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The influence of different characteristics on the probabilities of failure of sewer pipes

By

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Preface

For the past years, I have embarked myself into the adventure and challenge of studying and living abroad. I close a chapter of this experience with this thesis, which has been enriching in knowledge, challenge, patience and perseverance.

I would like to thank very specially my supervisor, Lisa Scholten, who accepted to work with me and always made time to help me and guide me. Lisa was always optimistic and helped me overcome the difficulties that happened in the process.

Further, I would like to thank the rest of the members of my committee. Oswaldo Morales for his time and patience explaining me, Rob Schoenmaker for listening to my explanations and making sure they were clear, and François Clemens for his support since the first day, his advice and corrections.

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Ana Margarita Montoya Montoya

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Executive summary

Sewer assets face a great challenge for being underground assets and for experiencing constant deterioration and aging.

Reactive decisions are no longer technically nor economically viable, and hence asset managers are migrating to the implementation of proactive strategies. Despite this, managers are making decisions that are poorly justified, based mostly in intuition. This is why it is important to improve the means to implement a more objective and justified proactive approach.

Risk-based decisions are a proactive strategy that may help the prioritisation and optimisation of maintenance and inspection strategies. It requires for its implementation the estimation of probabilities of failure and their consequences.

In this thesis, the analysis is oriented on the failure probabilities on sewer systems, especially on understanding the influences of different characteristics of the pipe (explanatory variables) on these probabilities. The outcome of the thesis answers the following research question:

"What is the influence of different characteristics on the probability of failure of the sewer pipes?"

Two sub-questions were stated to guide the research and help answering the main research question:

1. What defects can lead to sewer structural failure?
2. What physical characteristics make sewer pipes more prone to fail/deteriorate?

For the analysis the Dutch municipalities of Breda and Almere facilitated the results of several years of CCTV inspections of their sewers.

Due to the lack of availability of collapse records, this study considered a proxy of collapse, which is loss of watertightness on the pipes. Furthermore, defects that potentially cause loss of watertightness are used as a proxy of the loss of watertightness on a pipe. Defects are obtained from the CCTV reports.

The first sub-question was answered based on the proxy failure under study. It was found in the literature review ten defects that potentially cause loss of watertightness, which were classified according to the coding of the standard NEN 3399. These defects are: cracks (BAB), break (BAC), defective connection (BAH), intruding sealing material (BAI), displaced joint (BAJ), porous pipe (BAN), soil visible through defect (BAO), void visible through defect (BAP), infiltration (BBF) and exfiltration (BBG).

The second sub-question was answered based on some explanatory variables that were available in the dataset of the inspections, which included: sewer system type, materials, shape, diameter, length, and pipe's above ground material.

To answer this question, a descriptive statistical analysis and two survival methods were implemented: a non-parametric and a semi-parametric model.

The non-parametric model consists of an extended version of the Nelson-Aalen estimator of the cumulative hazard (ENE) and its derivative the Extended survival estimator (ESE). Implementing ESE, each characteristic was analysed using the aggregate information of the defects that potentially cause loss of watertightness, and each defect individually. This was done to identify the influence in the failure probabilities (the probabilities of occurrence of defects that potentially cause loss of watertightness).

The semi-parametric model that was used is the Cox proportional hazard function, used to estimate the risk ratio associated with one unit increase in one of the characteristics under study.

Results of the ESE model showed that:

The defects displaced joint (BAJ), infiltration (BBF) and defective connection (BAH), are the ones that have more incidence on the loss of watertightness for the two municipalities.

Based on the information of aggregate defects it was observed for both municipalities that the median survival probability is past 14 years.

Also, the analysis showed that stormwater sewers have a lower survival probability than foulwater sewers, that PVC pipes have a higher survival probability than concrete pipes, and that shorter pipes have a higher survival probability than longer pipes. In the case of the diameters, for the aggregate defects and defects displaced joint (BAJ) and defective connection (BAH), smaller diameters have a higher survival probability than larger ones. But this tendency is the other way around for defects like cracks (BAB), break (BAC) and porous pipes (BAN), where the diameter has a higher survival probability when are larger than when they are smaller.

Characteristics shape and above ground material were only analysed for Breda. It was observed that egg-shaped pipes have a lower survival probability than circular shapes, and that pipes with green fields and floor tiles above them have a lower survival probability than pipes that have above asphalt and pavement.

For both municipalities, the results of ESE showed that material is that characteristic that influences the most the probabilities of failure.

Results of the Cox proportional model showed that: Almere's results met the proportionality assumption and showed that the characteristics sewer system type and length are the one that influences the most the failure probabilities. Breda's data is no appropriate to be used with this model, as it does not meet the proportionality assumption. Recommendations of analysing Breda with an extended Cox are given, as this version of the model allows to use time-dependent variables.

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1 Introduction

1.1 Research background

Public utilities, like water, electricity and gas, play a major role in societies, in their economies and in their level of development. As societies continue to grow, the demand on drinking water and production of foulwater will also increase, and therefore more attention should be given to its management and treatment.

Sewer systems in particular, face a great challenge. Is not only about the increasing demand of their functions, but mainly about the fact that these are complex, underground assets experiencing constant aging and deterioration. This implies the requirement of great investments to assure high performance and failure reduction, while dealing at the same time with environmental and sanitary requirements, regulations, customer pressures and climate change (Ana & Bauwens, 2010; Fenner, 2000).

In the last decades, municipalities around the world have paid greater attention and made investments to expand their sewer systems to meet the growth of population. Yet, little of this budget has been directed to the rehabilitation of the existent sewer networks, resulting in several aging sewers in need of maintenance, repairs and replacement works (AWWA, 2012).

Particularly in Europe, most cities have aging sewer systems, adding a challenge to their management as a number of problems arise frequently, including corroded concrete, deterioration, cracks, collapse, clogging, among some others (WWAP, 2017).

