}\overline{\Phi}_{\mathrm{red,max}} \tag{3.7}$$

$$\overline{k} = 1 + \frac{\overline{p}_0}{g\overline{\rho}\overline{R}(t)} \tag{3.8}$$

$$\overline{\Phi}_{\mathrm{red,max}} = \frac{1}{4}\sqrt{12\left(\overline{k}+1\right)^2 + \left[\frac{1}{2}\left(\frac{L_0}{\overline{R}(t)}\right)^2 - 1\right]^2} \tag{3.9}$$

$$\overline{R}\,(t) = R_0 + \frac{1}{2}h_0 - \frac{1}{2}\overline{h}\,(t) \tag{3.10}$$

$$\overline{h}\,(t) = h_0 - \overline{v}_u\Delta t \tag{3.11}$$

where: R_0 is the radius of the vessel (pipe), h_0 is the thickness of the pipe wall, R_N is the nominal radius of the pipe, f_y is the tensile strength of steel, $\overline{\Phi}_{\mathrm{red,max}}$ is interval dimensionless maximum function of the reduced stress (bottom of the shell), L_0 is the length of the pipe, $\overline{k}$ is interval dimensionless pressure parameter, g is the acceleration of the earth, $\overline{\rho}$ is the density (parameter of interval type) of the transported mixture.

4. The estimation of the pipe durability – interval approach

4.1. Material parameters

Due to the lack of detailed data for the estimation of the intervals $\overline{X} = (X^-, X^+)$ the parameters of the interval number were determined from the following relationship.

$$X = X_0 - \Delta X \tag{4.1}$$

$$X^+ = X_0 + \Delta X \tag{4.2}$$

$$\Delta X = \frac{(X^+ - X^-)}{2} \tag{4.3}$$

$$X_0 = \frac{(X^+ + X^-)}{2} \tag{4.4}$$

where: X_0 is the average value, ΔX is a deviation from the mean value.

In the case of the rate of degradation for pipelines R1 and R2 the interval values $\sup(\overline{v}_u)$ and $\inf(\overline{v}_u)$ were taken as a lower limit v_u^- and upper limit v_u^+ obtained for a set of maximum deterioration rates $v_{u,i}$ for successive pipelines. In the case of a pipeline R1, the authoritative lower limit v_u^- was adopted on the basis of the measurements for the pipeline section R1(K9,K10), $v_u^- \approx 1.5$ mm/year while the upper limit v_u^+ was adopted on the basis of measurements of the pipeline section R1(K3,K4), value $v_u^+ \approx 3.6$ mm/year. Similarly, in the case of pipeline R2, a lower limit $v_u^- \approx 1.0$ mm/year based on the estimation of the pipeline section R2(K15,16) has been adopted, while the upper limit $v_u^+ \approx 2.9$ mm/year was based on the estimation of the pipeline section R2. In the case of an L2 pipeline the minimum and maximum value of the loss formation for the angle range was assumed as the limits of the intervals $\varphi \in \langle 135, 225\rangle$ (°), due to a single measurement in one section of the pipeline. This assumption was associated with the wear primarily to the pipe bottom area (in the case of settling of the mixture at the bottom of the pipe, damage may occur above the residual sediments.

The interval numbers defining the ranges of pressure variation were adopted according to the ranges of the work of the pipeline, declared in Table 2.

In the case of the density of the transported medium, it is assumed that the deviation value is about 10% of the average value. Therefore, value $\Delta\rho \approx 114$ kg/m^3 was adopted for the R1, R2 and L2 Due to the similar baseline average density of the medium for the R1 and R2 in both cases (including the L2 pipeline), the same intervals were adopted. The interval and deterministic variables that describe the operating parameters of the analyzed pipes were presented respectively in Table 3 and Table 4.

