REVIEW ON THE DEVELOPMENT OF UNIFORM FAILURE REGISTRATION (USTORE) IN THE NETHERLANDS

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Abstract

Deciding which pipeline to replace when is one of the main issues for asset management of the drinking water distribution network. Drinking water companies use decision support software tools (DSS) in their planning for pipe replacement. This DSS requires information about the risk of failure, i.e. the probability of pipe failure and the effect or impact of pipe failure. In 2008 the Dutch drinking water companies together with KWR launched the initiative USTORE for acquisition of uniform and consistent data about pipe deterioration. In USTORE data of pipes and pipe failures are uniformly registered. USTORE data is used in data analyses to gain knowledge about deterioration of pipe cohorts and to increase understanding of external effects which may cause pipe failure. Currently the USTORE database contains data of around 20.000 failures and 60.000 km of pipes. This paper evaluates the development of USTORE registration and reviews data analysis results, data quality issues and applications of USTORE failure data.

Keywords: failure registration, drinking water distribution system, pipe failure, failure database, pipe deterioration

1 USTORE: Development of a national pipe failure database

The Dutch water companies replace 0.5 – 1.5% of their drinking water distribution networks (DWDN) each year which requires a total investment of 200 – 300 M€/year. Failure registration and analysis creates the essential basis for a rational main replacement policy (Vreeburg *et al.*, 2013). During the first decade of the 21th century the need for asset management and the awareness of the lack of suitable pipe failure data led to the set-up of a uniform failure database in the Dutch drinking water sector (Vloerbergh *et al.*, 2012). In 2009 seven Dutch drinking water companies started to share failure data in USTORE. Uniform failure registration and data sharing creates several benefits:

- Sharing data increases the data quantity per pipe cohort, which decreases the statistical uncertainty of the analyses.
- Collaborating companies can use shared data to benchmark their own failure data.
- Sharing knowledge about failure registration in a community of practice creates the opportunity to learn from each other.

The collaborating water companies share their data using USTOREweb, which is the web-application for USTORE. Two types of datasets are shared in USTORE:

- Pipe failure data (failure date, location, failure type, cause and environmental circumstances) 1-4 times a year, depending on the work processes of the individual companies;
- Data of pipe cohorts (total length for each cohort, cohorts are differentiated to material, diameter and building year) once a year. Sharing pipe cohort data regularly is necessary because the drinking water network composition and size does change over time due to pipe replacement and network extension.

Figure 1 shows a timeline of the development of uniform failure registration in USTORE.

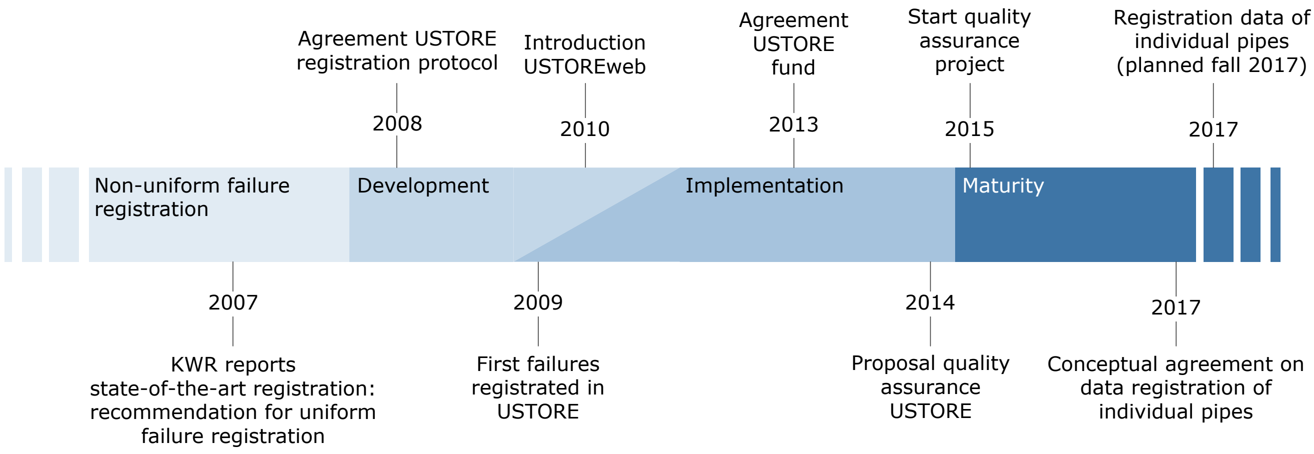

Figure 1. Development of USTORE during the past 9 years.

