Maintenance strategy for water networks: development and implementation of a high resolution risk based approach

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Abstract
The development of maintenance strategies for drinking water supply systems is usually based on the assessment of the condition of the pipes with regard to the remaining lifetime and the actual and desired failure rates. For this assessment, experiences with failures are needed which allow to determine a trend in failure rates. These experiences may arise from already occurred damages of the pipe system or from general relations between e.g. pipe material, age, corrosive properties of the water or the soil and the lifetime. These methods have the big disadvantage that damages must have been already occurred which is generally undesired.

Being prospective in the lifetime assessment without accepting a failure of the pipe, non-destructive pipeline inspection methods should be applied (e.g. smart pigs). Nevertheless, they are often not usable due to the fact of missing pipeline pig traps or too many hampering fittings in the distribution system (e.g. butterfly valves).

In the development of maintenance strategies usually only the occurrence of failures would be considered. To develop a risk based strategy the risk of failure needs to be assessed. The risk is being assessed by considering the probability or frequency of a failure and the resulting consequences. With regard to this approach an innovative high resolution risk assessment method for water nets which includes operational parameters, environmental conditions and their impact on the risk of failure was developed.

Due to the complex nature of this risk assessment which includes a number of assessed parameters, the utilisation of a GIS-software has been introduced. By doing so it was feasible to undertake a high resolution risk assessment considering more than 15,000 individual sections of the trunk main network. This resolution allowed the easy identification of high risk areas, so-called “hot spots”.

By defining plausible future scenarios, this concept is able to demonstrate the effect of insufficient maintenance in the next 10 to 30 or more years to the water supplier, which involve asset overaging, increasing failures and long time interruption of water supply. Based on the result of the risk assessment the required maintenance items (what and where) and a catalogue of maintenance actions (how and when) has been developed with regard to type and costs of maintenance. The application of the high resolution risk assessment strategy in combination with a GIS enables the user to visualise the outcome of the maintenance strategy and enhances the understanding of the results. The flexibility of this approach also represents a future value as the user can easily

integrate this method in an existing GIS system or even use it as the basis for a new one.

By means of the results of this strategy, the available annual maintenance budget of the asset owner could be utilised to implement an efficient risk reduction. It is also anticipated that the required funds will decrease below the current costs over the next years.

Introduction

Trunk mains are the ‘aorta’ of long distance water supply systems and have therefore a very significant importance for water supply engineering. Apart from reliably operating such systems, there exist high maintenance requirements to comply the required water quality and especially the security of water supply. Essential parts of maintenance involve inspection, service and rehabilitation of related pipes and their components.

Like any other technical systems, trunk mains are subject to degradation processes (e.g. caused by corrosion, embrittling, deterioration), which can have detrimental effects on the security of supply (e.g. pipe failure, turbidity, loss of water supply). Maintenance measures like technical service, repair and/or rehabilitation usually have a delaying effect on the deterioration process. As the process of degradation could not completely be stopped, parts of trunk main systems need to be replaced in some point of time.

Compiling a maintenance strategy for urban water supply systems most commonly failures rates respectively leakage rates are used as the characteristic parameter to determine the condition of the pipe network (DVGW 2010a). Referring to trunk main systems it is necessary to include additional parameters especially like information to the failure risk due to the effect that the extent of required maintenance cannot solely be based on failure rates consider the security of supply and economics.

Due to their high transport capacity and their commonly low redundancy trunk main systems have a significant importance for the water supply engineering (DVGW 2011a). From this, additional requirements are necessary to use the condition assessment of water pipes as basis of a reliable and sustainable maintenance strategy. To detect the amount, cycle and location of a qualified maintance strategy (herein: sanitation or rehabilitation) for trunk mains a new concept of risk assessment was developed. The target of the innovative concept is the plausible combination of deterministic and probabilistic assessment methods like service life prediction, static calculations, condition assessment, geo-referencing analysis and detailed monetary assessment.

This conception permits a very detailed risk assessment of any pipe sections. Based on this it is possible to identify the required maintenance measures (what and where) and combined with related costs the results will be compiled to a catalogue of measures (how and when).