In the case of the Netherlands, a large-scale construction of sewer systems started between 1950 and 1970 (van Riel, 2016). Taking these dates into account and the fact that these assets have an estimated average lifespan between fifty and ninety years, increases the field of expenditure for rehabilitation and replacement, and interest for their management, as the keep aging (Dirksen & Clemens, 2008; van Riel, Langeveld, Herder, & Clemens, 2012).

Sewer asset management was traditional more convenient and more economic to confront with reactive management strategies, repairing mainly failures that occurred. But the more these infrastructures age, the less viable, economically and technically speaking, it is to continue using this strategy (Caradot et al., 2017). The older these systems get the more concern will grow about their performance and the increase of failure probability. Therefore managers are migrating to the implementation of proactive management approach, which is aimed at avoiding failure, and at being more cost-effective than the reactive approach (Fenner, 2000).

Despite the current transition to use and apply the proactive-approach, managers are making decisions that are poorly justified, as most of the methods that are being put into practice are mainly intuitive and with high uncertainty, including the data used and the strategies implemented (Elachachi, Breysse, & Vasconcelos, 2006; van Riel, 2016).

The availability of data is the cornerstone of evidence-based decision-making, but unfortunately in sewer systems, most of the time there is only a limited amount of information available of the asset and its quality is questionable (Dirksen et al., 2013; Rokstad & Ugarelli, 2016; Stanić, 2016). The data used is mostly recollected through visual inspections, being closed circuit television (CCTV) the most popular one, commonly used to identify the defects of the pipes according to standard methods (Stanić, 2016). Unfortunately this kind of procedure has several disadvantages: it is costly, for which it is not performed frequently and only in some determined pipes; it does not provide quantifying information about the pipes (like pipe's deformation, hydraulic capacity or structural strength); and it also is affected by the subjective interpretation of footage by the inspector (Stanić, Lepot, Catieau, Langeveld, & Clemens, 2017; Ten Veldhuis, Dirksen, & Clemens, 2009).

Regarding the strategies that are implemented most frequently in sewer management decision making, they are based on the pipe's age and the condition class of the pipes. Research has shown that many managers consider pipe age as an approximation of the pipe failure probability and make their decisions, whether to intervene or not, based on the assumed technical service life (van Riel, 2016). However, age-related deterioration of sewer pipes is unclear (Fenner, 2000), and by considering it, other factors of pipe deterioration are being ignored.

The condition class- based strategy, for instance, refers to the quantification of the magnitude of the defect of the pipe in a scale from 1 (no deterioration observed) to 5 (critical state) based on a rating protocol used on visual inspections. This strategy is influenced by subjectivity, as they depend on the given interpretation of the inspector (Dirksen & Clemens, 2008). Also the results of this strategy are questioned, as it is found inappropriate to measure in a discrete ordinal way a condition class which is in fact a continuous function (Scheidegger, Hug, Rieckermann, & Maurer, 2011).

Other strategies, like risk-based asset management, are starting to be implemented more often by sewer managers (MacGillivray, Hamilton, Strutt, & Pollard, 2006). In contrast with the aforementioned strategies, risk- based asset management not only considers the interruption of the service, but also takes into account costs, quality of the service, environmental impact, company reputation, and other consequences that might be of interest to the manager (Trotter, 2017).

In practice, sewer pipes might fail due to structural or to hydraulic circumstances (Anbari, Tabesh, & Roozbahani, 2017; Kley & Caradot, 2013). The risk of failure of these pipes is measure based on the consequences of failure multiplied by the probability of failure of the individual pipe (Baah, Dubey, Harvey, & McBean, 2015; Halfawy, Dridi, & Baker, 2008). Several authors have presented different ways of estimating the consequences of failure. As explained by Baah et al. (2015), the most common methodologies include the use of a weighted multicriteria decision matrix system or the use of a fuzzy logic approach, both method assigning scores to a list of socio-economic and environmental impact criteria (Baah et al., 2015).

On the other hand, the probabilities of failure can be estimated with different statistical methods. Nevertheless, this estimation can be difficult, mainly because most municipalities have only scarce data of inspections and of past failure events (typically these assets have low failure rates) (Kleiner, 2001).

Aiming to contribute to the estimation of the probabilities of failure for risk decision making, the present research seeks to explain the influence that some covariates have on the failure probabilities of sewer pipes.

1.2 Problem statement

Decision making on sewer management for maintenance and planning, is directed to sewers that do not meet the required performance criteria, including structural stability, watertightness and flow gradient (Korving, 2004).

As explained in the Sewerage Rehabilitation Manual (1983), the failure of a sewer normally originates where an initial defect started that allowed further deterioration to occur, which can lead to pathogen exposure, pollution of groundwater, waterways and wetlands and can cause damage to roads and other infrastructure (Anbari et al., 2017; WRC, 1983).

Collapse, which is the complete loss of the pipes resistance and consequential break, is considered the severest structural failure in a pipe (Anbari et al., 2017). Studies have shown, that minor defects, such as displaced joints, cracks, breaks, defective connections, among others, can lead to major structural problems (WRC, 1983). Most of these defects are related to the loss of watertightness of the pipe, and may allow the occurrence of infiltration and/or exfiltration events, which can possibly displace and move soil particles of the pipe's bedding and lateral support, creating voids and affecting the supporting capacity of the pipe, causing subsidence or, most extremely, collapse (Cardoso, 2008; WRC, 1983).

Considering this, and the fact that was explained previously about the concern of the sewer pipes getting older, it is important to improve the means to implement proactive approaches. This is why, methods are required that can optimise and prioritise any work by predicting and assessing the sewer condition and the aforementioned performance criteria (Fenner, 2000). Being risk-based assessment a proactive strategy, it is important to estimate the probabilities of failure and consequences, to guide and indicate the manager when to inspect and/or intervene deteriorated assets to avoid failures that can have high consequences (Marlow et al., 2007).

