

Shared failure data for strategic asset management

J. H. G. Vreeburg, I. N. Vloerbergh, P. van Thienen and R. de Bont

ABSTRACT

Failure data are a valuable source of information on the condition of underground assets. Systematic registration of relevant items on cause, nature and circumstances of each occurring failure is, however, complicated in day-to-day practice. Moreover, in a network of limited size it takes a long time to obtain a statistically relevant amount of data. Dutch water companies in collaboration with the KWR Watercycle Research Institute have joined forces and developed a data standard and central database to store and analyse failure data. As of early 2012, 66,000 km of network are monitored, providing around 2,500 records on failure annually. All in all it provides solid information needed for strategic asset management that helps to support well established asset management plans.

Key words | data enrichment, failure data, strategic asset management, web-based database

J. H. G. Vreeburg (corresponding author)

I. N. Vloerbergh

P. van Thienen

KWR Watercycle Research Institute,

PO Box 1072,

3430 BB, Nieuwegein,

The Netherlands

E-mail: jan.vreeburg@kwrwater.nl

J. H. G. Vreeburg

Wageningen University,

PO Box 17, 6700 AA Wageningen,

The Netherlands

R. de Bont

Dunea water company,

PO Box 34, 2270 AA Voorburg,

The Netherlands

INTRODUCTION

Ageing drinking water distribution networks are one of the major threats to the continuous supply of drinking water in cities (Segrave & Pronk *et al.* 2008). The water companies are not the only service providers that face the challenge of dealing with this threat. Modern cities have a variety of underground infrastructures providing services like electricity, sewerage, gas, cable, heating, etc. which inevitably age and need maintenance to sustain the service delivery. Literally on top of this the road surfaces need maintenance to accommodate the increasing traffic loads. These problems are most prominent in centres of cities with an intensive use of all of these infrastructures. Failure of one of them may start a chain reaction with important consequences. The problems of ageing infrastructures are not limited to city centres; they also manifest themselves in the suburban areas with similar technical consequences upon failure. For the customer, the failure frequencies of all the services that are provided add up. The economic consequences of a single failure may not be so dramatic, but the combination of failures is; the threat is in the numbers.

Strategic asset management (SAM) has been adopted by many of the asset owners and asset users to maintain the network and safeguard the service levels. Although not

defined uniformly, the overall goal of SAM is to maintain the assets in such a way that an optimal service can be provided reliably against minimal total costs. Observed a bit more closely, SAM mainly comes down to balancing the concepts of 'optimal service' and 'minimal costs'.

For drinking water supply the definition of 'optimal service' translates easily into 'continuous supply of sufficient quality with sufficient pressure'. The definition of 'minimal costs' is more difficult: repeated repair is in many cases economically more cost effective than pro-active replacement. Even if extra costs of disruption and interrupted supply, including customer compensation, are taken into consideration repeated repair is still cheaper than integral replacement. However, unplanned customer interruption is considered very undesirable by the Dutch water companies, probably even outranking the bare economics of replacement. With this in mind the balance between 'optimal service' and 'minimal costs' translates into 'replace just before failure'. This determines the strategy of maintenance and makes the prediction of increased failure risk of paramount importance.

In this paper the added value of data sharing is demonstrated, following a uniform registration protocol to build up

vital knowledge on the deterioration processes of clusters of pipes.

STRATEGIC ASSET MANAGEMENT: MAINTENANCE STRATEGIES

In general three strategies for asset management or asset maintenance can be distinguished: Failure-Dependent Maintenance (FDM), Time-Dependent Maintenance (TDM) and Condition-Based Maintenance (CBM). Characteristics of these strategies are as follows:

- FDM
 - Minor consequences of failure: it is cheaper to repair than to prevent *or*
 - Costs for condition assessment are larger than prevention (or consequences) of failure *or*
 - Lack of a clear and measurable parameter condition deterioration *or*
 - Failure cause is random.
- TDM
 - A deterioration process that clearly depends on time or usage *and*
 - The condition can be improved through maintenance or replacement.
- CBM
 - A clear deterioration process *and*
 - A measurable parameter determines the condition *and*
 - The representative condition parameter can be measured against economically justifiable costs.