Risk assessment of trunk main systems

Risk can be described as the product of likelihood and consequences (Haskins 2007). In regard to trunk mains, risk can be calculated for any pipe sections using the factors showing in Figure 1.

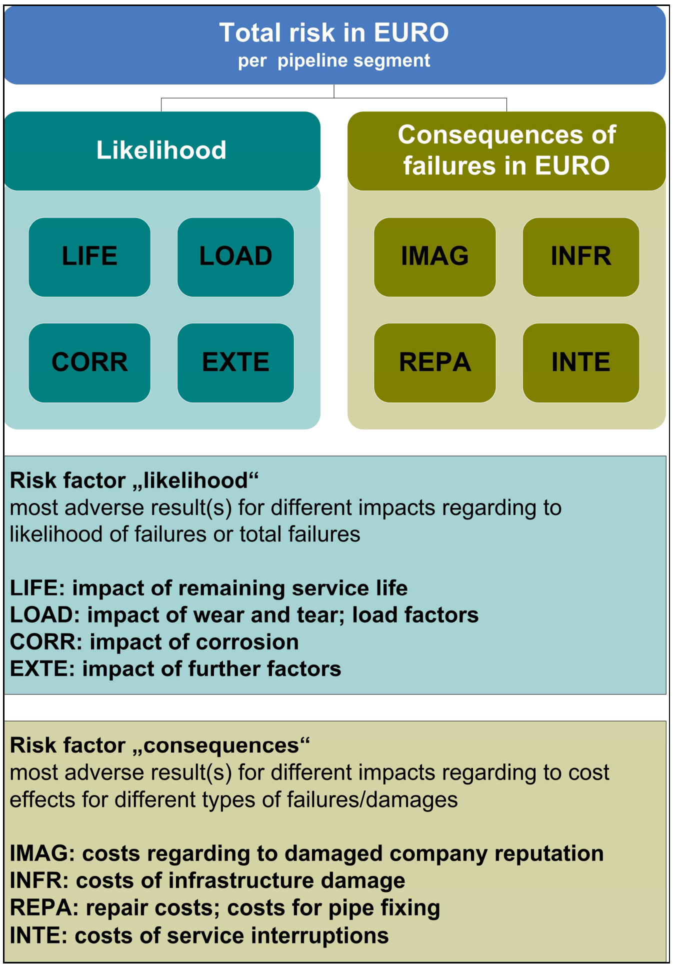


Figure 1: Main factors for calculating the total risk due to pipe segments

In comparison to other technical systems of similar relevance, relevant data and information needed for a detailed risk assessment of trunk mains are often not yet part of a central data system like network information system (NIS) or geographic information system (GIS). Valuable additional information, e.g. detailed installation depth, are not recorded by digitalizing the maps or can be only found in the scanned plans. But without an adequate data basis, performing a risk assessment is very difficult and has many limitations (Sorge et al 2013). Due to the fact that data and information may be available in different formats the risk assessment must incorporate quantitatively and qualitatively characteristics. Non-numerical information must be subjected to suitable mathematical treatment.

The objective of the presented method is the utilisation of all available data and its optimal analysis and interpretation by applying a semi-quantitative approach. The semi-quantitative approach includes qualitative data and information such as:

- pipe material (incl. condition, pipe statics, year of commissioning, geometry etc.),
- bedding conditions (incl. loading conditions, soil corrosiveness),
- land use (roads, buildings in pipe vicinity),
- operations (incl. security of supply)

and the remaining service life of pipes as a quantitative criteria.

The semi-quantitative approach additionally enables to a monetary assessment of failures and risks. In this way current and prospective pipe segments which have the highest risk (inclusive the remaining costs) can be identified and compared to the costs for damage prevention (= costs for rehabilitation). Once the rehabilitation costs are lower than the predicted damages (= risk costs for a specific pipe section), this relevant pipe section should be repaired or renewed.

As mentioned above, figure 1 shows different influences with varying risk likelihood. For an overall view the varying impact of each individual criterion on the overall risk per pipe section is considered by the introduction of weighting factors which are defined in conjunction with the respective water utility. If required, additional criteria, respectively parameters, can be included to design the assessment tool being as flexible as possible. This relationship is shown in table 1 for one example.