For this reason, special attention is required and directed to understand the pipes characteristics that have significant influence on the probability of failure of the sewer pipes. This is especially relevant for objective risk-based decision making, especially because in practice, sewer managers make their decisions based on intuitive judgement, adding subjectivity and uncertainty to the decision (van Riel, 2016). The methods proposed should fit the data characteristics, considering the fact that sewer data provides information about the condition of the pipes at the time of the inspection and not when the event (failure) occurred, as is the case for water distribution systems (Scheidegger, Leitão, & Scholten, 2015).

1.3 Case studies

In the Netherlands, municipalities are responsible for the development, management and maintenance of the water management facilities (Gemeente Almere, 2011).This also includes the duty to collect and transport urban foulwater up to the foulwater treatment plant (Gemeente Almere, Waterschap Zuiderzeeland, Stadsstromen, & Mani, 2017), where the task of cleaning and purifying is taken by the Water board. Also municipalities are in charge of the duty to care for stormwater run-off and the duty to prevent structural adverse consequences due to groundwater (Gemeente Almere, 2011; Gemeente Breda, 2009; Ministry of Housing Spatial Planning and the Environment, 2004)

As part of their management and maintenance duties, municipalities monitor regularly the condition of the sewer systems by performing visual inspections, which report the location and characterization of the defects observed. The analysis of this thesis is done with the sewer visual inspections of the Dutch municipalities of Breda and Almere. The location of these two municipalities in the Netherlands can be observed in Figure 1.1. Further information of the case studies is presented in chapter 5.

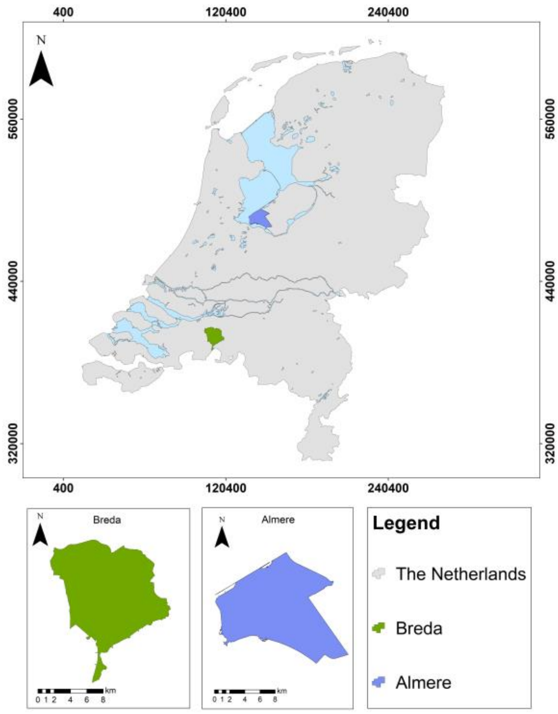


Figure 1.1 Location of the municipalities of Breda and Almere in the Netherlands (own illustration)

1.4 Structure of the thesis

As a short guide for reading this thesis, the structure is as follows. After this introduction, Chapter 2 presents a literature review of the main topics which are dealt with during this research. Chapter 3, explains how the research is design in order to answer the research questions. Following, chapter 4 presents the methodology with the data gathering and data analysis explanation. Next, chapter 5 presents a brief description of the case studies used in the research and relevant information about the municipalities. Chapter 6 presents the descriptive statistics and results of the analysis. Chapter 7, 8 and 9 presents a discussion, conclusion and recommendation about the results and answers the main research question.

2 Literature review

2.1 Sewer asset management

Asset management as defined in the standard ISO 55000:2014, is the coordinated activity of an organisation to realise value from assets (ISO, 2014b). Basically, is a discipline concerned with applying technical and financial judgement and management practices when decisions are required about what assets are needed to meet the organisation's objective and then acquiring and logistically sustaining the assets over their whole life up to disposal (Hastings, 2015). Asset management is important for organizations as it helps to improve financial performance, services, efficiency and effectiveness; to make investment decisions; to manage risk; to demonstrate social responsibility and to enhance reputation ((The Institute of Asset Management) IAM, 2012).

In an increasing concern for foulwater utilities, sewer asset management aims to maintain infrastructure in a condition that is compatible with economic, environmental and sanitary standards (Ibrahim, Cherqui, Gauffre, & Werey, 2007). As described by Mashford et al, 2011), sewers are aging underground assets, large (in terms of the length of the pipes), heterogeneous (in terms of the parts, characteristics, shapes and operating context) and susceptible to different deterioration processes. These reasons add to the requirement of an appropriate asset management to maintain the system serviceability, as well as to minimized the cost for rehabilitation, and to reduce the risks (van Riel et al., 2012).

As mentioned in chapter 1, it used to be more convenient to address sewer asset management into repairing only the occurring failures, in other words, to implement a reactive strategy. But the more these assets age this is nor technical, nor economically viable, reasons why managers are starting to implement more and more a proactive approach, eliminating problems or reducing the risk before any event occurs.

However, regardless of the effort to avoid failure decision making for sewer asset management lacks argumentation and to some extent is mainly based on intuition (van Riel, van Bueren, Langeveld, Herder, & Clemens, 2016). Lack of argumentation refers to the practice of managers to consider basic decision argumentation factors like age, visual inspection results and others, with local circumstances. By incorporating the local circumstances, complexity is added to their decision making and results on the use of intuition over analytical reasoning (van Riel et al., 2016). This makes transparency and reproducibility harder to achieve. Specially for public infrastructure asset management, the lack of these two characteristics makes it hard to explain and justify the course of action and to guarantee that the decisions are cost-effective (Van Riel, Langeveld, Herder, & Clemens, 2016).