Table 3. List of interval variables that describe the operating parameters of the analysed pipes

Model parameter	$\overline{X}_{R1}$	$\overline{X}_{R2}$	$\overline{X}_{L2}$
Rate of erosion, $\overline{v}_u$ (mm/year)	$\langle 1.5, 3.6\rangle$	$\langle 1, 2.9\rangle$	$\langle 0.3, 3.3\rangle$
Pressure, $\overline{p}_0$ (at)	$\langle 5, 12\rangle$	$\langle 5, 12\rangle$	$\langle 5, 14\rangle$
Density of the mixture, $\overline{\rho}$ (kg/m^3)	$\langle 1024, 1252\rangle$	$\langle 1024, 1252\rangle$	$\langle 1024, 1252\rangle$

Table 4. List of deterministic parameters that describe the geometry of the analysed pipes

Model parameter	X_{R1}	X_{R2}	X_{L2}
Nominal diameter of the pipeline, D_n (mm)	1000	1000	800
Initial wall thickness, h_{w0} (mm)	16	16	16
Element calculation length, L_0 (m)	20	20	20

The results obtained from analytical calculations for the shell model taking into account the interval approach and the MC method (300 random sampling) are graphically illustrated in Fig. 6 and 8, where a uniform system of designations has been adopted. The following designations have been adopted in the drawings: a) the upper limit of the interval the thickness of the pipe wall h^+ (upper limit of the set) – 1, b) the lower limit of the interval the thickness of the pipe wall thickness h^- (lower limit of the set) – 2, c) reduced stress σ^+_{red} (upper limit of the set) – 3, d) reduced stress σ^-_{red} (lower limit of the set) – 4, e) reduced stress $\sigma^{\text{avg}}_{\text{red}}$, obtained for average values – 5, f) reduced stress values obtained using the method of MC – 6.

The analysis of the proposed approach to estimate the durability of pipes allows one to forecast the time of occurrence of the first failure t^- and the time interval during which this failure will occur $\overline{t}_{A1} \in \langle 3, 4\rangle$ years. According to the results obtained after time t^- the pipes should be turned over and subjected to the next cycle of life. The estimated total durability of the piping systems (the time interval during which the pipes safety work) will be $t_{\text{eksp}} \in \langle 6, 8\rangle$ years.

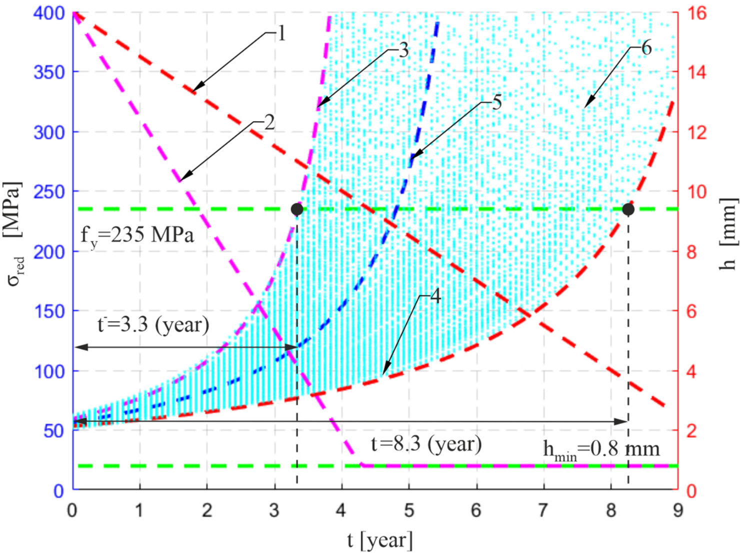

Fig. 6. Results of the calculations of the estimated time interval $\bar{t} = \langle t^-, t^+ \rangle$ of pipeline failure R1 (description in the text)