Table 1: Propability of occurence of different influences on the condition of trunk mains and associated extent of damage

likelihood		basis of calculation or evaluation	associated extent of damage			
			IMAG	INFR	VERS	REPA
total failure	E_{RND}	1/RND	X	X	X	
	E_{LAST}	= 1 breaking point	X	X	X	
single damage	E_{KORR}	external corrosion (DVGW GW 9) and/or internal corrosion (DIN 50930-6, DIN EN 12502)	X	X	X	X
	E_{EXTE}	e.g. VDI/VDE 2180 (VDI/VDE 2010)	(X)[1]			

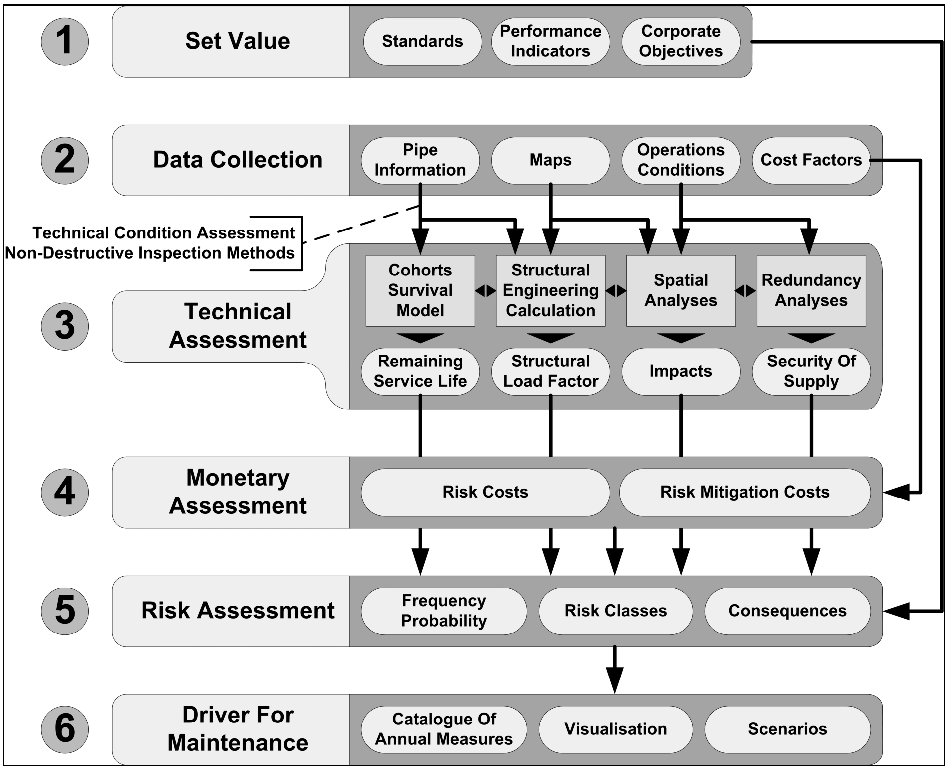
[1]Assumption : Unfavourable conditions may guide to a total failure of water supply also if this damage is not in personal negligence. This may result in a negative consumer perception and can be characterized as an image damage for the water company.

E_{EXTE} characterize external influences like foreign damages e.g. within civil engineering or pipeline construction. Influences like mining subsidence or landslide are part in the parameter E_{LAST} and are used for calculating loading capacity and fracture behaviour.

Structure of the risk assement approach

The structure and the contents of the risk-based maintenance strategy for long-distance water supply systems based on the semi-quantitative approach are shown in Figure 2.

Figure 2: Phases of a risk-based maintenance strategy for trunk mains.



The individual steps are described in more detail in the following sections.