Decision making transparency is affected by the system complexity and the process complexity. The first refers to the interactions the asset's elements and their surrounding environment, where a correct performance assessment and understanding of the deterioration processes are required to make decisions. The second refers to the network of involved stakeholders and the direct and indirect interaction and cooperation with them (i.e. road managers, urban developers, etc.) (Van Riel et al., 2016). The process complexity is out of the scope of the present research.

Regarding the system complexity, the deterioration models and condition assessments play a role in assisting managers on making decisions, specially about ''where'', ''when'' and ''how'' inspection, replacement or rehabilitation pipe strategies should be implemented with the available budget (Ugarelli & Di Federico, 2010; Van Riel et al., 2016). Nevertheless, the just mentioned intuition affects the course of these decisions, as a consequence of the amount and quality of the available data and the implementation of the commonly used strategies (age and condition-state based), that were explained in chapter 1, and the subjectivity behind them.

Accurate prediction of sewer conditions helps managers in their decision making, and also reduces the lack of argumentation and the just mentioned intuition, by enforcing objectivity in their decisions. For this, different models of sewer deterioration and sewer failure have been developed, some of which will be explained in paragraph 2.4.

Furthermore, the accuracy and reliability of the decisions managers make will not only depend on the models they use, but on the sources of information they implement to detect and quantify the failure or deterioration of the elements (Stanić, Langeveld, & Clemens, 2014). Authors like Stanić et al. (2014), identified different sewer failure events by applying Hazard and Operability analysis (HAZOP) and based on each, they also identified the information needed to assess each failure and where to get it, in order to make rational decisions.

2.2 Risk-based decisions

The standard ISO 55000:2014, explains that asset management translates the organisation's objectives into asset-related decisions, plans and activities using a risk-based approach (ISO, 2014a).

Risk based approach is a typical kind of asset management strategy that defines risk tolerability criteria and prioritises the activities according to the criticality of the asset and the level of risk associated with it ((The Institute of Asset Management) IAM, 2012).

To implement risk-based management two factors are required:

1) An estimation of the probability of failure of individual pipes within the sewer asset
2) A consequence of failure model which states the magnitude of impact.

Once these factors are obtained then the calculation of risk can be performed:

$$Risk = probability\ of\ failure * consequence\ of\ failure \qquad (1)$$

The estimation of the risk will guide manager on their judgement of the actions they should take to achieve the best results based on the organisation's objectives, and the public health protection and prevention of urban flooding (Davis, 2015; MacGillivray et al., 2006).

The consequences of failure estimation has been reviewed by different authors. Baah et al., (2015), refers to the most commonly used methodologies to estimate the consequences which are the weighted-sum multicriteria decision matrix and the fuzzy logic approach.

The probability distribution of a failure time of an individual from an homogeneous population can be estimated with the survival function, the probability density function and the hazard function (Kalbfleisch & Prentice, 2002). Survival function is the probability of an individual surviving to time x; the probability density (or probability mass) function, is the unconditional probability of the event's occurring at time x , and the hazard function, is the chance an individual of age x experiences the event in the next instant in time (Klein & Moeschberger, 2003).

As specified by authors Khan et al. (2004), the process of risk analysis consists on the assessment, management and communication of risk. Maintenance and inspection planning based on risk analysis, minimises the probability of failure of the assets and its consequences, prioritises the inspections based on the criticality and estimated risk values of the system and thus increases the sewer network performance (Anbari et al., 2017; Khan & Haddara, 2003). The risk-based inspection and maintenance strategy (RBIM) can be used to develop inspection and maintenance plans and programs to reduce the overall risk of failure of the operating facilities and the scope of work and cost that is required (Khan & Haddara, 2003; Khan et al., 2004).

2.3 European and Dutch standards and about visual inspections

In the Introduction, it was mentioned that sewers in the Netherlands are subjected by different standards which are published by the Netherlands Standardisation Institute (in Dutch: Nederlands Normalisatie Instituut, NEN).

In 1987, the NRP 3220, code of practice for sewerage management was introduce in the Netherlands and updated in 1994. This code provides a framework and regulates municipal sewerage management, as well as instructs which processes to follow, which plans need to be made, and how to adopt resolutions (NLIngenieurs Sewer Systems Workgroup, 2009).

The management (asset management) of the outdoor drainage system is described in 'NEN-EN 752 Outdoor sewerage'. This standard is based on the European Standard EN 752 (first published in 1990's), but was adapted to the Dutch running practices (NEN, 2015a; NLIngenieurs Sewer Systems Workgroup, 2009).

The European standards that regulate the coding of the observations made during an inspection were implemented in 2004 and correspond to 'EN 13508-1 Investigation and assessment of drain and sewer systems outside buildings -Part 1', and 'EN 13508-2 Research and assessment of the external sewers - Part 2: Coding system for visual inspection' (NLIngenieurs Sewer Systems Workgroup, 2009). These standards were also adapted to the specific Dutch situation, that is characterized by the design of the sewer system in flat and low-lying areas, and highly meshed systems, and which includes the above-mentioned code of practice NRP 3220. The result of these adaptations are the standards NEN 3398 and NEN 3399, which ensure that all inspectors speak in the same terms (NEN, 2015a; NLIngenieurs Sewer Systems Workgroup, 2009).

The 'NEN 3398 Drains and sewers outside buildings: Inspection and condition assessment of objects' (*Buitenriolering: onderzoek en toestandsbeoordeling van objecten*), sets requirements for sewer inspections and for assessing the condition of sewer components. The standard 'NEN 3399 Drains and sewers outside buildings: Classification system for visual inspection of objects' (*Buitenriolering: classificatiesysteem bij visuele inspectie van objecten*), stipulates which codes from NEN-EN 13508 apply to the Dutch situation, and which do not (NEN, 2015a; NLIngenieurs Sewer Systems Workgroup, 2009).