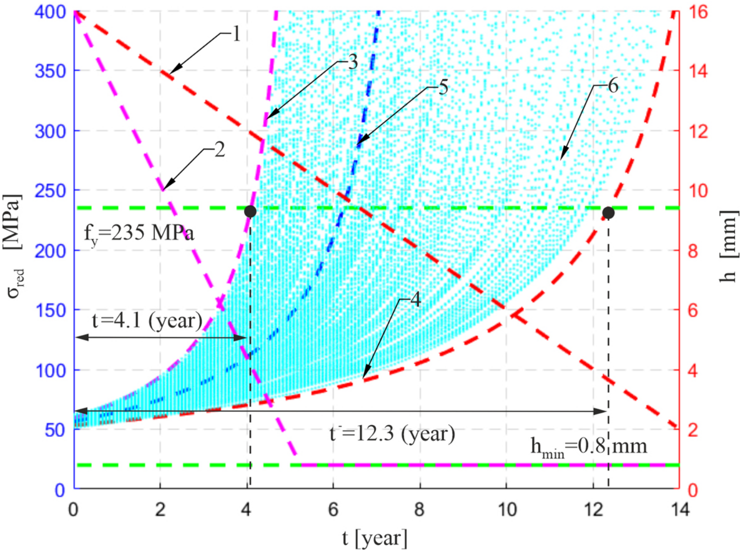

Fig. 7. Results of the calculations of the estimated time interval $\bar{t} = \langle t^-, t^+ \rangle$ of pipeline failure R2 (description in the text)

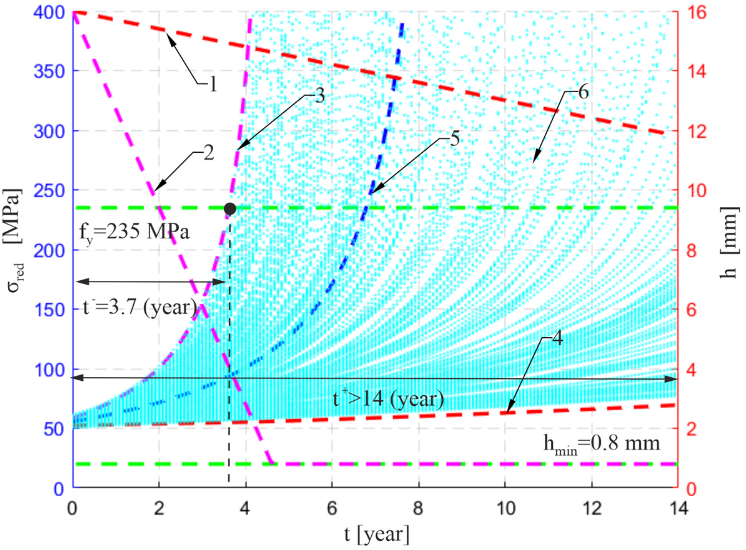

Fig. 8. Results of the calculations of the estimated time interval $\bar{t} = \langle t^-, t^+ \rangle$ of pipeline failure L2 (description in the text)

5. Conclusions

The calculation results are based on a simplified model, based in turn on the theory of shell structures, in which the assumption of the uniform abrasion of piping systems around the entire perimeter was adopted. This assumption does not fully reflect the operating conditions of the pipelines, where the mechanism of uneven wall abrasion is a dominant one. When analysing the degradation of the pipe, the electrochemical and chemical influences that may possibly occur and lead to a decrease of the material parameters and its yield strength were also ignored.

However, both the results of the calculations obtained and the approach to the estimation of durability should be considered prospective.

References

[1] H.C. Meng and K.C. Ludema, “Wear models and predictive equations: their form and content”, *Wear*, vol. 181–183, pp. 443–457, 1995, doi: 10.1016/0043-1648(95)90158-2.

[2] A.M. Lospa, R.G. Ripeanu, and A. Dinita, “Erosion modelling: a systematic review of available models and equations”, *IOP Conference Series: Materials Science and Engineering*, vol. 724, no. 1, art. no. 012037, 2020, doi: 10.1088/1757-899X/724/1/012037.

[3] R. Cuamatzi-Meléndez, M. Hernandez Rojo, A. Vázquez-Hernández, and F. L. Silva-González, “Predicting erosion in wet gas pipelines/elbows by mathematical formulations and computational fluid dynamics modeling”, *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*, vol. 232, no. 10, pp. 1240–1260, 2018, doi: 10.1177/1350650117745418.

[4] S.M. Rump and M. Kashiwagi, “Implementation and improvements of affine arithmetic”, *Nonlinear Theory and Its Applications, IEICE*, vol. 6, no. 3, pp. 341–359, 2015, doi: 10.1587/nolta.6.341.