<u>Set value definition</u>

The risk-based maintenance strategy is being compiled under consideration of regulatory framework conditions - the so-called set values. Based on set values, the water utility company defines its aspired medium to long-term level of supply in respect of technical, economic, environmental and safety-related aspects. Typical set values, for example, can be defined for:

- acceptable failure rates (failures per year and kilometre),
- acceptable water leakage rates (percent/year; m^3/year),
- maximum down time and service interruption (duration per year, per failure),

- annual available budget for maintenance (e.g. service, repairs, rehabilitation),
- maximum insurance cover per failure event.

Benchmarks for long-distance water supply systems are listed in worksheets of DVGW (W 400-3, table 2 or W 392, table 4). In mostly cases the data tools are not sufficient for forecasting tendencies so it may be difficult interfering damages and water loss rates in a reliable way. The presented concept solves this problem by incorporating additional parameter to determine the likelihood of damages/failures/disruption like

- average service life of material groups,
- materials characteristic (crack characteristic, crack susceptibility),
- installation parameter (e.g. soil corrosiveness),
- site density (e.g. high traffic and distributed load).

Data collection

The implementation of technical condition assessment, remaining service life prognosis and assessment of bedding and operations conditions of the trunk main system in conjunction with the overall risk assessment, are mainly based on data provided by the water utility. Often not all required data are readily available within the water utility. The need of procurement of missing data will be judged on its relevance for the assessment. Missing of relevant data for risk analysis may be the first serious risk (DVGW 2008). In these cases, an appropriate data collection, a data search and documentation may decrease the risk without necessity of single pipe rehabilitation. Even the cost-benefit ratio for this kind of data collection can be calculated as risk (in Euro) by comparing the information quality of the available (low information) data pool and the extended data pool with improved performance. In the case of missing data or uncertainties (e.g. missing data of the passive corrosion protection) in general less favorable values are used for evaluation – closely linked with an increasing of the risk value.

Typical data for data collection are listed below:

- inventory data (pipe diameter, material, age, burial depth, etc.),
- data from hydraulic network calculation program (pressure, flow rate, flow direction, etc.),
- NIS/GIS data (e.g. geo-referenced maps, digital terrain models, working fund,),
- inventory documentation (maps, such as site plans, section drawings),
- statistics on pipeline failure,
- operations data (repair costs, water quality, cathodic corrosion protection),
- technical reports and documents on pipeline condition,
- details of repair durations,
- experience of operating personnel.

Geo-referenced Analysis (GIS based)

A geographical information system (GIS) is being used to not only visualize existing data (e.g. network plan) but also to create new information by combining various kinds of data. An example is the highlighting of endangered dense urban areas where due to the proximity of buildings a potential pipe failure would have significant consequences (undercutting of streets; damages at buildings). Before the intersection and combination of geo-referenced information is being performed, the trunk main system needs to be divided into meaningful pipe sections (so-called sectioning). In a first step a rough sectioning is sufficiently. Using a hydraulically cross sectioning of the trunk main, the following parameter are under consideration:

- service pipes, connections, valves
- nominal size, pipe material, date of commissioning.

By utilising the earlier mentioned GIS-intersection, relevant geo-referenced input data and its impact on likelihood and consequences can be allocated to each individual pipe section. After that, a detailed sectioning is being performed, based on specific properties such as:

- critical infrastructure (e.g. motorways, railway embankments, culverts),
- critical terrain structures (e.g. extreme burial depths or inclines),
- sensitive customers in pipeline vicinity or with a direct connection (e.g. trade and industry)
- bedding in protective tubes (impinges risk-decreasing).

The experience of the operation staff is also sought, in particular, in regards to suspicious or critical pipe sections. Detailed sectioning is the basis for identifying isolated vulnerabilities in the trunk main system (so-called hot spots) - these localised pipe sections are loaded with a significant higher risk than adjacent sections. Measures to reduce risk (usually pipe rehabilitation) should therefore, among other things, focus on these sections.

Structural integrity

A very significant influence on the likelihood of failures/breakage of pipelines is given by the loading capacity of the pipeline. Loads are impacts of

- traffic, area and soil loads and
- internal pressure.

External impacts cause tension (stress) in the tube wall which can lead to a fracture of the pipe when the system resistance (allowable stress) is exceeded. The resistance of the structural component is dependent on

- strength properties such as elastic modulus, as well as bending tensile strength,
- pipe geometry (diameter, wall thickness).