Visual inspections techniques are used, in order to identify defects on the sewer pipes (Lepot, Stanić, & Clemens, 2017). The inspection process follows the next steps (Dirksen et al., 2013):

1. Collection of images: generally, a CCTV camera is used to collect images from within the sewer pipes;

2. Recognition of the defects: This is done by the inspector while evaluating the footage. The number and type of defects to be identified is determined by the prescribed coding systems.

3. Description of the defects: The description is done in more detail by making a characterisation, a quantification of its magnitude and identifying its location.

In the NEN 3399, sewer pipe defects are classified and coded as presented in Table 2.1 (NEN, 2015b).

Table 2.1 Defects coding on sewer pipes according to NEN 3399

Code	Description	Code	Description
BAA	Deformation (flexible pies only)	BAM	Weld failure
BAB	Cracks	BAN	Porous pipe (concrete only)
BAC	Break / collapse	BAO	Soil visible through defect
BAD	Defective brickwork or masonry	BAP	Void visible through defect
BAE	Missing mortar	BBA	Roots
BAF	Surface Damage	BBB	Attached deposits
BAG	Intruding connection	BBC	Settled deposits
BAH	Defective connection	BBD	Ingress of soil
BAI	Intruding sealing material	BBE	Other obstacles
BAJ	Displaced joint	BBF	Infiltration
BAK	Defective lining	BBG	Exfiltration
BAL	Defective repair		

The quantification of the codes is done by the inspector, based on the magnitude of the defects they identified. A classification from 1 to 5 is given to each defect, which as explained by the NEN 3399 mean (NEN, 2015b):

- Class 1: the relevant state aspect is not or only to a very small extent observed in accordance with the specification in the tables,
- Class 2, 3, and 4: the relevant state aspect is found in a form that is greater than class 1;
- Class 5: the relevant state aspect is observed in the maximum form.

Nevertheless, the use of frameworks or standards does not guarantee high quality of the obtained data. As it can be notice, the distinction between classes 2 to 4 is not clear. Further descriptions of the classes are provided for some of the defects in NEN 3399, yet the differences are not easy to quantify and therefore are open to discussion on their veracity. Different studies have questioned the subjectivity and quality of the data collected in the inspections and the classification given to each defect. Studies have shown that the visual sewer inspection data are poorly reproducible (Dirksen, Baars, Langeveld, & Clemens, 2012). It is also mentioned that due to the fact that the analysis of defects is subjective and depend on the experience and skills of the inspector, errors are inevitable (Dirksen et al., 2013; Wirahadikusumah, Abraham, & Iseley, 2001). Furthermore, data should be handled with care as some aspects may not be visible on the footage, or when the opinion of inspectors may be conditioned due to the performance of several inspections in the same district for a large period of time (getting used to some features, and resting importance) (Dirksen & Clemens, 2008). Authors Dirksen et al. (2013), studied the consistency of visual sewer inspected data and concluded that the probability of a defect not observed although present (false negative) is about 25%, whilst the probability of a defect observed although not present (false positive) is about 4%.

Uncertainties of the data can be linked to the three types of subjective assessment of the information, identified by Dirksen et al. (2013):

- The recognition of defects
- The description of defects
- The interpretation of inspection reports

2.4 Sewer deterioration and failure

Diverse methods or models have been developed regarding the sewer conditions, and can be used to optimise and prioritise proactive approaches in sewer management.

This section presents a brief review about some sewer deterioration models that can be found in the literature. Accurate predictions of the future conditions of sewer systems will make easier the role of managers especially when considering if they should rehabilitate or replace the pipes, and when planning and defining long-term strategies and budget requirements (Kley & Caradot, 2013). The effective use of deterioration models can contribute to the goals of reducing construction, operation and maintenance costs in sewer, as well as to reduce the risk of failure of systems (Baah et al., 2015; Wirahadikusumah, Abraham, & Castello, 1999).

Sewer deterioration processes specifically, are mainly reviewed to provide necessary background to the structural condition assessment of the sewer networks (WRC, 1983). It is important for the manager to predict future deterioration in order to determine rehabilitation and maintenance strategies (Scheidegger et al., 2015). In particular the following benefits can be achieved when modelling the pipes' deterioration (Ana & Bauwens, 2010): (1) avoidance of premature asset failure, (2) risk management implementation associated with failures and mitigation of the failure consequences, (3) accurate prediction of the future expenditure requirements, and (4) enhancement of maintenance strategies.

Usually assets, including sewer pipes, deteriorate with age. However, research has proved that an older pipe is not necessarily in a worse state than a newer pipe (Kley & Caradot, 2013). As it is explained by Gedam et al (2016), pipe deterioration usually follows no specific trend line, for which it is always hard and challenging to predict its behaviour due to various factors involved: physical, environmental and functional factors. Physical factors include pipe's characteristics (diameter, age, length, and slope). Environmental factors refer to the surrounding conditions of the pipe (soil, bedding, traffic volume, water level). The functional factors depend on the maintenance strategies adopted by the municipality or sewer company (Gedam et al., 2016).

Different studies have been carried out on identifying and understanding the factors that cause structural deterioration and pipe failure. Two kind of models have been identified: Process-based and Data-based models.

- Process-based models evaluate the quantitative relationship between deterioration factors and sewer condition using mathematical equations (Kley & Caradot, 2013). These empirical models are deterministic, and are based on the physical, chemical and biological phenomenon that lead the pipe to deteriorate.

  An example of these kind of models is the ExCorr, which estimates the external corrosion of concrete by evaluating the soy aggressiveness and moisture and the cement's quality (Kley & Caradot, 2013).

  Unfortunately these models are often too simplistic and reflect little reality of the deterioration process, adding to the fact that they do not account for the uncertainty that is associated with the asset deterioration and failure, and the scarcity of data for modelling these techniques (Ana & Bauwens, 2010; Kley & Caradot, 2013).

- Data-based models use only the pipes historical data and try to find relations among the data. The artificial intelligence models and the statistical models are part of this group.