2 Data analysis results

2.1 Failure frequency analysis

Data in USTORE is most commonly used to calculate failure frequencies of pipe cohorts. The collaborating drinking water companies use these information for benchmarking their own failure frequencies . The increase of the available number of failures per cohort in USTORE with time creates the opportunity to perform better statistical analyses in two possible ways (Kleiner and Rajani, 1999):

- Decrease of the statistical uncertainty by maintaining the current cohort definitions;
- Definition of more specific pipe cohorts, while maintaining an acceptable level of statistical uncertainty.

Failure frequency analysis was used in 2012 to determine the pipe cohorts which have the highest number of failures relative to their cohort length (Figure 2). A straight line would represent an equal contribution of all cohorts to the number of failures per year. The curved line shows that some pipe cohorts (left in Figure 2) contribute more to the number of failures than others (right in Figure 2), which is an input for DSS tools and created the possibility to replace the pipe cohorts which contribute most to the total number of failures per year (relative to cohort length).

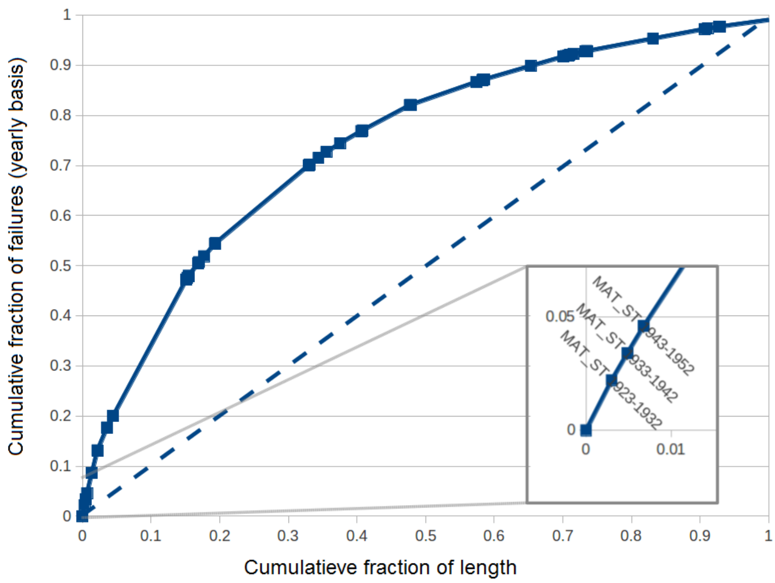

Figure 2. Contribution of pipe cohorts to total number of failures/year (relative to cohort length). The detailed view shows the worst cohorts in terms of failure frequency (early 20th century steel pipes).

The current USTORE data format does not contain spatial pipe data on single pipe level. Without additional data, the current USTORE database can therefore not be used to find relations between failure frequency and external explanatory factors for pipe failure. This will possibly change in 2017 as is described below in this paper. In order to enable research on the correlation between the pipe failure frequency and environmental parameters (such as soil and climate) spatial data of individual drinking water pipes was shared by the drinking water companies on ad-hoc basis. The following sub-paragraphs give a brief introduction on these studies.

2.2 Effect of weather parameters and impact of climate scenarios

The effect of weather parameters on pipe failure frequencies was studied over the past 5 years. The purposes of these studies were:

- Improvement of the understanding of the relation between pipe failure and weather parameters and testing of hypotheses based on physical models (Wols and Van Thienen, 2014; Wols et al., 2016);
- Prediction of the number of failures based on (1) ageing of pipes, (2) change of failure frequency due to ageing and (3) change in material composition of the DWDN and (4) the impact of climate scenario's on this number (Wols and Van Thienen, 2016).

