Study on failure rate analysis for water distribution pipelines

Yasuhiro Arai, Akira Koizumi, Toyono Inakazu, Haruhiko Watanabe
and Masahiro Fujiwara

ABSTRACT

Many of the waterworks facilities in Japan were constructed during the rapid economic growth period. Today, the deterioration and renovation of these aged facilities have become a pressing issue. There are approximately 600,000 km worth of water pipelines laid out across Japan, accounting for about 70% of the nation's water-related assets (totalling ¥40 trillion). To provide water that is safe to use, it is necessary to improve and innovate water purification technologies; not only that, it is also vital to properly maintain and manage the pipelines. The current research aims to apply reliability engineering in the waterworks field as one possible approach and to show its viability; it will also obtain vital messages revealed within pipeline incident data. In other words, we collected the information concerning water distribution pipeline incidents through questionnaire surveys and then analysed the cumulative failure distribution (unreliability) by pipeline material, the failure probability density and failure rate, among others.

Key words | failure probability density, failure rate, questionnaire survey, reliability engineering, unreliability, water distribution pipeline

Yasuhiro Arai (corresponding author)
Akira Koizumi
Toyono Inakazu
Department of Civil and Environmental Engineering,
Tokyo Metropolitan University,
Tokyo,
Japan
Tel.: +81 42-677-1111 ext. 4574
E-mail: *y-arai@tmu.ac.jp*

Haruhiko Watanabe
Central Research Institute,
Nihon Suido Consultants Co., Ltd,
Tokyo,
Japan

Masahiro Fujiwara
Japan Water Research Center,
Tokyo,
Japan

INTRODUCTION

Many pipelines that make Japan's waterworks system were installed during the rapid economic growth period (1950s–1970s) and the renewal of these old and deteriorating pipelines has become a serious issue. As the water pipelines are installed underground, they go unnoticed by the general public, which leads to a lack of public concern in their daily lives. However, it goes without saying that to pass on to the next generations a high-quality service, as well as providing safe tap water, will require continuous efforts in the maintenance and management of pipelines.

To this end, we can turn to the quality management of items like industrial products for ideas, where detailed information on defective and flawed items is being collected. In such cases, the data obtained are statistically analysed to reveal the attributions of failure in each product, with feedback also given to product design in the upper stream of the production process. This approach is developed on a foundation of reliability engineering and is considered viable in view of the most effective approach for maintenance and the timing of response to incidents (Shiomi 1982).

Consequently, this research will employ this reliability engineering based approach to process data yielded from our questionnaire survey on the actual state of water distribution pipelines (hereafter 'pipeline incident data'). In other words, it will examine the period up to when leakage is reported for each type of pipeline material, reveal the changes over the years per failure rate (failure rate curve) and present useful advice on future maintenance. We then present an overview of the survey data used for

doi: 10.2166/aqua.2010.108

this research and deal with fundamental information concerning reliability engineering. In later sections the analytical results concerning ductile iron pipes, steel pipes and PVC pipes will be provided, giving attention to the changes of pipe form or distortions in the failure rate curves, while considering the possible link between suspected causes such as shifting of period of installation and changes of pipeline specifications.

DATA COLLECTION

The survey conducted for this research focused on waterworks entities nationwide, with questionnaires distributed to obtain information on leakages related to water distribution pipelines that occurred during 2004 and 2005. The actual survey comprised questions such as those related to the installation year of problematic pipes and the types of pipe, joint and coating. The questionnaires were then sent to each subject business entity. This research focuses only on commonly installed pipes excluding exposed pipes (including water pipe bridges and common ditch pipelines) and leakages caused by human error (including faulty installation or damages to the pipes due to other construction works). From the results gathered from the questionnaires we were able to obtain data concerning a total of 2,621 incidents, of which there were 485 cases where data concerning the period leading up to the leakage incident (defined as the number of years spanning from the year of installation to the year of detection of incident) could not be determined.

