Comparative analysis of water-pipe network deterioration—case study

Małgorzata Kutylowskā,* and Maria Orłowska-Szostakb

a Faculty of Environmental Engineering, Wrocław University of Technology, wyb. St. Wyspianskiego 27, Wrocław 50-370, Poland
b Faculty of Civil and Environmental Engineering, Gdansk University of Technology, ul. G. Narutowicza 11/12, Gdansk 80-952, Poland

* Corresponding author. E-mail: malgorzata.kutylowska@pwr.edu.pl

Abstract

The paper presents a comparative analysis of water-supply network deterioration in three Polish cities. The comparison was made on the basis of operating data (from the period 2007 to 2012) received from water utilities. The comparison is necessary to determine whether and to what extent water utilities should improve the technical condition of their water-supply networks. On average in cities A, B and C, failure rates \( \lambda \) (fail km\(^{-1}\) a\(^{-1}\)) of water mains, distribution pipes and house connections were 0.20, 0.24 and 0.53; 0.17, 0.32 and 0.50; and 0.01, 0.48 and 1.63, respectively. The failure rates of the main and distribution conduits were higher in winter than summer, due to the weather conditions and the pipes’ shallow depth. Smaller diameter pipes were more vulnerable. One city is exposed to mining exploitation and most cracking observed on the main and distribution pipelines arose from this. As the literature and these investigations indicate, the technical condition of water supply systems in Poland is still improving and rates of deterioration decreasing.

Key words: damages, deterioration, failure rate, water-supply network

INTRODUCTION

Technical, economic and reliability analyses should be the basis of designing, using and renovating water supply systems. Nowadays, improvements in water service quality and operational safety are necessary due to greater reliability requirements for all buried infrastructure, not only for water systems, but also for sewerage systems (Każmierczak & Kotowski 2015).

Reliable operation of water-pipe networks is also essential to achieve the standards required for reducing fault numbers, leakage and water loss, as well as increasing water quality. Research into the reliability and deterioration of municipal systems is quite advanced in Poland and elsewhere (Hotloś 2007; Arai et al. 2010; Kwietniewski & Rak 2010; Gheisi & Naser 2013; Kowalski & Miszta-Kruk 2013; Scheidegger et al. 2013; Kutylowska & Hotloś 2014; Kutylowska 2015a, 2015b).

Studies, relating to water-supply network deterioration, indicate that the condition of the networks in Poland has been steadily improving. Nevertheless, the frequency of pipe failures is still higher than in other European countries (Kappeler 2009; Hug & Pielorz 2010; Kappeler 2010; Józwiak et al. 2010), which is due to the many years of neglect between World War II and system transformation in 1990. The neglect included the lack of proper maintenance and planned modernization of the supply systems, and poor workmanship and material defects in the pipes.

The aim of this study is to analyze and compare the deterioration of water supply systems in three Polish cities. The comparison is necessary to determine whether and to what extent the water utilities should improve the technical condition of their networks. The results of the analyses will be useful to...
and exploited by water supply system operators. Other researchers may also gain insight into how advanced deterioration analysis studies of Polish water-supply networks are and compare the technical condition of water conduits in Poland with those elsewhere.

**Methodology and range of studies**

Operating data from water utilities are used all over the world to estimate network and pipe deterioration levels. The registration and mode of collecting operational data will influence the precision of the analysis. The range of investigations depends on the size and quality of the database, which should contain: the types, numbers, causes and effects of water pipe damages, including information on the material, and length and diameter. The more precise the research, the better the conclusions and proposals to the water utility for improving the technical condition of buried infrastructure. Using information about registered damage, a failure and deterioration analysis of the water-supply networks in three Polish cities was carried out. These networks were used as case studies to estimate water pipe deterioration.

Modeling of water pipe deterioration is very popular nowadays (Lei & Saegrov 1998; Bogárdi & Fülöp 2012; Scheidegger et al. 2013; Kutyłowska 2015a, 2015b). A comprehensive review of the models used in the first decade of the 21st century was presented by Clair & Sinha (2012). Many mathematical models, both statistical and physical, are used to estimate failure frequency, and suggest renovation methods or the optimal time of replacement (Loganathan et al. 2002; Yamijala et al. 2009; Shahata & Zayed 2012; Kutyłowska 2015a, 2015b). Before modeling, it is necessary to use operating data to calculate principal deterioration and reliability indicators, e.g. availability \( K_g \), failure rate \( \lambda \), and probability of work without failure \( P(t) \). This paper describes, first, the deterioration of water-supply networks in Polish cities estimated on the basis of operating data. The next step would be modeling.