Primarily these studies are an example of the opportunity for analyses which would possibly give no meaningful output if they were performed on datasets of single companies. This is shown by the following example: in 2012 no significant correlation was found between the failure frequency of asbestos-cement (AC) pipes and the mean daily temperature (TG). Two years later the same study showed a significant relation between both parameters (Wols and Van Thienen, 2014). Results of more recent work on this topic are shown in Figure 3 (Wols *et al.*, 2016). This LESAM paper gives a summary of this work.

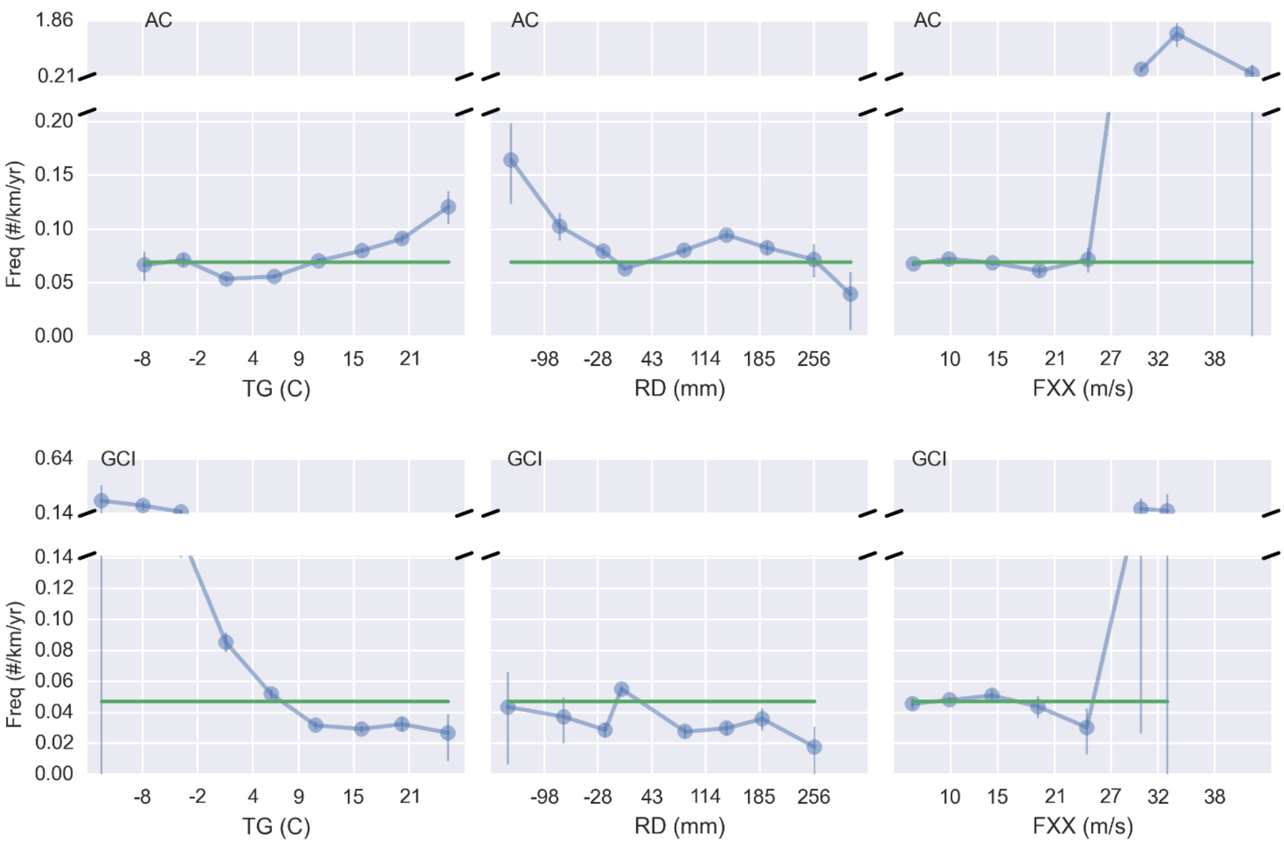

Figure 3. Relation between weather parameters and failure frequency for asbestos-cement (upper) and cast iron (lower) pipes. The error bars show the 80% confidence interval (Wols et al., 2016). In this research the same relations are studied for pipes of PVC, PE and ductile iron.