Most water companies in the Netherlands apply FDM as their main practical strategy of the asset management process. For the present situation this is economically a well justifiable option. The average annual failure rate is 0.07 failures/km and the average physical leakage loss is around 3–5%. In practice this means one failure for every 14 km of pipe per year. Costs of repair and actual loss of service are low compared with costs that are associated with replacement of pipes on a large scale.

The FDM strategy is typical for networks that are relatively new and still have a low failure rate. However, from a customer point of view the failure rates of various services (gas, electricity, etc.) add up. If five infrastructures are used,

all with the same failure frequency as the Dutch drinking water, than the resulting failure frequency would be 0.35 failures/km/year, or one every 3 km every year. In time, when the condition of the network deteriorates the criterion ‘minor consequences of failure’ as part of the boundary conditions for FDM will not be valid anymore. The alternative strategies for FDM are TDM and CBM which both require a good insight into the deterioration process.

For appropriate application of TDM the deterioration process should be fairly straightforward and be directly connected to the aspect of age of the pipes. However, it is usually a combination of factors that determines a specific age dependency.

The alternative strategy to TDM is CBM which requires more detailed knowledge of the deterioration process. A specific requirement is that the progress of the deterioration process can be determined by measuring a specific parameter or a set of parameters. The costs of these measurements should also be in balance with the benefits of targeted maintenance. The inhomogeneity of corrosion depths in a cast iron pipe can be mentioned as an example of the difficulties of measurements. All in all the TDM is the preferred asset management strategy.

DETERIORATION PROCESS OF ASSETS

The deterioration process of assets may affect the material integrity but also the functional integrity. The material may lose volume due to corrosion or leaching or may lose strength, for instance in the deterioration of steel in reinforced concrete pipes. Functionality may be lost by displacement of the pipes affecting the joints.

Much effort is put into new and innovative inspection techniques for the actual condition of the underground assets. Dedicated condition assessment techniques are expensive and exclusively targeted at the condition of the material or the joints. The pipe mostly has to be excavated for access; the use of special tools and expertise adds to the costs. Dedicated inspection techniques in a targeted inspection programme are suitable to test specific hypotheses in a scientific way. For instance, the hypothesis that pipes made of a certain material have limited life expectancy in an acid ground can be investigated.

Pipes of various materials are used under different conditions which influence the deterioration process. Local

aggressive conditions affect material and even the diameter of the pipes is a factor in the lifetime expectancy: larger pipes last longer. The combination of factors determines the deterioration curve of materials and constructions. Each combination of factors results in a specific cohort of pipes of which the deterioration process is time dependent.

The network of a typical drinking water company in the Netherlands has several cohorts in which combinations of material, age, soil conditions, etc. are combined. Just observing the failures in various cohorts shows that the number of failures in each water company is relatively low and that it is difficult to analyse trends on that scale (Vloerbergh & Blokker 2009).

Within the joint research programme of the Dutch water companies (BTO), data on these cohorts of pipes are shared, extending the length of the network that can be observed. To be able to share those data, protocols and a good data model had to be designed, which will be described in the following sections.

POTENTIAL DATA SOURCES

In day-to-day practice there are many opportunities for obtaining data on pipes and pipe materials. Prominent are failures with the consequential repairs offering samples of damaged pipes. These samples have in common that they are 'end-of-life' and give information on the end stage of the condition.

However, statistics show that about 50% of failures are due to third party damage. Samples of these incidents are not 'end-of-life' but somewhere in their service life. The material that can be harvested from these incidents represent a host of ages and conditions and contain valuable information.

Although maintenance and failure data are relatively abundantly available, this source of information is under-used. The failure frequency in the Netherlands results annually in over 8,000 failures. Fifty percent of these failures are more or less spontaneous and represent pipes at the end of their lifetime. These are important to determine the 'just-before-end-of-life' moment.

To facilitate data sharing, Dutch water companies, in cooperation with KWR Watercycle Research Institute, took the initiative to develop the USTORE database and the USTOREweb application to record and store data on failures

in a uniform fashion. Uniformity is the key for sharing the data. The USTORE database stores failure data exclusively.