The state of sections with leakage was roughly divided into two categories, 'body' and 'joint', for the survey; the data collected per pipe type are presented in Table 1. It became clear that, while leakage in the 'body' occurred mostly in ductile iron pipes without a polyethylene sleeve (hereafter 'no PS'), cast iron pipes and steel pipes, 'joint' leakage was found mostly in PVC pipes (excluding HIVP). Furthermore, Table 2 shows detailed data on leakage for each of the body and joint parts. This shows that the most common cause of leakage in the body of ductile iron pipes 'no PS' is 'pitting corrosion' (43.1%), while for the joint it is the 'connecting accessory (bolt, etc.) degradation' (60.4%). In the case of cast iron pipes, leakage in the body occurred mostly due to 'longitudinal cracking' (33.7%), followed by 'transversal cracking' at 25.1% and 'breakage' at 18.9%. For the body of steel pipes, the main cause is as with ductile iron pipes 'no PS': 'pitting corrosion' (66.2%). Meanwhile, PVC pipes suffer at the joint mostly due to 'cracking' (84.5%), followed by 'joint dislocation' at 10.1%. For the body, 'longitudinal cracking' amounted to 64.3%, with 'transversal cracking' at 25.8%.

When we make a histogram using data collected from a total of 2,136 cases of pipeline incidents where the total period of installation underground can be determined, and we show the types of pipe in categories of 'ductile iron pipes', 'cast iron pipes', 'steel pipes', 'PVC pipes' and 'others' (asbestos cement pipes, polyethylene pipes, etc.) in five-year increments, we get the results shown in Figure 1.

As overall characteristics we see PVC pipes, which experience more leakage, peaking at between 30 and 35 years after installation, while with cast iron pipes we get data that show the tendency for leakage in pipes that have endured long years before the incidents (earlier year of installation). The analyses that ensue dealt with a total of five pipe types: ductile iron pipes (DIP), cast iron pipes (CIP), steel pipes (SP), asbestos cement pipes (ACP) and PVC pipes (VP). In regard to the different years when the various pipes began being used and spread across the nation, if we were to trace 50 years back from the period subject to the survey (years 2004 and 2005), as the data gathered were from the common period of each pipe type, the current research could only deal with data 'under fifty years' after installation prior to leakage incidents.

Table 1 | Leakage point position by pipe classification (body and joint comparison)

	Ductile cast iron pipes					
	With PS	**No PS**	**Cast iron pipes**	**Steel pipes**	**PVC pipes**	**Asbestos cement pipes**
Body	26	181	243	157	291	64
Joint	35	96	34	28	497	79

Table 2 | Leakage point position by pipe classification (causes)

	Ductile cast iron pipes					
	With PS (%)	**No PS (%)**	**Cast iron pipes (%)**	**Steel pipes (%)**	**PVC pipes (%)**	**Asbestos cement pipes (%)**
Body						
Overall uniform corrosion	23.1	17.1	11.5	27.4	0.7	0.0
Pitting corrosion	34.6	43.1	10.3	66.2	4.8	3.1
Longitudinal cracking	19.2	13.8	33.7	1.9	64.3	43.8
Transversal cracking	11.5	12.2	25.1	3.2	25.8	14.1
Breakage	3.8	11.6	18.9	0.6	4.1	35.9
Other	7.7	2.2	0.4	0.6	0.3	3.1
Joint						
Joint dislocation	34.3	24.0	29.4	3.6	10.1	2.5
Breakage	8.6	1.0	0.0	17.9	3.6	6.3
Deterioration of accessories	25.7	60.4	17.6	10.7	0.4	13.9
Cracking	2.9	2.1	14.7	21.4	84.5	5.1
Packing deterioratrion	14.3	10.4	2.9	3.6	0.8	72.2
Other	14.3	2.1	35.3	42.9	0.6	0.0

As for the subject pipeline incident data ($n = 1{,}853$, 140 waterworks), the results are given in Table 3, showing the collected data per five years after installation.