The result of the research on the effect of weather parameters also showed a significant relation between the failure frequency and the weather parameters rain deficit (RD) and maximum daily windspeed (FXX). The conclusions below follow from this research:

- Main daily temperature (TG): The relation between temperature and failure frequency strongly depends on material. Failure of PVC and PE pipes does not significantly depend on the temperature. For AC pipes the failure frequency positively correlates with temperature. For ductile and cast iron pipes the opposite effect was found. For both AC and PVC pipes the pipe building year had no influence on the relation between failure frequency and temperature. For larger diameters the effect of temperature is less for AC pipes.
- Rain deficit (RD): the extent to which drought contributes to pipe failure depends on the pipe material and the soil properties. Rain deficit dependencies were found for some combinations of pipe material and soil parameters. Positive correlations were found for AC and PVC pipes in clay/peat soils. The positive correlation between failure frequency and drought could be physically explained by uneven soil settling (which causes pipe stress) due to rain deficit.
- Maximum daily wind speed (FXX): The effect of wind is evident for all pipe materials. This was first observed in the most recent study on the effect of weather parameters (Wols *et al.*, 2016). It was shown that uprooting of trees forms an important cause of failure during severe storms (Figure 4). Massive uprooting of trees is more likely to occur early in the autumn season, as more leaves are present at the trees. This example also shows that understanding outcomes of statistical analyses requires knowledge of physical processes.

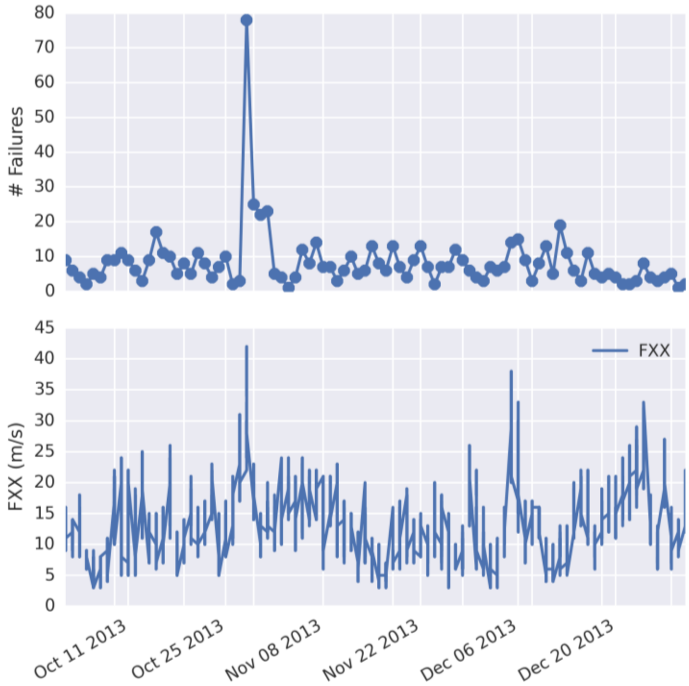

Figure 4. Relation between weather parameters and failure frequency for AC (upper) and CI (lower) pipes. The error bars show the 80% confidence interval (Wols et al., 2016).

Physical explanations of positive correlation between weather parameters and pipe failure are further elaborated in Wols and Van Thienen (2014).

Research on the relation between weather parameters and pipe failure was used to develop a methodology which can be used to predict the number of failures for future climate scenario's developed by the Royal Netherlands Meteorological Institute (Wols and Van Thienen, 2016). This study showed that the effect of climate change on the DWDN in the Netherlands is small compared to the expected changes in the DWDN due to ageing of pipes and pipe replacement.