Further impacts are

- soil aggressiveness (e.g. corrosion of metal),
- drinking water quality (e.g. carbonation of asbestos cement),

To determine the structural load factor in conjunction with performing a risk assessment of trunk mains, the current and allowable component tension needs to be determined under consideration of certain safety factors. Suitable algorithms for this purpose can be found in ATV-DWA-A 127 (ATV, 2000), which also observe the influence of installation and bedding (sand or ground water).

If required input variables cannot be determined, it is advisable to make a conservative but plausible estimate (e.g. for traffic loads, bedding conditions, coverage levels, etc.). Another way to determine missing input variables is the so-called technical condition assessment. At this, single pipe samples are taken from the supply network which are then examined and evaluated. These findings may also be carried over to the same pipe type and may supplement or replace the parameters mentioned above. The pipe sample should be taken during remedial works at the failure site or by selective excavation (if technically and economically feasible). For each pipe section a structural load factor can be calculated and it is possible to identify pipe sections with a theoretical load factor > 100% and a very high certainty of a pipe failure (e.g. breaks/cracks/deformations). In addition, the calculation of the maximum allowable operating pressure may be carried out by utilising the results of the static calculations for brittle pipe materials - these results may be later relevant for pressure management.

<u>Redundancy - security of water supply</u>

Assessing the scale of supply outages also allows an evaluation of the security of supply at the same time. The following criteria are suitable:

- duration of supply interruption (this could be also used as a set value – e.g. avoiding interruptions > 24 h),
- number of affected customers (e.g. total number, sensitive customers, supply contracts),
- redundancies within the supply system (e.g. additional supply feed-in, network loops),
- possibilities of a contingency supply (type, quantity, availability, setup time),
- flow rate (e.g. Q_{max})
- feed-in quantities and consumption.

Pipes with high flow and a maximum number of connected customers are generally the sections with the highest vulnerability regarding interruption of supply. This is being intensified by the brittleness of pipes (fractures are generally associated with greater water losses than leaks through cracks or perforations), and an aggravated accessibility of the potential failure site (prolonged supply interruption).

The consequences that are caused by condition-related pipe failure are also being taken into account. However, not part of a risk-based maintenance strategy is the consideration of risks caused by:

- climate change (e.g. water scarcity),
- acts of terror,
- regulatory requirements,

- removal of redundancy,
- service and handling error.

These risks are hardly or even not manageable at all by the application of common maintenance methods such as rehabilitation or renewal. But an upgrading of the presented method is generally possible and results in a general risk management system (Staben et al. 2010).

Service life prediction

To forecast medium to long term trends regarding condition or risk development, a time component in addition to the previously mentioned input variables is required. For this purpose the projected service life of each individual pipe section is deemed very suitable which is based on the inventory data with information about:

- pipe material / pipe-generation,
- year of commissioning/decommissioning,
- installed pipe lengths,
- nominal size classes.

As long as a pipe is still in operation its estimated remaining service life can only be predicted. As part of the risk-based maintenance strategy the remaining service life of each pipe material class is being determined by

- applying appropriate prediction algorithms, such as the cohort survival model (Herz, 2002; Sægrov et al. 2007),
- information from literature (DVGW, 1997),
- empirical values of staff members.

The resulting data, after technical review, are used for additional calculations. For trunk mains it may be necessary to forecast the remaining service life for up to nine different material groups (e.g. grey cast iron, steel, pre-stressed concrete pipes). Taking into account the various types of manufacturing and construction within a material group, further subdivisions result in so-called material classes and pipe generations (Sorge, 2007). By the division into material classes the chronological development and improvement of pipe manufacturing processes is considered, including the development of corrosion protection, bonding techniques as well as strength and material properties.

Monetary assessment

For a complete risk assessment, a monetary quantification of risk is highly recommended since the use of an uniform monetary unit facilitates some degree of comparability within the results. This is particularly important in maintaining a risk management system within a water supply company. This is helpful when it comes to determine what level of risk can be tolerated or at which point a non-acceptable risk can be mitigated by rehabilitation measures. Relevant cost categories can be as followed:

A)• Risk associated costs

- cost of repair (remedial works at a pipe section),
- loss of revenue.
- damage to nearby infrastructure (damage on buildings, undermining of streets),
- risk mitigation costs.