RELIABILITY ENGINEERING

This section describes the 'failure rate' within reliability engineering (Fukui 2006). The term 'failure rate' is used to denote 'the rate of failure per unit time of a particular item at the moment when that item is operational'. That is, to show the probability of failure occurrence of an item (Shimizu 2006) that is capable of functioning up to a particular point in time within a continued unit time period, with the total number of incidents within the unit time being divided by the total operating time (= number of operational items [remaining number] $*$ unit time). This concept is defined through the formula:

$$\text{Failure rate} = \frac{\text{Total failure occurrence}}{\text{Total operating time}}$$

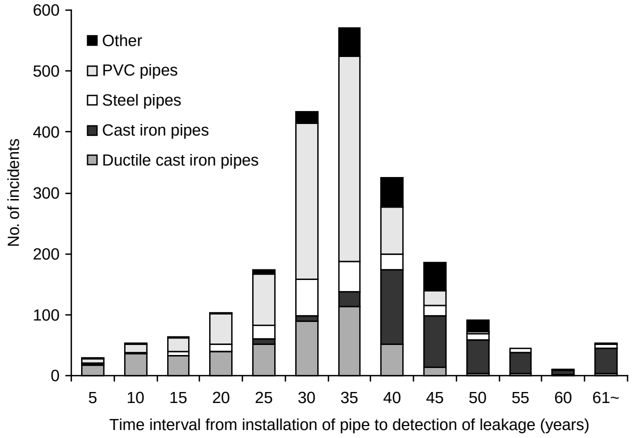

Figure 1 | Distribution of pipeline incidents with time since installation.

In actual calculation, the unreliability function (cumulative failure distribution function) $F(t)$ is found through Equation (1) (Fukui 2006), where $R(t)$ denotes reliability function, $s(t)$ indicates the number of operational items (remaining number) at the time, and N stands for the total number of items. This analysis considers $t = 50$, with 0 remaining items.

$$F(t) = 1 - R(t) = 1 - s(t)/N \tag{1}$$

Based on this unreliability function $F(t)$, we then find the failure probability density function $f(t)$ and failure rate

Table 3 | Pipe incident data ($n = 1{,}853$)

		Ductile cast iron pipes					
		With PS	**No PS**	**Cast iron pipes**	**Steel pipes**	**PVC pipes**	**Asbestos cement pipes**
1	0–5	13	2	0	1	6	0
2	6–10	18	15	0	1	12	0
3	11–15	21	7	0	6	20	0
4	16–20	13	23	0	11	43	0
5	21–25	16	33	5	25	72	0
6	26–30	10	70	8	60	236	14
7	31–35	3	93	23	50	317	32
8	36–40	0	48	123	25	76	43
9	41–45	0	13	85	18	23	36
10	46–50	0	0	55	10	3	16
		94	**304**	**299**	**207**	**808**	**141**

$\lambda(t)$ through Equations (2) and (3).

$$f(t) = \frac{\mathrm{d}F(t)}{\mathrm{d}t} = -\frac{\mathrm{d}R(t)}{\mathrm{d}t} \tag{2}$$

$$\lambda(t) = \frac{f(t)}{R(t)} = \frac{(-\mathrm{d}R(t)/\mathrm{d}t)}{R(t)} \tag{3}$$

[%/h] is used as the unit of failure rate (with a [1/time] dimension). In the case of segment data, the number of failures occurring within a time period $\Delta t(= t_i - t_{i-1})$ is gathered for calculation. The estimated value λ_i of segment i at this point is called the value of point estimation.

By classifying the time change of failure rate $\lambda(t_i)$ we get the following three patterns (Shiomi 1982):

i. DFR (decreasing failure rate) type: initial failure period (infant death period)
ii. CFR (constant failure rate) type: random failure period (youth, prime period)
iii. IFR (increasing failure rate) type: wear-out failure period (senile period)

As the order of occurrence of the failure periods given above appear in a curve not unlike the contour of a Western bathtub, the curve is thus known as the 'bathtub curve' (Murotsu *et al.* 1996). The three failure periods that make up this bathtub curve are comparable to the change in the death rate of humans. In other words, the death rate of newborn infants to children up to five years of age is high, but it decreases as we go up to the age group of 10–20 years of age, after which the death rate increases as we age (Kumamoto 2005). However, as we can determine from the water pipeline incidents subject to this study, the main causes are either random, or corrosion over long years or deterioration of functionality; therefore, type (i) shall be eliminated from further examination of the failure rate curve leaving the focus only on types (ii) and (iii) (Arai *et al.* 2008).