2.3 Effect of traffic loads

When drinking water pipes are exposed to external loads, the internal strain will be higher compared to a case without external loads, which may accelerate the process of pipe deterioration. The possible contribution of traffic loads to pipe failure was studied (Moerman *et al.*, 2016). Spatial data of roads was used as a surrogate for traffic load. A two way approach was used:

- Comparison of failure frequencies at locations with potential for peak traffic loads (such as road crossings and speed bumps).
- Multiple Regression Analysis on multiple factors which can explain pipe failure, including the presence of roads.

The outcomes are twofold: on average, no significant contribution of road presence to pipe failure was found. However, significant higher failure frequencies were found for pipes near to road crossings. Expert judgement of this effect lead to two hypotheses for this effect:

- Higher failure frequencies at crossings are caused by higher vertical dynamic loadings at the road surface induced by accelerating traffic.
- At road crossings often multiple (perpendicular) crossings of the pipe network and roads are found Higher failure frequencies at road crossings are caused by point loadings which occur due to stiffness differences of road construction and the surrounding soil.

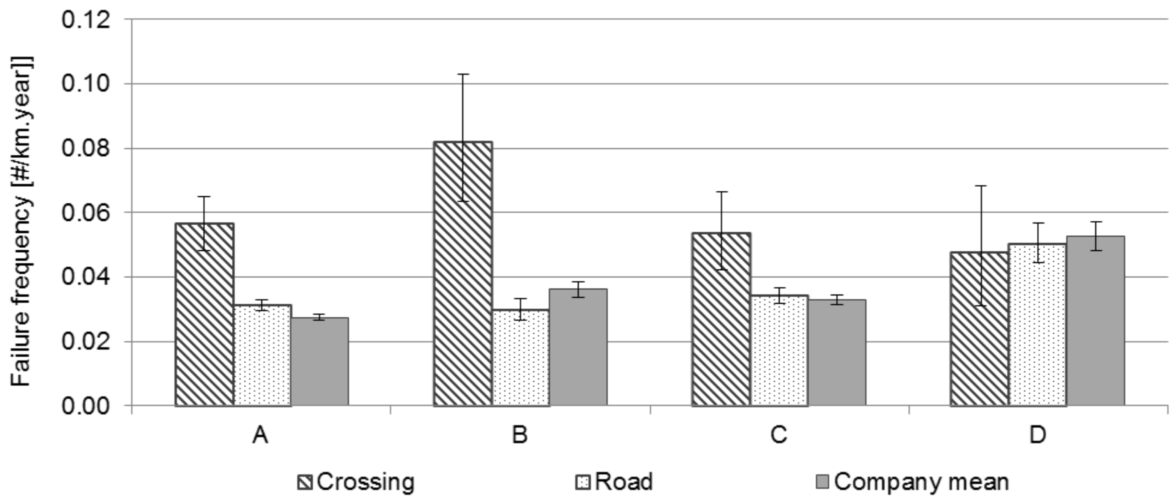

Figure 5. Comparison of failure frequencies at crossings, roads and average frequencies. Failures due to digging activities of third parties are removed from the results. The bands show the 95% confidence interval based on a Poisson distributed failure behaviour (Moerman et al., 2016).

Based on this research the conclusion can be drawn that the presence of roads itself does not contribute to pipe failure. This outcome was (i.a.) used as input for the design of a new registration protocol wherein fitters are no longer asked to register the eventual presence of roads close to the pipe failure location.

2.4 Effect of pressure

The effect of the hydraulic pressure on pipe failure was topic of research in a large data-mining study in 2015 (Vries *et al.*, 2016). Former work showed a positive correlation between water demand and temperature (Wols and Van Thienen, 2014). As a result, larger differences in internal pressure over time may occur. Therefore failure frequencies were calculated for pipe cohorts with a different pressure regime (based on outcomes of hydraulic calculation software). The results for AC, DI, GCI and PVC pipes are shown in Figure 5. Both the maximum pressure and maximum pressure difference were calculated assuming an average day demand. Figure 6 shows an increase in failure frequency for a higher pressure difference. A direct relation between failure, pressure and temperature could not be obtained as the combination of pressure data and temperature data for a certain location and time is not available.