  Artificial-intelligence-based models, have as advantage the capacity to deal with complex problems, although they have limited capacity to identify explicitly possible causal relationships, as they are more data-driven than model-driven (Ana & Bauwens, 2010; Kley & Caradot, 2013).

Neural Networks is a type of data-based deterioration models. The implementation of Neural Network predict output from input information, as these models try to find the mathematical relationship between predictors (i.e. deterioration factors) and responses (i.e. discrete sewer condition classes) from the inspection data. Other models are the Fuzzy Set Theory (e.g. Kleiner et al. 2006), and the Expert System (i.e. Merill et al. 2004) (Ana & Bauwens, 2010; Kley & Caradot, 2013).

Statistical models, on the other hand, use probabilistic models to relate deterioration or failure factors to historical data of graded pipe conditions, taking into account the uncertainty that is not considered in the process-based models (Kley & Caradot, 2013). Some commonly used statistical deterioration models for sewer systems were reviewed in the articles by Ana & Bauwens (2010) and in the report for the Berlin Water Competence Centre (Kompetenzzentrum Wasser Berlin) by Kley & Caradot (2013), among which are: the Cohort survival model, The Markov-chain based model, the semi-Markov model, logistic regression and discriminant analysis .

Ana & Bauwens (2010) suggest a subdivision of the statistical models: pipe group model and pipe level model. The first considers the entire sewer network or cohorts (pipes similar features which may influence their deterioration) and are useful to support strategic asset management and to enable the evaluation of the efficiency of several scenarios at the network scale. The pipe level models take the individual properties or characteristics of each pipe into account (covariates to predict deterioration), and are useful to set priorities and justify asset management operations and investments (Ana & Bauwens, 2010; Kley & Caradot, 2013).

Additionally, it is important to mention that there are other statistical models for pipe deterioration and failure development which are oriented to water distribution networks. The difficulty when using these models for sewer modelling has to do mainly with the data. Water supply systems data contain information about when the events (failure) occur, while sewer systems data only presents the condition of the pipes at the time of the inspection (Scheidegger et al., 2015).

In the article by Scheidegger et al. (2015), the authors presented a review to describe and compare different failure models for water distribution pipes and the estimation of their failure rate (Eisenbeis (1994); Gustafson & Clancy (1999); Pelletier (2000); Le Gat (2009); (Economou, Kapelan, & Bailey, 2008; Kleiner & Rajani, 2010; Le Gat, 2009; Røstum, 2000; Scheidegger, Scholten, Maurer, & Reichert, 2013; Watson, Christian, Mason, Smith, & Meyer, 2004)) . Failure rate is a generally used metric to mathematically express failure models, and it is explained as a function of time expressing the probability density per unit of time that a failure will occur within an infinitesimally short time after a certain time (Scheidegger et al., 2015; Trotter, 2017).

Kleiner & Rajani (2001), also presented a review of statistical models for predicting water main breaks. They introduced the following classification and some of the models: (1) deterministic models: time-exponential models, time-linear models, (2) probabilistic multivariate models: proportional hazard models, accelerated lifetime models, time dependent Poisson model, and (3) probabilistic single variate models: cohort survival models, Bayesian diagnostic model, Semi-Markov process and Break Clustering.

In order to obtain accurate results from these deterioration and/or failure models, the quality of the data plays a major role. In the articles by Scheidegger et al. (2013) and Scheidegger et al. (2015), three limitation of the data are presented: 1) right censoring, 2) left truncation and 3) survival bias (See Figure 2.1).

- Right censoring: As long as there are pipes in service, then the data is right censored. This corresponds to the time since the last failure or construction until the end of the observation window. Pipes without recorded failures until the end of the observation period must not be excluded from the analysis.
- Left truncation: this happens when a pipe was installed before the beginning of the observation period (or window). As a consequence, it is not known how many failures occurred before the recording period.
- Survival bias or absence of replaced pipe data: used to indicate those pipes that were replaced but were not recorded in the data, in order to keep this as a representation of the current status of the network.

These properties are illustrated in Figure 2.1:

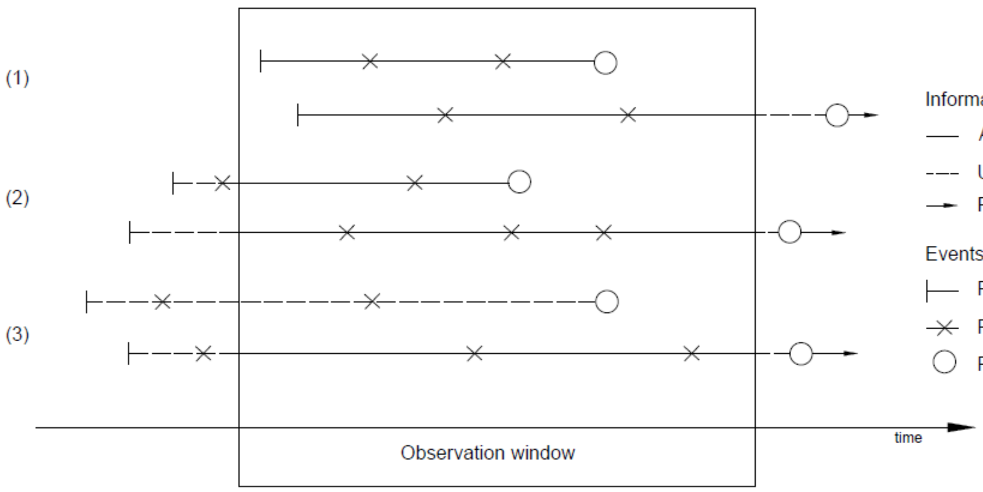


Figure 2.1 Common data situations for model calibrations (adapted from Scheidegger et al. 2013). Three scenarios with different data availabilities: (i) All failures of the pipes are recorded and data of replaced pipes remain in the data set; ii) Failures before are not recorded, the number of failures per pipe is unknown; iii) The total number of failures per pipe is unknown and data of replaced pipes is unavailable

These limitations must be taken into account to obtain realistic results. Scheidegger et al. (2013) and Carrión et al (2010) presented examples considering these properties.