The value of \( \lambda \) is determined from operational data using formula 1 (Kwietniewski et al. 1993; Kowalski & Miszta-Kruk 2015; Kutyłowska & Hotłoś 2014):

\[
\lambda(\Delta t) = \frac{n(\Delta t)}{L \cdot \Delta t}
\]

where

- \( \lambda(\Delta t) \) unitary failure rate (constant time interval \( \Delta t \)), fail km\(^{-1}\).a\(^{-1}\);
- \( n \) number of pipe failures in unit time interval \( \Delta t \);
- \( L \) average pipeline length in time \( \Delta t \), km;
- \( \Delta t \) observation time, a.

The failure rate indicator described by Equation (1) is that most commonly used worldwide. The deterioration analysis should be both understood and easy to apply by users, which is why Equation (1), which is simple, is used to assess the network’s reliability level. The failure rate is calculated, compared and discussed in this paper in relation to networks in cities designated A, B and C (Water Utility Operating Data 2014). It is the conventional way for determining water pipe deterioration. The numbers of pipe faults and failure rate changes over time, like the causes, are generally random, which makes typical mathematical description quite difficult. It is important to remember planned and random pipe renovation exercises, too. This factor depends on the economics, the upgrading schedule, and any damage registered previously, and has a significant influence on the general description of water system deterioration (Kutyłowska 2015b).
RESULTS AND DISCUSSION

Basic information on the water-supply networks studied

City A is of medium size and has about 40,000 inhabitants, almost 100% of whom have piped connections to the system. The pipes were installed or renovated in the second half of the 20th century, and the network conveys an average of 7,500 m$^3$ d$^{-1}$. Water pressure in the system is stable and about 0.3 to 0.4 MPa. The network consists of: (1) grey cast iron and PE mains with diameters of DN 150 to 800 mm, (2) distribution pipes with diameters of DN 50 to 315 mm, made variously of ductile or grey cast iron, steel, PE, PVC or asbestos cement (AC), (3) house connections with diameters of DN 20 to 150 mm, made of steel, grey cast iron, PE, PVC or lead.

City B has about 70,000 inhabitants almost 100% of whom are connected to the system. The daily average supply is about 8,300 m$^3$ d$^{-1}$. Because of the topography and the height of the buildings, there are two water supply zones with pressures of 0.36 MPa and 0.56 MPa, respectively. The network includes: (1) and main conduits of both grey cast iron and steel transit, with diameters of DN 350 to 700 mm, (2) distribution pipes with diameters of DN 80 to 250 mm, made variously of grey cast iron, steel, PE, PVC or AC, (3) house connections with diameters of DN 25 to 200 mm, made of steel or PE.

City C is one of the largest in Poland and has about 440,000 citizens. On average 65,600 m$^3$ d$^{-1}$ are pumped into the network. Water pressure in the network differs in the mains and distribution conduits, being 0.6 to 0.8 MPa and 0.2 to 0.7 MPa, respectively. The main conduits – generally of grey or ductile cast iron, or steel – have diameters of DN 300 to 1,200 mm. The distribution conduits, with diameters of DN 80 to 280 mm, are made of grey cast iron, PE, PVC or AC. House connections diameters range from DN 20 to 150 mm.

The network lengths cities A, B and C are shown in Table 1. The lengths of the mains was reasonably stable during the study, but a significant increase in the total length of house connections was noted in city A (ca. 22%). This was caused by very extensive development, when new customers were connected to the network. The total length of distribution pipes increased by only 7% and 5% in cities A and B, respectively. In city C the increase in distribution pipe length was more significant at about 10%.