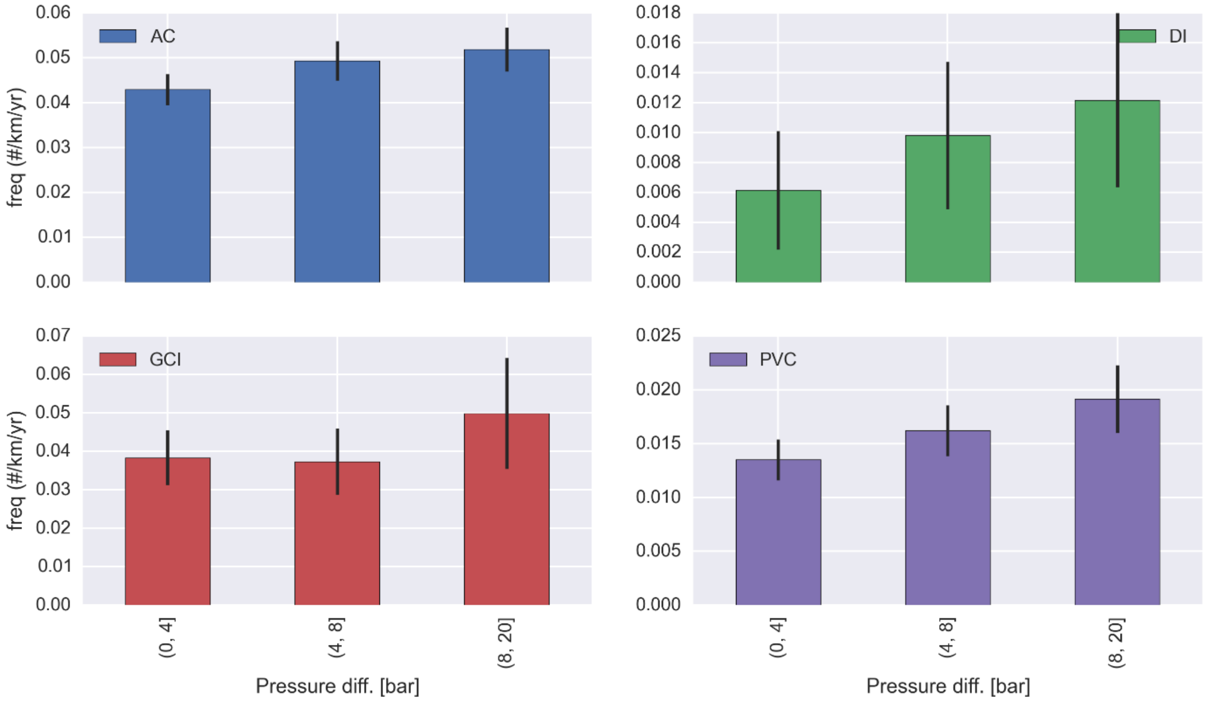

Figure 6. Effect of maximum pressure difference at an average day demand on pipe failure frequency for different pipe materials. Three cohorts of hydraulic pressure were defined: (0, 4]; (4, 8] and (8, 20] (Wols et al., 2016). Pressure differences are in meters water column or kPa · 10^{-1}.

2.5 Application of failure data in other studies

The first an main goal of uniform registration of pipe failure is the creation of a rational basis for pipe replacement for now and in the future. However, also for research purposes failure data in USTORE appeared to be very useful. As an example USTORE data was used during the development of an quantitative microbial risk assessment methodology (QMRA) for the DWDN. The QMRA consists of multiple steps which can lead to infection of customers. This chain starts with infection of the drinking water in the DWDN which typically may occur through pipe failure (which means an open connection between the soil and the drinking water).

Failure data from USTORE was also used to map the potential for certain pipe cracking and pipe inspection techniques.