2.5 Failure and the defects that may cause it

Classification of sewer failures are resumed in two categories: structural and hydraulic failures (Anbari et al., 2017; Kley & Caradot, 2013). Structural failures are any failure that affects the components on the structure of the network (erosion, corrosion, deformation and collapse). Hydraulic failures are referred to those failures that cause problems in the foulwater flow, either by reducing the capacity of the pipe or increasing the flow rate (leakage and blockage) (Anbari et al., 2017).

Collapse, is considered the severest structural failure in a pipe (Anbari et al., 2017). The process to structural failure is determined in three stages (WRC, 1983):

- Stage 1:an initial defect is formed
- Stage 2: deterioration process originates due to the defect
- Stage 3: structural failure occurs

Considering the impact created due to stage 1, it is important to understand the characteristics that may cause more vulnerability to the pipes.

Nevertheless, keeping track of collapse events is difficult due to the risk aversive strategies that most administrations have (van Riel, Langeveld, Herder, & Clemens, 2014), and therefore, to the lack of recorded data. Therefore, it is also important to understand the processes or prior failures, that can be classified in stage 2, and that may lead to the structural failure. As mentioned in the introduction, the loss of watertightness induces vulnerability to the pipes which may lead to washing of soil particles, creation of voids and damage to the pipe's bedding and lateral support, and finally the chance of collapse (WRC, 1983).

Watertightness means that exfiltration or infiltration may not occur to the pipe. Although this failure does not contemplate that the structure is not functional, the fact that it occurs involves a series of consequences that affect not only the stability of the pipe but also has impact in the operation and maintenance of the network. Water tightness is also part of the requirements of the standard NEN-EN 752-2 stablished for sewers (Korving, 2004). The defects that lead to this failure are reviewed in this section.

Infiltration is defined as the unwanted flow that results from an ingress of water into the sewer system. Infiltration is most often related to high groundwater levels, but there are other occasions where it may occur due to storm events or due to leaking water mains in the proximity of the sewer pipes (Davies, Clarke, Whiter, & Cunningham, 2001; NEN, 2011). On the other hand, exfiltration corresponds to the escape of foulwater from the sewer pipes into the surrounding ground and takes place during dry weather (Desilva et al., 2005; NEN, 2011). It is assumed that when groundwater can infiltrate, foulwater also can exfiltrate under given circumstances (Vollertsen & Hvitved-Jacobsen, 2003).

Some of the consequences that may arise due to the event of infiltration are related to the migration or washing of soil into the pipe, creating voids or air cavities in the bedding of the pipe which may affect the pipe's stability and lead to a collapse (Desilva et al., 2005). Also, infiltration has as consequence the reduction of the designed hydraulic capacity of the pipes, due to the amounts of additional water into the system, as well as increasing costs of the foulwater treatment of the additional flow (Abraham, Wirahadikusumah, Short, & Shahbahrami, 1998; Cardoso, 2008; NATO, 2004).

On the other hand, exfiltration may lead to the loss of fine aggregates of the surrounding soil, which may cause settlement problems, often accompanied with cracks, and the probability of later occurrence of other problems like subsidence or collapse (Anbari et al., 2017; Desilva et al., 2005). Exfiltration is often of untreated sewage which might contain high levels of suspended soils, pathogenic microorganisms, pollutants, oxygen-demanding organic compounds, oil and grease and others. This affects the water quality of the groundwater, surrounding lakes, streams, and is a risk to the health of those people who live nearby and a threat to the aquatic life (Amick & Burgess, 2000).

In order to avoid these consequences from happening, it is important to identify those defects that potentially allow the occurrence of this failure. In the ASCE Manual 'Existing Sewer Evaluation and Rehabilitation', infiltration is defined as the water that enters a sewer system from the ground through cracked or broken pipes, displaces joints and improperly made connection (ASCE, 1983). The Environmental Protection Agency of the United State in 'The White Paper on Rehabilitation of Wastewater Collection and Water Distribution Systems' indicated "significant percent of infiltration in any collection system is the result of service connection defects such as cracked, broken or open-jointed pipes" (EPA, 1991). Authors like Fenner (1990), identified that most infiltration happens trough pipe joints. Cardoso (2008) wrote in her study, that cracks and fissures allow both the occurrence of infiltration and exfiltration. This argument is supported by Burn et al. (1999), were the authors mention that cracks may function at any time, releasing sewage (exfiltration) or allowing groundwater to enter the sewer (infiltration). Desilva et al. (2005), believe that most of the gravity sewers are installed with leaks in the joints, causing future settlements that are accompanied with cracks, void creation in the surface bedding, further displacement of the joints, breaks, deterioration of the pipe wall and further disturbing of the stability of the pipe (Davies et al., 2001). Furthermore, Davies et al. (2001) identified the importance of sewer joints and their sealing material to ensure water tightness.

To illustrate a bit how these defects can lead to losing the watertightness, the different stages of a cracked pipe and a pipe that suffered subsidence are presented in Figure 2.2, based on the situations of rigid pipes (concrete, clayware and brick) described in the (WRC, 1983).