FAILURE DATA: A DIFFICULT SOURCE EMPOWERED BY USTORE

Most water companies keep failure records of some sort. Their most basic use is to describe them in annual reports. Different aspects of failure records are used at different levels within a water company. There is a large variety in type and consistency of data recording because the main driver is not the same for every company or application. Data needed to produce a proper work order are different from data used for the analysis of the cause of failure which is different from information on the actual progress of the repair needed to send a bill. All data are connected to the one incident and generated at different levels within the organisation.

The quantity, quality and content of the data, however, determine to what extent they can be used to provide insight into the (remaining) lifetime of pipe cohorts. In 2007 the registered failure data of a number of Dutch water companies were analysed, showing that despite the incomplete registration and varying data quality, some trends could already be made visible (Vloerbergh & Blokker 2007). Based on the outcomes of this study, a design was made for a uniform failure registration system to enable exchange of failure data (Vloerbergh & Blokker 2010).

Figure 1 shows an example of data and the representation of it. It also shows that in 2 years in a row the number of failures in cast iron pipes increases in the winter months, which is in line with practical experience.

HOW MANY DATA ARE NEEDED?

The target 'replace just before failure' can be translated into 'replace when the risk of failure exceeds a critical level'. This means that the exact time of failure cannot be predicted, but that the risk of failure can be estimated following the observed failures within a certain cohort.

The procedure for determining if a cohort of pipes nears the critical failure risk is demonstrated with an example. Assume a certain cohort of pipes that shows a time

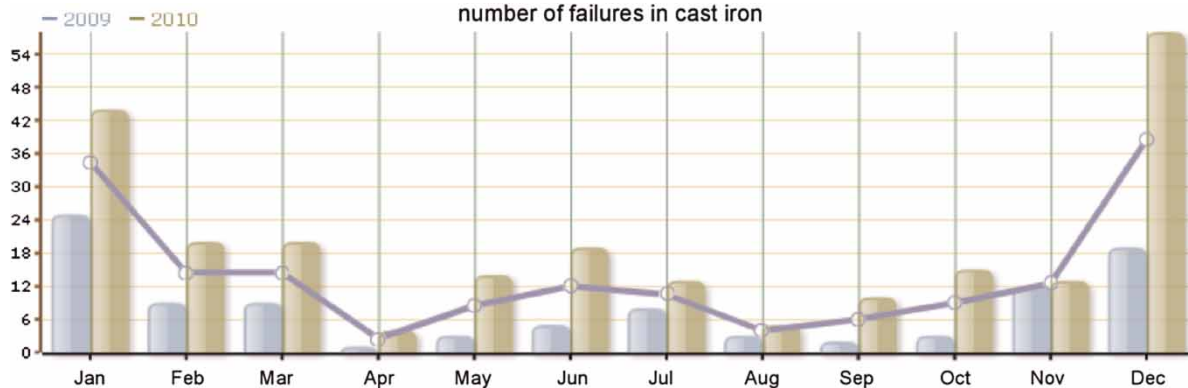


Figure 1 | Two years of registered failures in cast iron depicted per month. An increase in the number of failures in the winter months (December until March) suggests a relation between ambient temperature and failure frequency.

dependent (increasing) failure frequency. This pipe cohort is divided into bins of ages sufficiently narrow to be considered uniform: the failure frequency is constant within the age bin. Under these conditions a Poisson distribution can be assumed for the actually occurring failures. The question now is to what extent the observed number of failures is representative of the mean failure rate in this age bin.

Table 1 shows the number of observations that should be made to obtain a value for the failure frequency that is within 10% accuracy within a 95, 90 and 80% reliability threshold. In other words: we know for 95% (90, 80%) sure that the observed number of failures deviates less than 10% from the actual number of failures. The figures in the table are based on the standard reliability interval calculations for the Poisson distribution. It says for instance that 280 failures should have occurred within this cohort to be 90% certain that the calculated failure frequency within this cohort is within plus or minus 10% of this calculated value. Note that the accuracy of the number of failures

Table 1 | Relation between the accuracy and reliability and the minimal number of observations based on the standard reliability interval calculations for the Poisson distribution

Accuracy [%]	Reliability [%]	Minimal number of observations
+/- 10	95	400
+/- 10	90	280
+/- 10	80	175
+/- 20	95	101
+/- 20	90	73
+/- 20	80	46

is not dependent on the total length of the observed cohort of the network, because only the number of occurrences is relevant in a Poisson process. The calculated failure frequency is of course dependent on the length and time observed.