B costs of risk prevention

- replacement costs.
- costs of redesigning (allocation of pipes).

Risk assessment

For each indexed pipe section – these can be up to a several thousand – an indication of its likelihood and corresponding consequences (extent of damage) are being calculated. They are associated with normalized values between 0 to 1 and the extent of damage in EURO. It is not more necessary to visualize the risk by a commonly used risk matrix with 25 risk categories. Indicating the risk in EURO it is also possible to compare different plant sections regarding to their risk even if they are evaluated by different maintenance strategy concepts. Beside the description of the current risk a description of a risk development for future is possible. The partial influence of the rest service life on the likelihood of a total failure but also a normal damage can be calculated for each pipe section with special regard to risk and time dependence.

Maintenance requirements

To determine the maintenance requirements the acceptable risk derived by the definition of set values must be known. It is assumed that only replacement measures exert influence on the achievement of an acceptable risk level. Furthermore, it is assumed that for the replacement of identified trunk mains state-of-the-art pipe materials are being used. In this case the risk will be reduced because

- the likelihood of damages/failures is minimized (high service life and high strength characteristics of the new material) and
- the extent of damages are reduced (no installation of materials with brittle fracture characteristics).

Since it is known how much funding per year is available for maintenance and also how much the estimated renewal costs per pipe meter will be, it is therefore possible to forecast the number of pipe sections which can be replaced depending on the annual budget available. Based on these (updated) figures, the overall risk score is then re-calculated. On this basis a detailed action plan (catalogue of measures) is created which lists the most urgent, annually renewing pipe sections until the desired overall risk score is reached or subsequently maintained. Conversely, the demand for financial resources can be identified which would be required to achieve a certain risk score in a predetermined time frame (e.g. 10 to 20 years).

Practical approach

Meanwhile, this presented concept has been already successfully implemented in three trans-regional German long-distance water supply companies (Sorge et al, 2012).

The systematic implementation of the risk-based maintenance strategy (implementation of rehabilitation and replacement measures) result in a performance enhancement of the pipe condition and ensure the following short to long term effects

- prevention of damage costs resulting on missing maintenance measures,
- minimizing of repair costs due to condition deterioration and damages,
- slowdown of repair costs and damages, less interruption of water supply,
- protection and upgrade of the corporate image,
- prevention of insurance protection stop in the case of damages as a result of missing rehabilitation.

Results and conclusion

The implementation of the presented approach of a risk-based maintenance strategy considers the following general recommendation on maintenance of supply systems (DVGW 2006, DVGW 2010b, Heyen 2011):

- improvement or preservation of the supply quality due to total costs as close as possible,
- reduction of damages and supply interruptions,
- reduction of the endangerment of human, external systems and environment,
- improvement of the data quality due to the fact that the sustainability of a maintenance strategy significantly depends of the available data pool.

Conventional approaches for compiling maintenance strategies for trunk main systems are almost solely based on the account of the pipe age and its failure rate (failure per year and kilometre). Such approaches for the development and evaluation of a maintenance strategy for trunk main systems are only suitable to a limited extent as significant influences on the likelihood of failures are inadequately considered. Furthermore, parameters such as failure rates do only apply to a limited extent for the compilation of the risk assessment of trunk main systems. Even a single failure can already lead to considerable expenses for repair, compensation and supply crunch. This may be a non-tolerable risk. The concept presented here allows the identification of trunk main sections which have the most urgent maintenance need due to their overall risk, concerning pipe failure and security of supply. More than a risk indexing approach, this concept allows the simulation and assessment of different maintenance scenarios (e.g. various investments or “do-nothing”-scenarios) regarding the security of supply and risk costs. Limited available financial resources are rather spent most efficiently by concentrating on pipe sections with the most urgent maintenance needs. By consistent implementation a reduction of maintenance costs may be achieved in most cases in the medium to long-term.

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