RESULTS AND DISCUSSION

When we use Table 3 to find the unreliability function for each type of pipe we get the result shown in Figure 2. What requires attention here is that, since data for the period of 0–20 years after installation of CIP and ACP are

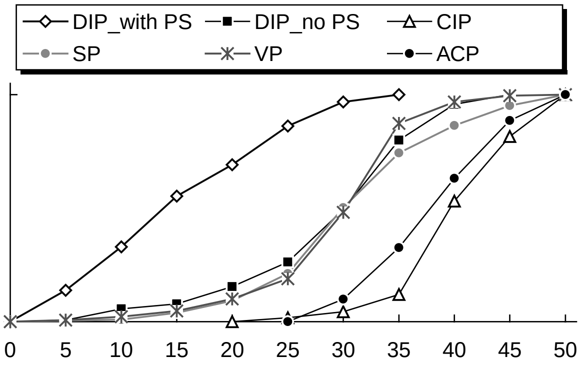

Figure 2 | Unreliability functions.

not obtained from the current survey, no information is reflected in the findings concerning incidents that occur either immediately after installation or at a relatively early stage. In addition, given that supplies of materials for CIP and ACP in Japan terminated in 1972 and 1986, respectively, further analyses will exclude these pipes. The analytical results and examination details concerning DIP, both with and without PS, SP and VP are given below.

Ductile cast iron pipes (DIPs)

Figure 3 shows the failure probability density function $f(t)$ and failure rate $\lambda(t)$ for DIP with no PS ($n = 304$). Due to the fact that no data was found this time for problematic pipelines of this type of pipe that have been installed for over 46 years, the final time interval is given as '41–45 years' instead of '46–50 years'. If we look at the failure rate curve we can see that it is a typical CFR type curve; while a slight increase is detected at time interval $k = 2$, it does not show any peculiar tendency.

Meanwhile, if we look at Figure 4, DIP with PS ($n = 94$), we can see that there are no data for this type of pipe for the period of over 36 years after installation and the final time interval ends at '31–35 years'. The polyethylene sleeve method was devised in the 1950s in the US and UK, and was adopted for actual pipelines in Japan in 1968. Since our research concerns the years 2004 and 2005, data for pipelines using PS (beginning in 1968 and spanning 36–37 years) are likely to have the longest period of installation among all subject pipelines. If we look at the failure rate curve we can see distortions occurring in the first and latter halves of the period after installation. From the failure probability density curve we can also see that, while there should be a tendency for smooth decrease beyond the '11–15 years' period, we can detect a tendency for increase during the '21–25 years' and '26–30 years' periods. With regard to PS, since the amendment of the Japan Ductile Iron Pipe Association standards (JDPA Z 2005-1984) in 1984 there have been repeated changes in physical attributions and other aspects of PS. It is therefore possible that variations in performance (anticorrosive effects) of the PS may exist before and after this time period. Given that the period subject to the survey were years 2004 and 2005, pipelines installed prior to the amendment would have been installed for over 20 years, which corresponds to the period in the latter half of the failure probability density curve with higher failure rate. In other words, the reason for the rising of the density curve may be attributed to the pipelines installed with newly adopted PS.

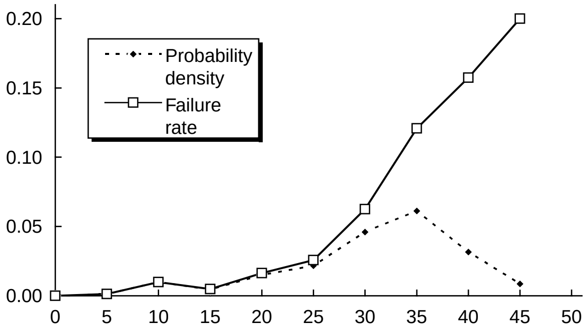

Figure 3 | Failure probability density function and failure rate of DIP (no PS).

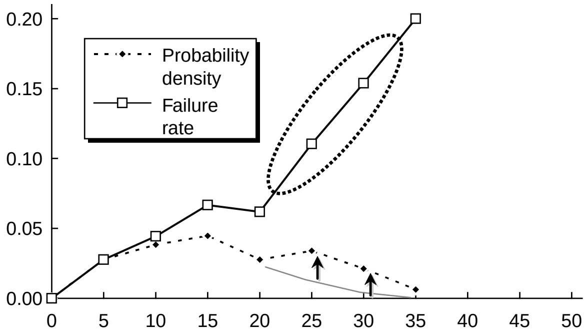

Figure 4 | Failure probability density function and failure rate of DIP (with PS).