For the application of SAM the critical failure risk is translated in a critical failure frequency that complies with predetermined reliability and accuracy thresholds. These thresholds determine the number of failures needed and that determines the extent of the network to be monitored. This is demonstrated in the next paragraph with an example.

The presumed deterioration process is exponential in time, but constant within time bins of 10 years. The critical failure frequency is set at 0.25 failures/km/year. This means annually one spontaneous failure every 4 km of pipes (six to eight times higher than the present Dutch failure rate). The alerting level is set at 0.2 failures/km/year. The accuracy of the alerting level should be at least 90% within an accuracy range of 10%. That means that at least 280 observations of spontaneous failures should be observed within the age bin of 10 years, resulting in a minimal length of pipelines of 1,400 km at 0.2 failures/km/year. If there are three to four age bins at least 4,200–5,600 km of this particular cohort should be observed with regularly distributed ages. Note that these numbers of failures do not have to be observed in 1 year to get a failure frequency that complies with the set reliability and accuracy thresholds. When the critical or alerting level of failure frequency is reached, they will occur in 1 year.

If fewer observations are done within the various age bins, the accuracy and reliability of the calculated failure frequency decreases, but also the actual failure frequency is less

than the critical values. If for instance 46 failures occur in the age bin of 1,400 km during 1 year, the calculated failure frequency is 0.04, with 80% reliability within 0.048 and 0.032. Observing the failures for a longer time (assuming that they keep occurring at the rate of 40–50 per year) it will take proximately 5 years to get a reliable and accurate enough figure. Another possibility is to observe a five times longer network, which is the goal of participating in the USTORE database.

JOINING FORCES TO ACCELERATE DATA ACQUISITION

In the Dutch situation failure data come with an average of one incident per 14.3 km of total network length per year. Up until now 20 cohorts of pipes have been defined (Vloerbergh & Blokker 2009). If the figures of the aforementioned example are used, resulting in a minimal length of 1,400 km of the oldest age bin per cohort this makes the total length needed to be observed at least 28,000 km. If more age bins should be observed within the accuracy and reliability thresholds and there are four age bins per cohort, than the total length of network should be at least 112,000 km. In reality the total length would be much more, because the smallest cohort determines the total length of the network to observe, and age, material and diameter distributions of the pipes are not uniform within the network.

The overall failure frequency within the Dutch water utilities shows that there are probably not many cohorts that approach a critical failure frequency. It will take time before statistically reliable outcomes can be generated by a single company on the Dutch scale (10 water companies with a total of 117,000 km of pipes).

As said, to this end USTORE and USTOREweb were developed to provide a uniform failure registration system with as much relevant information as possible. Uniformity is necessary to make the data interchangeable. A prerequisite is the similarity of cohorts within the various networks. The purpose of USTORE is to combine data on failing assets irrespective of the cause of failure and gain knowledge about the behaviour and lifetime of pipe cohorts and factors influencing the occurrence of failures.

Since 2009 five water companies have been registering their failure data according to USTORE agreements.

During 2012, three more water companies will have joined the USTORE system leading to a network of approximately 66,000 km. With the participation of eight companies, the information multiplication factor is considerable. Not all cohorts are relevant for all participants and not all companies have the same size, making the ‘knowledge-acceleration-factor’ not uniform for each participant. Given the minimal lengths of cohorts and the number of possible cohorts, an increase in the number of participating companies is still wanted and needed.

USTORE IN PRACTICE

The starting point of USTORE is the data form that was agreed upon with the original users of USTORE. An obvious but difficult requirement is that field workers are well trained *and* have time reserved in their daily routines to register the important data at the source: on the side of the pit! In the basic USTORE registration process, six steps can be distinguished:

1. Gathering data: Field workers register characteristics of the pipe and surroundings in USTORE format (digitally).
2. Recording data: Data are stored in an off-line company database.
3. Exchanging data: Data are uploaded to the central system.
4. Validating data: Within USTOREweb consistency is checked and incorrect or incomplete data are filtered out.
5. Analysing data: KWR analyses the data.
6. Reporting data/use in AM tools.