Table 1 | Length of water-supply network in three analyzed systems

<table>
<thead>
<tr>
<th>Pipeline function/Length in km</th>
<th>Year/City</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main conduits</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>10.5</td>
<td>10.5</td>
<td>10.5</td>
<td>10.7</td>
<td>10.7</td>
<td>10.7</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>28.2</td>
<td>28.2</td>
<td>28.2</td>
<td>28.2</td>
<td>28.2</td>
<td>31.0</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>195.0</td>
<td>193.2</td>
<td>194.7</td>
<td>194.6</td>
<td>200.0</td>
<td>200.1</td>
<td></td>
</tr>
<tr>
<td>Distribution conduits</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>81.9</td>
<td>82.9</td>
<td>84.0</td>
<td>87.1</td>
<td>88.6</td>
<td>88.8</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>109.8</td>
<td>110.6</td>
<td>113.4</td>
<td>113.8</td>
<td>114.6</td>
<td>115.5</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>789.8</td>
<td>803.5</td>
<td>827.2</td>
<td>831.4</td>
<td>859.1</td>
<td>878.9</td>
<td></td>
</tr>
<tr>
<td>House connections</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>39.7</td>
<td>42.8</td>
<td>45.1</td>
<td>47.3</td>
<td>49.3</td>
<td>51.0</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>41.3</td>
<td>42.0</td>
<td>43.3</td>
<td>44.1</td>
<td>44.7</td>
<td>45.2</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>208.2</td>
<td>214.7</td>
<td>218.6</td>
<td>218.5</td>
<td>225.2</td>
<td>227.7</td>
<td></td>
</tr>
</tbody>
</table>

The most typical materials and their proportional lengths in the main and distribution conduits in the cities, for the final year of the study (2012), are shown in Figure 1. In city C, about 0.6% of the total length was made of reinforced concrete.

Most water pipes (66.1%, 55.2% and 51.2% for cities A, B and C, respectively) are made of cast iron (either grey or ductile), which has been used for many years (more than a century). In many Polish cities, the main and distribution pipes are still made of these materials. Almost a third of the total...
length in all three cities was plastic, however, and some pipe sections were replaced with new materials like PE and PVC. In Polish systems, completely new and renovated pipe sections have been made of PE for the last 20 to 40 years (Kwietniewski & Rak 2010). Steel is also an important material (Yves & Eisenbeis 2000). AC pipes, however, are regularly replaced with conduits made of new and safer materials. In the cities studied, no more than 11% of the total length of main and distribution pipes was made of AC.

The deterioration and failure analysis was carried out only with reference to linear objects like pipelines. Non-linear objects (valves and hydrants) were not considered because the total number of installed fittings was unknown, so that their failure frequency indicator could not be calculated.

Numbers and types of faults

The total numbers of faults taken into account in the deterioration analysis are shown in Table 2. During the six-year study, the numbers of pipeline faults in cities A, B and C were 269, 372 and

<table>
<thead>
<tr>
<th>Year</th>
<th>City</th>
<th>Main conduits</th>
<th>Distribution conduits</th>
<th>House connections</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>A</td>
<td>5</td>
<td>22</td>
<td>28</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>9</td>
<td>28</td>
<td>31</td>
<td>68</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>2</td>
<td>332</td>
<td>374</td>
<td>708</td>
</tr>
<tr>
<td>2008</td>
<td>A</td>
<td>1</td>
<td>19</td>
<td>27</td>
<td>47</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>4</td>
<td>39</td>
<td>22</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>0</td>
<td>390</td>
<td>392</td>
<td>782</td>
</tr>
<tr>
<td>2009</td>
<td>A</td>
<td>3</td>
<td>22</td>
<td>27</td>
<td>52</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>5</td>
<td>37</td>
<td>15</td>
<td>57</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>0</td>
<td>380</td>
<td>410</td>
<td>790</td>
</tr>
<tr>
<td>2010</td>
<td>A</td>
<td>4</td>
<td>23</td>
<td>25</td>
<td>52</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>2</td>
<td>36</td>
<td>15</td>
<td>53</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>8</td>
<td>466</td>
<td>338</td>
<td>812</td>
</tr>
<tr>
<td>2011</td>
<td>A</td>
<td>0</td>
<td>10</td>
<td>12</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>4</td>
<td>27</td>
<td>16</td>
<td>47</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>0</td>
<td>416</td>
<td>323</td>
<td>739</td>
</tr>
<tr>
<td>2012</td>
<td>A</td>
<td>0</td>
<td>21</td>
<td>20</td>
<td>41</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>5</td>
<td>48</td>
<td>29</td>
<td>82</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>0</td>
<td>406</td>
<td>291</td>
<td>697</td>
</tr>
<tr>
<td>Total</td>
<td>A</td>
<td>13</td>
<td>117</td>
<td>139</td>
<td>269</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>29</td>
<td>215</td>
<td>128</td>
<td>372</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>10</td>
<td>2,390</td>
<td>2,128</td>
<td>4,528</td>
</tr>
</tbody>
</table>
4,528, respectively. As noted above, cities A and B are medium-sized, while city C is one of the biggest in Poland. This is one of the main reasons why city C has more than 10 times more failures than the others. About 48%, 64% and 53% of all failures were observed on main and distribution conduits in A, B and C, respectively. All other faults were in house connections. The average failure rate was 44, 62 and 754 per annum in the systems in A, B and C, respectively.