Steel pipes (SPs)

Next, the failure rate curve of SP, as shown in Figure 5, shows a rising tendency as the number of years after installation becomes longer. It appears the have two main transitional stages at the middle and end. As pointed out by existing reports, joints of SPs with a nominal diameter under 700 mm are not coated inside during onsite welding, regardless of the specification and year, and can thus lead to internal corrosion. We added the number of 'welded joint' incidents per time interval from data obtained on SP leakage incidents and calculated the percentage. As shown in Table 4, tendencies vary according to the time interval, with '26–30 years' at 58%, '41–45 years' at 72% and '46–50 years' at 90%, clearly indicating the fact that there have been time intervals where many incidents occurred in

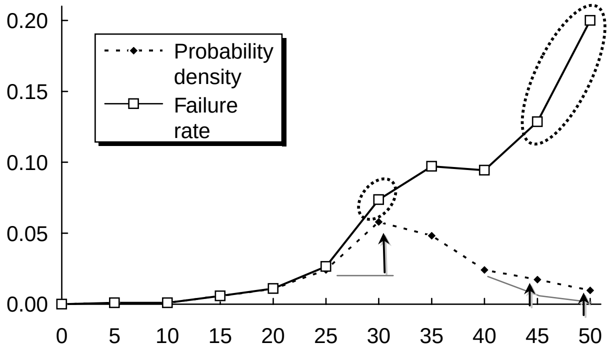

Figure 5 | Failure probability density function and failure rate of SP.

pipelines with ‘welded joints’. From the fact that this time interval corresponds to the period where the probability density curve rises, we can postulate that the pipeline incidents involving ‘welded joints’ may be the cause of the distortion of the curve.

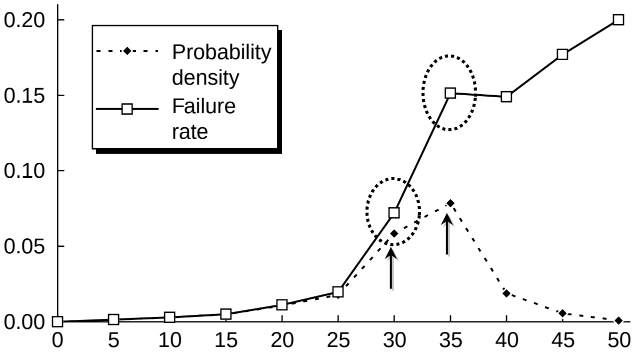

Figure 6 | Failure probability density function and failure rate of VP.

PVC pipes (VPs)

Furthermore, we can confirm that the failure rate curve of VP shown in Figure 6 also demonstrates an increase in line with the passing of years. However, if we compare this with the data for SP, where the final time interval is also ‘46–50 years’, we can see that the changes are different in that a noticeably rapid increase of failure rate exists after the ‘26–30 years’ period. As VP are made from resin materials and despite the fact that they do not corrode due to rust or electrical contact such as in the case of steel pipes, it has been pointed out that they are prone to problems such as the pipes breaking during installation because of boulder stones and other factors, as well as leakage at the joint due to shifting of the pipes caused by external pressure.

With regard to the welding in particular, while there is the ‘TS joint’ (the joint attached with taper sized solvent welding method) as one way of joining pipes, the leakage incidents caused by the lack of strengthening and methodological factors prompted the amendment of the Japanese Industrial Standards (JIS) in 1979. Specifically, for joints with a nominal diameter measuring between 75 and 150 mm that are considered to be faulty, improvements were carried out by either modifying the socket taper or increasing the thickness of the inner part of the socket. To investigate the link between the number of incidents with VPs and TS joints, we added up the number of cases involving TS joints in each time interval and calculated the ratio [%] for each case.