Steps 1 and 2 are organised within the participating company. They form the basic process for the data acquisition. It requires an attitude and conviction within the company that storing information on failures is at least as important as actually repairing the failure. In fact this is the core of the concept: information on failures is a substantial part of the SAM policy.

Steps 3, 4 and 5 are facilitated by the web-based application USTOREweb. In step 5 KWR makes general, anonymous analyses on cohorts and reports to participating companies. Each company is able to access their own data in the database and make tailored analyses. The rest of the data are anonymous, but may be used in general terms

(e.g. performing company independent analyses or comparing company statistics to statistics for the complete database to put the former in perspective). Step 6 is a flexible step resulting in general reports and dedicated use of the knowledge into asset management tools and investment plans.

Presently, KWR and the Dutch water companies are exploring the possibility of extending the database into a European or even global network of data. This will increase the value of analysis and enable the comparison of typical features of national networks with each other.

EXAMPLE OF KNOWLEDGE BASED SAM STRATEGY

In November 2011, the USTORE database contained 2,386 asbestos-cement (AC) failures. From these failures 1,415 were considered spontaneous. These were sorted into 10 year age bins. Most of the failures were gathered within a 2 year period (2009–2010). The results are plotted in Figure 2. The calculated failure frequencies are presented within the 95% reliability range showing for the age bin 1950–1959 reasonable reliability levels.

The highest reliable failure frequency is 0.07 (1950–1959) and that is considered to be at neither the critical or

alerting level. In the older size bins the number of failures is limited but, given the short length of the observed pipes in these age bins, the failure frequency is higher than the failure frequency in the ‘younger’ age bin. In principle there is no ground to extrapolate the failure frequency over the age bins with reliable failure frequencies to older age bins. There is as much reason to assume a stable as an exponential growing failure frequency. Over time the pipes will shift in age bins, but their failures stay in the original age bin. In due time the length of pipes in the older age bins will grow, resulting in more failures and more accurate failure frequencies. Only then a reliable development of the failure frequency can be determined.

Caution should be exercised when interpreting the data. In the example the cohort division was only based on age and material. Targeted analysis of the failure mechanism shows that AC pipes in acid ground are more prone to leaching than those in sandy soils. Three hundred and eighty three of the 1,415 failures occurred in acid (peaty, clayish) soils, 617 in sandy soils. Failure frequencies cannot be calculated because the total length distribution into soil types is not known at this stage. This bias demonstrates that figures should be used with care as long as not all relevant information is known. It also shows the