[5] A. Neumaier, *Interval methods for systems of equations (encyclopedia of mathematics and its applications)*. Cambridge: Cambridge University Press, 1991, doi: 10.1017/CBO9780511526473.

[6] G.I. Hargreaves, *Interval analysis in matlab*. Manchester, UK: The University of Manchester, 2002. [Online]. Available: https://eprints.maths.manchester.ac.uk/1204/1/narep416.pdf. [Accesed: 17. Oct. 2017].

[7] M. Sága, V. Dekýš, and M. Vaško, "Some aspects of probability and possibility theories for numerical analysis of uncertain mechanical systems", *Acta Mechanica Slovaca*, vol. 14, no. 4, pp. 92–101, 2010, doi: 10.2478/v10147-011-0039-3.

[8] E. Hansen, "Interval arithmetic in matrix computations, part I", *Journal of the Society for Industrial and Applied Mathematics Series B Numerical Analysis*, vol. 2, no. 2, pp. 308–320, 1965, doi: 10.1137/0702025.

[9] E. Hansen and R. Smith, "Interval arithmetic in matrix computations, part II", *SIAM Journal on Numerical Analysis*, vol. 4, no. 1, pp. 1–9, 1967, doi: 10.1137/0704001.

[10] G. Mayer, *Interval analysis: and automatic result verification*. Berlin, Boston: De Gruyter, 2017, doi: 10.1515/9783110499469.

[11] N. Metropolis and S. Ulam, "The Monte Carlo method", *Journal of the American Statistical Association*, vol. 44, no. 247, pp. 335–341, 1949, doi: 10.2307/2280232.

[12] C. Szydłowski, Ł. Smakosz, M. Stienss, and J. Górski, "Monte Carlo simulations of the fracture resistance degradation of asphalt concrete subjected to environmental factors", *Archives of Civil Engineering*, vol. 69, no. 1, pp. 245–257, 2023, doi: 10.24425/ace.2023.144171.

[13] K. Magnucki, *Wytrzymałość i optymalizacja zbiorników cienkościennych*. Warszawa–Poznań, Polska: Wydawnictwo Naukowe PWN, 1998.

[14] R.D. Richtmyer and R.E. Moore, "Interval analysis", *Mathematics of Computation*, vol. 22, no. 101, pp. 219–222, 1968, doi: 10.2307/2004792.

Zastosowanie metody przedziałowej do oceny czasu eksploatacji rurociągów

Słowa kluczowe: rurociągi, erozja, liczby przedziałowe, niepewności

Streszczenie:

Problemy erozji rur spowodowane transportem materiału zawierającego odpady poflotacyjne stanowiące mieszaninę frakcji pyłowej, piaskowej i iłowej stanowią bardzo ważny problem w zakresie eksploatacji kopalń i zakładów wydobywczych rudy miedzi. W odniesieniu do KGHM Polska Miedź S.A. problem odnosi się do eksploatacji rurociągów o łącznej długości przekraczającej 250 km, a to z kolei przekłada się na znaczne ponoszenie nakładów finansowych, związane z kosztami eksploatacji rurociągów, jak i ich awariami. Fundamentalnym problemem z punktu widzenia eksploatacji rurociągów w KGHM Polska Miedź S.A. jest bardzo duże zużycie rur do transportu odpadów poflotacyjnych, jak również określanie czasu bezawaryjnej pracy elementów konstrukcji systemu rur. Awarie wiążą się ze znacznymi nakładami finansowymi, poważnymi ograniczeniami w eksploatacji oraz w niektórych przypadkach, nawet z zatrzymaniem eksploatacji. W pracy skupiono się na zastosowaniu równań teorii powłok [12] w ujęciu przedziałowym do oceny trwałości systemów orurowania. Obliczenia wykonano stosując klasyczne modele interwałowe z zastosowaniem bibliotek INTLAB [4]. Poprawność otrzymanych rozwiązań weryfikowano stosując metodę Monte-Carlo [11] przy założeniu jednostajnego rozkładu zmiennych losowych.

Received: 2023-08-14, Revised: 2023-09-05