Table 5 shows that, while time intervals of $k = 1–5$ see TS joints occupying 40–50% of incidents, that ratio becomes higher in the time intervals of $k = 6–10$, with over 80% in all cases except for when $k = 10$. Since our survey targets the years 2004 and 2005, data collected from incidents involving pipelines installed prior to 1978 (previous specifications before the amendment of JIS) were those from the time intervals of $k = 6–10$. If we take a closer look at $k = 7$, we can see that incidents caused by TS joints accounted for 302 incidents (95%) out of the 317 total incidents within the pipeline classification in question. It is indisputable that there were great differences in the actual state of incidents involving TS joint pipelines before and after the amendment of JIS. We believe that this may have an effect on the shaping of the failure rate curve.

Table 4 | The rate of welded joint on SP

		Units overall	**Units with welded joint**	**Percentage of welded joint (%)**
1	0–5	1	0	0
2	6–10	1	1	100
3	11–15	6	5	83
4	16–20	11	4	36
5	21–25	25	7	28
6	26–30	60	35	58
7	31–35	50	17	34
8	36–40	25	8	32
9	41–45	18	13	72
10	46–50	10	9	90
		207	**99**	

Table 5 | Rate of TS joint on VP

		Units overall	**Units with TS joint**	**Percentage of TS joint (%)**
1	0–5	6	3	50
2	6–10	12	2	17
3	11–15	20	8	40
4	16–20	43	24	56
5	21–25	72	38	53
6	26–30	236	204	86
7	31–35	317	302	95
8	36–40	76	68	89
9	41–45	23	23	100
10	46–50	3	2	67
		808	**674**	

CONCLUSIONS

The current research has been conducted by analysing pipeline incident data based on reliability engineering and with the aim of proposing useful advice on planning of water pipeline renewal. By examining the shape created from the failure probability density function $f(t)$ and failure rate $\lambda(t)$, we have come to the following notes worthy of attention in regard to DIPs, SPs and VPs.

DIPs

While these are covered with polyethylene sleeves (PS) that promise an anticorrosive effect, attention should be given to pipelines using PS during the early stage of adoption (prior to the amendment of the standards in 1984).

SPs

Apart from the length of years after installation, attention should also be given to the differences in specifications of SPs, particularly when it comes to 'welded joints'. We have reported separately on their link to incidents caused by no internal coating and we believe it is vital that this be reflected in the planning of pipeline renewals.

VPs

Our investigation and analyses in this study have indicated that there are clearly high risks of leakage incident occurrence with VPs with TS joints installed prior to the amendment of JIS (before 1978) compared with pipelines installed after the amendment. For this reason, it is desirable that immediate actions are taken to mend this situation where such pipelines are installed.

Finally, the future issue would be to secure sufficient data in order to conduct analyses with considerations given to different installation environments and other factors. We emphasize the necessity of the continuous investigation of the actual state of pipeline incidents.

ACKNOWLEDGEMENTS

This paper contains research results yielded through the New Epoch Project conducted by Japan Water Research Center. We would also like to thank every waterworks-related business entity for their kind participation in our survey and to everyone involved for their efforts in assisting us with the investigation and data organization.

REFERENCES

Arai, Y., Koizumi, K., Inakazu, T., Watanabe, H., Kunizane, T. & Hayashi, M. 2008 Environmental system research thesis collection: estimation of failure rate of water distribution pipeline based on questionnaire survey. *Environ. Syst. Res. Thesis Collect.* **36**, 125–130.

Fukui, Y. 2006 *Introduction to Reliability Engineering*. Morikita Publishing, Tokyo, pp. 1–14.

Kumamoto, H. 2005 *Modern Reliability Engineering: Numberic Conversion and Conceptualization of Risks*. Corona Publishing, Tokyo, pp. 95–128.

Murotsu, Y., Shao, S. & Yonezawa, M. 1996 *System Reliability Engineering*. Kyoritsu Shuppan, Tokyo, pp. 9–29.

Shimizu, S. 2006 *Introduction to Reliability Designing for Mechanical Purposes*. Suurikogakusha-sha, Tokyo, pp. 1–20.

Shiomi, H. 1982 *Reliability Engineering*. Maruzen, Tokyo, pp. 20–45.

First received 30 September 2009; accepted in revised form 20 January 2010