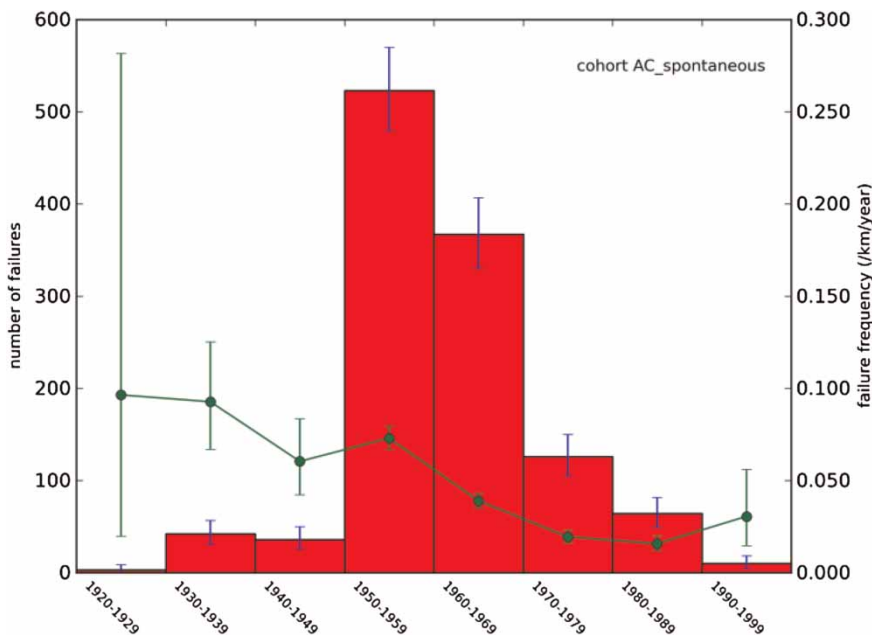


Figure 2 | Observed failures in different age bins for spontaneous failures in AC pipes. Failure frequencies (right axis) are calculated and the 95% reliability range is indicated. Especially in the older age bins the uncertainty increases.

importance of registration of soil information in pipe information systems.

The SAM strategy could now be to concentrate on improving the failure data registration and completing all soil data to investigate the influence of acid soils as targeted research. Detailed analysis of failures in the older parts of the network will give more information on the failure mechanism and shed light on the necessity of further subdivision of the AC-age cohorts.

DISCUSSION

Individual failures of pipes are impossible to predict. However, this is not really necessary for SAM. Long-term development of failure risk within certain boundaries of accuracy and reliability is of much more importance. Reliable early detection of trends requires a large amount of data. As is shown some 280–400 failures are necessary to calculate a reliable and accurate failure frequency in one cohort. The SAM goal is to reduce risk of failure by replacing pipes just before they reach a critical risk level (failure frequency). Given the long planning periods to replace cohorts of pipes the development towards a critical level should at least be predicted on a level of decades. Age bins are now practically set on decades; having smaller age bins will give more detailed knowledge on the progression of the failure risk, but will also limit the number of failures in an age bin. In particular, the oldest age bins are the most interesting, but also the smallest. On the other hand, they will also have the highest failure frequencies.

Compared with targeted research through dedicated inspection of pipes, recording and sharing failure data is relatively cheap, but knowledge development takes time. The uncertainty that should be explored is that development of failure frequency could be exponential, resulting in a very rapid development from alerting level to critical level. Sharing data in order to have more failures in potentially critical age bins increases the knowledge development more timely and accurately. Data should be precise and complete.

The example showed illustrates the importance of proper cohort definition. In this case the potentially deciding factor

of acid soils in combination with AC pipes results in an increasing risk level that could develop exponentially. This does not necessarily apply to the same AC pipes in stable sandy soils. Making this distinction in cohorts is of paramount importance in long-term planning for SAM, because if not, the failure frequency in acid soils would potentially be underestimated and that in sandy soils overestimated.

However, even with the presently observed 66,000 km, the monitored number of failures is not adequate to have accurate estimations of the failure frequency development for many cohorts. Extension of the number of participating companies, even outside of the national borders, is considered to expand on the network length and increase the accuracy and reliability of failure frequencies especially in the older age bins.

CONCLUSION

Valuable data become available when pipes fail. Analysis of systematically and uniformly stored data gives information for SAM. It reveals relations between pipe material/place-ment conditions and failures that enable prediction of residual lifetimes of pipes in similar circumstances, so-called cohorts. Combining data from different companies accelerates this process considerably, leading to accurate and reliable early detection of realistic failure risks.

REFERENCES

- Segrave, A., Pronk, W., Ramaker, T. & Zuleeg, S. 2008 Global trends affecting the water cycle. *Techneau*. <http://www.techneau.org/fileadmin/files/Publications/Publications/Deliverables/D1.1.7.pdf> (accessed February 2013).
- Vloerbergh, I. N. & Blokker, E. J. M. 2007 Failure data analysis – a Dutch case study. *LESAM 2007-2nd Leading Edge Conference on Strategic Asset Management*, Lisbon, Portugal.
- Vloerbergh, I. N. & Blokker, E. J. M. 2009 Sharing failure data to gain insight in water network deterioration. *LESAM 2009*. Miami, USA.
- Vloerbergh, I. & Blokker, M. 2010 Sharing failure data to gain insight into network deterioration. *Water Asset Management International* **6** (2), 9–14.

First received 10 November 2012; accepted in revised form 8 February 2013

Reproduced with permission of copyright owner.
Further reproduction prohibited without permission.