Damage to smaller diameter pipes predominated among distribution conduits. The pipes’ diameter is closely connected to the function performed in the water supply system, which is why water mains are less vulnerable (see Table 2). Hence there is an inverse correlation between fault numbers and pipeline diameters: the former decreasing as the latter increases, due, perhaps, to the pressure fluctuations inside the pipe. In water mains, pressure fluctuations are lower than in distribution pipes and house connections. As noted by Hotloś (2007), the number of faults is related to the water pressure inside the pipe. The most vulnerable pipes were house connections with diameter of DN 25 to 50 mm. A similar relationship between failure rate and diameter was observed in Canadian water supply systems (Pelletier et al. 2003).

In cities A and B, those pipelines (water mains, distribution conduits and house connections) made of plastic or AC suffered only cracking, those made of grey cast iron suffered slight corrosion, and mainly transverse and longitudinal cracking. Steel pipelines failed, in almost 100% of cases, because of material corrosion. Information about the kind of failure was not registered in city C. The relationship between the type of failure and the pipe material was also noted recently by Arai et al. (2010) and Mora-Rodríguez et al. (2014).

Some 98% and 67% of all observed failures on water mains and distribution conduits, were transverse and longitudinal cracks, in cities A and B, respectively. This arises from the material used to make the pipelines. For house connections the relationship was inverted and most failures were described as corrosion pits.

Precise definition of water pipe failure causes is very difficult because they occur randomly. Operational studies indicate that the main causes of damage are: water and soil corrosiveness, excess pressure, large pressure fluctuations and water hammer, frost penetration into the ground surrounding the pipeline, and ground instability in mining areas. As a result, pipelines suffer different kinds of damage, such as: the breaking of pipes and pipe joints, longitudinal and/or transverse cracking, perforation (corrosion pits), and damage to fittings (Bittner & Heine 1998; Hotloś 2007; Kutyłowska & Hotloś 2014).

Pipe deterioration

Figures 2–4 show the results of pipe deterioration in cities A, B and C from 2007 to 2012. The failure rates for all types of conduits are shown.

The values of indicator λ (failure rate) for the networks in A and B are approximate. In A, the deterioration rate of house connections has decreased more than twofold since 2007, from 0.89 to 0.40 fail km⁻¹·a⁻¹. On average during the study, the house connection failure rate in city A was 0.53 fail km⁻¹·a⁻¹. Almost the same value of λ was observed in city B, where the average service pipe failure rate amounted to 0.50 fail km⁻¹·a⁻¹. In this city, however, there was no significant decrease in house connection failure rate, unlike city A where many pipe sections have been renovated or replaced. The failure rate for main conduits fell from 0.48 to 0.00 fail km⁻¹·a⁻¹, and was 0.20 on average during the study, in city A. Some failure rate fluctuations were observed in city B, but the average for water mains there amounted to 0.17 fail km⁻¹·a⁻¹. The average values of λ for distribution pipes were 0.24 and 0.52 fail km⁻¹·a⁻¹ in cities A and B, respectively.