3 Data quality improvement

Since a couple of years the USTORE project contains an extra focus: data quality. Initially the quality system contained a set of agreements, that were not uniformly implemented. From inquiries and data quality analyses the following issues appeared:

- Data quality is different for different water companies.
- Water companies use different interpretations for failure definition and use different system boundaries.
- Impossible combinations of registered parameters occur (e.g. a welded connection for PVC pipes).
- Environmental parameters a quite often registered as ‘unknown’.

To come to a mature registration system a further improvement was necessary of procedures on registration and data-handling. To improve data quality in USTORE in a durable way a quality assurance project was started. The goal of this project is to reach agreement on measures for data quality improvement which are described in a ‘practice code for uniform failure registration’. There are three types of measures which are implemented to increase data quality: (1) uniform agreements on definitions, (2) improved parameter description and data source choice, (3) improvement of working procedures through e.g. better communication. The following measures were or will be taken to further improve data quality in USTORE:

- Agreement on uniform definition of:
    - Pipe failure;
    - System boundary: pipes and failures of transport mains, distribution mains and raw water mains are registered only. Failures are registered for a selection of appurtenances.
    - Key activities in the process of failure data acquisition, enrichment and analysis.
- Agreement on data quality checks in every collaboration company. With respect to differences in work processes these checks are described in outlines.
- Better description of registered parameters; only questions are asked which can be objectively answered (to a reasonable extent) by pipe fitters. In practice this condition lead to a simplification in the registration of the failure cause.
- The registration protocol consists of parameters which can only be obtained on-site (e.g. failure cause, failure type, exact location of failure) and parameters which could be obtained from certain data sources. The fitters workflow should only consists of parameters for which the fitters view is necessary. Data which can (also) be obtained from other data sources (e.g. pipe data from the pipe database, soil data from soil charts, etc.) should be obtained from these sources. This decreases the workload for pipe fitters and increases the data consistency (reproducibility, repeatability).
- Water companies are encouraged to improve the communication between pipe fitters (practice) and asset managers (analysts/theory). Communication between these groups can be improved by feedback sessions in which the asset managers show the benefits of the fitters' work for asset management.
- Parameter description in pipe fitters works flows should match with practical situations. Communication between pipe fitters and asset managers is necessary to obtain this. This is part of the implementation at the level of individual drinking water companies.
- To improve and/or maintain the knowledge level of pipe fitters, e-learning sessions can be used to train fitters which registration parameters fit best on examples of pipe failure. This approach also improves the aspect of reproducibility; the extent to which different pipe fitters choose the same registration parameters in a certain situation.
- To enhance the possibility of data quality benchmarking datasets which are uploaded to USTOREweb will be provided with a data quality label which is determined by the presence of working procedures for data quality and quantity checks and the extent to which the database consists of impossible parameter combinations.
- In the future water companies will receive automatically a feedback on the quality of their uploaded data. This feedback will be based on knowledge rules (e.g.: it is unlikely that Dutch ductile iron pipes have an installation year before 1970).

5 Future work

USTORE is an on-going project of data collection and quality improvement. Future work will be on collection of individual pipe data. The USTOREweb application is recently further developed to deal with large amounts of GIS data of all individual. This creates opportunities to combine pipe data with other data sources (e.g. data of soil movement and composition, road data, tree databases, etc.) which is input for further multiple regression analyses which enables a better understanding of pipe failures. The combination of pipe and failure data on single pipe level also creates the possibility to apply single pipe failure prediction models in the future.

Within the context of UKNOW a new project was started wherein statistical models (using USTORE data) are combined with a physical model to improve the understanding of pipe failure and to predict the failure frequency of pipe cohorts. This physical model was originally developed to calculated pipe stresses caused by soil settling (Wols and Van Thienen, 2013). This mechanical model, called Comsima®, was developed in Python to calculate pipe stresses for large amounts of pipes in a GIS database, based on pipe specifications (material, diameter, wall thickness) and internal and external loads as hydraulic pressure, soil settling, traffic loads and soil load. To correct for data uncertainty all parameters are modelled as probability density functions which are input for a Monte Carlo analysis. Recently the model was further developed to account also for pipe degradation.

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