A different situation was observed in city C. The water main failure rate during most of the study was to zero. Failures occurred only in 2007 and 2010, when λ was, respectively, to 0.01 and 0.04 fail km⁻¹·a⁻¹. This leads to the conclusion that the excellent technical condition of the mains in C
probably arises from planned modernization and proper maintenance. On average, the distribution
pipe failure rate was $0.48$ fail km$^{-1}$·a$^{-1}$. During the six year study, the technical condition of the dis-
tribution pipes in city C was almost constant, varying between $0.42$ and $0.56$ fail km$^{-1}$·a$^{-1}$. The rate of
deterioration of house connections in C was higher than in A or B, and $\lambda$ varied between $1.28$ and $1.89$
fail km$^{-1}$·a$^{-1}$, with an average of $1.63$. Most house connections (ca. 60%) are of galvanized steel,
which should be replaced and renovated. The trend of house connection replacement remains the same because the change to PE pipes has been about 7% per annum up to now. In comparison, house connections in other Polish cities were also characterized by relatively high rates of failure, up to as much as 2.00 fail km$^{-1}$·a$^{-1}$ (Kowalski & Miszta-Kruk 2013).

In some parts of Germany, for comparison, the rate of deterioration of main and distribution pipes is significantly lower, at about 0.10 fail km$^{-1}$·a$^{-1}$ (Hug & Pielorz 2010). The correct technical conditions depend not only on small pressure fluctuations and planned renovation, but also on planned inspections. Planned inspections are still rare in Poland in comparison with, for example, Switzerland, where (according to benchmarking investigations) the whole network may be inspected every year in some cities (Kappeler 2009; Kappeler 2010).

The deterioration of the networks in cities A and B (Figures 5 and 6) was also evaluated on the basis of the failure rate of the main and distribution conduits in the autumn–winter period (November to February inclusive) and the spring–summer months (March to October). For city B, in 2011 and 2012, and city C, such evaluation was not possible, because damage registration did not include exact information about the season in which failures occurred. The failure rates of the main and distribution pipelines in the observation years were 1.2 to 3.2 and 0.5 to 1.5 times higher in the autumn–winter period than in the spring–summer period, in A and B, respectively. The weather conditions and the shallow pipe-laying depth were determined as the causes of pipeline failure. Bittner & Heine (1998), and Rajani et al. (2012) also showed that an increase in pipe deterioration is observed in the colder season. Gould et al. (2011) carried out studies concerning the relationships between some climate parameters and failure frequency, and found strong correlations between climate and pipe failure rate.

**Figure 5** | Failure rate of main and distribution pipes depending on season, city A.

**Figure 6** | Failure rate of main and distribution pipes depending on season, city B.
CONCLUSIONS

The main aim of this paper was to describe water-supply network deterioration (on the basis of operational data from water utilities) in Poland, using three systems as case studies. Both the literature and these investigations show that the technical condition of water networks in Poland is still improving and the amount of deterioration decreasing.

The results from the study were:
- The total number of failures was 269, 372 and 4,528 in cities A, B and C, respectively. Smaller diameter pipes were more vulnerable.
- Water pipe deterioration was established using the indicator $\lambda$, called the ‘failure rate’.
- The average failure rates were 0.20 fail km$^{-1}$·a$^{-1}$ for water mains, 0.24 for distribution pipes and 0.53 for house connections in A’s network.
- The average value of $\lambda$ was similar in city B, and amounted to 0.17 fail km$^{-1}$·a$^{-1}$, 0.32 and 0.50 for mains, distribution pipes and house connections, respectively.
- Distribution pipes and house connections are more prone to failure in city C. On average, failure frequency amounted to 0.48 and 1.63 fail km$^{-1}$·a$^{-1}$, respectively.
- The failure rates for the main and distribution conduits (cities A and B) were higher in winter than summer due, perhaps, to the weather conditions and the shallow pipe-laying depth.
- City B is exposed to mining exploitation and most of the cracking observed on the main and distribution pipelines arose from that.

As the extent of water supply network deterioration is slightly higher in Poland than other countries, some recommendations can be given to the water utilities in cities A, B and C. Total modernization of the networks, with renovation of the most vulnerable conduits (especially house connections) should be carried out. Planned inspections and active leakage control are also quite important tasks.

The study results have made it possible to organize the databases and define failure frequency in selected Polish water-supply networks, with respect to the ages, types and diameters of the pipelines. Future investigations will contain more advanced analysis based on reliability theory, which will be applied to systems operations as well as to create systems control criteria.

ACKNOWLEDGEMENTS

The authors thank the water utilities in cities A, B and C for enabling the use and analysis of their operational data.

The fellowship was co-financed by the European Union and the European Social Fund

REFERENCES


Water Utility Operating Data 2014 (number and kinds of failures, the basic information about the water-pipe network) given by in city A, B and C.