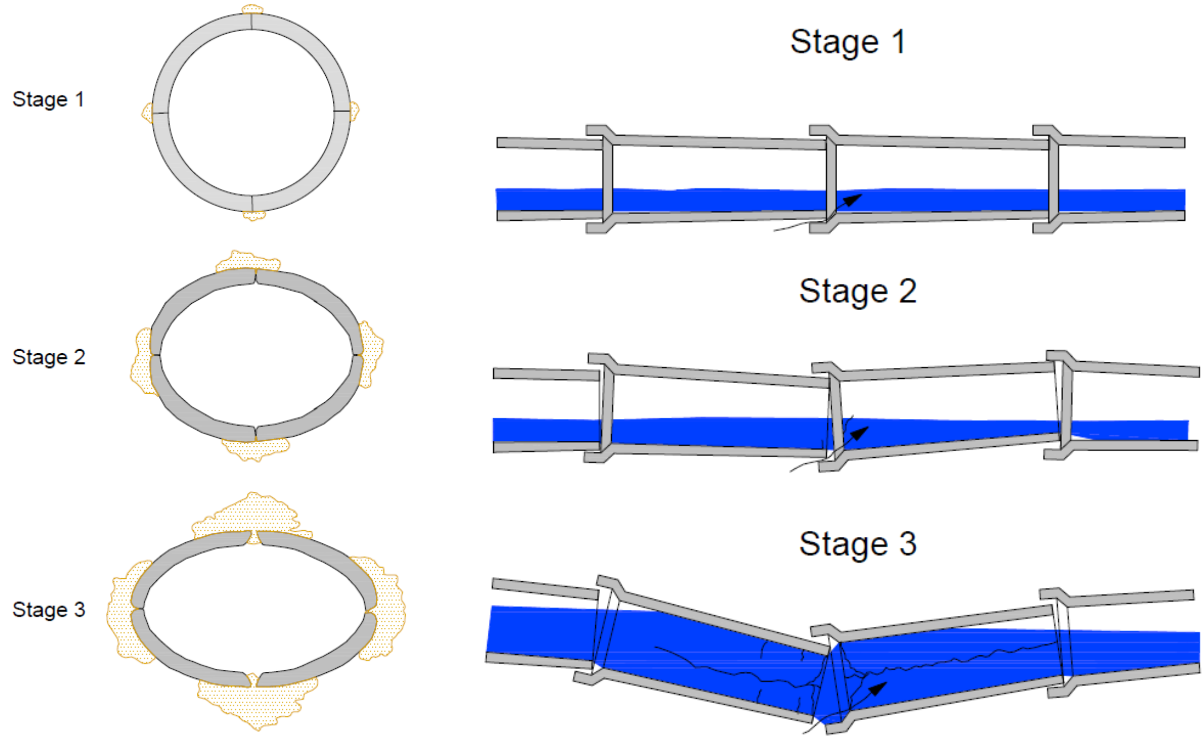


Figure 2.2 Left: different stages of a cracked rigid pipe. Right: subsidence of rigid pipes (adapted from WRC, 1983)

For the different stages of a cracked rigid pipe, the stages mean:

- Stage 1: Loss of watertightness. crack may be caused by bad laying practice or overload of the pipe. At this stage the pipe remains supported and in position by the soil surrounding the pipe.
- Stage 2: Soil particles are washed, leading the side support to be lost. Cracks may increase, deformation will start. Probabilities of collapse increase.
- Stage 3: Pipe moves outwards and soffit to drop: The side support is lost. Once deformation exceeds 10%, the pipes is likely to collapse.

For the subsidence of rigid pipes, the stages mean:

- Stage 1: gap at joint or at lateral connection. Watertightness is already lost. Fine soil may be washed inside the pipe
- Stage 2: Loss of soil support, allows the pipe to drop, opening joints and increasing the inwash of soil.
- Stage 3: Joint displacement causes cracking of pipes: Process accelerates and subsidence occurs which may cause cracking, deformation, and possible collapse

Wolf et al. (2006), presented the case study of the city of Rastatt in Germany, where defects that might induce exfiltration were assessed. Similar to the already mentioned defects, the study identified joint displacement, cracks, breaks and improperly installed connections as the main ones.

In view of all this information, and the defects coding according to NEN 3399 presented in Table 2.1, the following Table 2.2 aggregates the defects that may potentially cause the loss of water tightness that were found in the literature.

Table 2.2 Defects that potentially cause the pipes to lose watertightness

Code	Description
BAB	Cracks
BAC	Break
BAH	Defective connection
BAI	Intruding sealing material
BAJ	Displaced joint
BAN	Porous pipe (concrete only)
BAO	Soil visible through defect
BAP	Void visible through defect
BBF	Infiltration
BBG	Exfiltration

2.6 Pipes characteristics that might make it more vulnerable

This section presents a review of some studies and authors that have seek the main characteristics of the sewer pipes that influence more their structural deterioration. It is important to notice that these characteristics are case specific and cannot be considered generic truth. Nevertheless, the fact that some of these characteristics are common for several cases, gives a hint to managers on which possible characteristics may add more vulnerability to their network.

Ana et al. (2009) reviewed the influences of the physical characteristics of the pipes on the structural deterioration of the sewer system of Leuven (Belgium), using a logistic regression. They concluded that age, material and length had a higher influence on deterioration.

Ana & Bauwens (2010) presented a list with the factors known to have an influence on pipe structural deterioration. These factors were divided in four categories: Physical, Environmental, Operational and Construction factors. Table 2.3 presents these factors.

Table 2.3 Factors by Ana and Bauwens (2010) that influence sewer structural deterioration

Physical factors	- Pipe age - Pipe shape - Pipe size - Sewer depth - Sewer length	- Sewer material - Sewer slope - Sewer type - Joint type - Joint material
Environmental factors	- Groundwater level - Infiltration / exfiltration - Presence of trees	- Soil/backfill type -Traffic and surface loadings
Operational factors	- Sediment level - Sewage characteristics	- Maintenance and repair strategies
Construction factors	- installation method	- Standard or workmanship

Carvalho et al. (2018) presented the results of a study using three different statistical variable selection algorithms (mutual information indicator, random-forest built-in measures and the stepwise search approach) to identify the most relevant factors for to predict sewer deterioration. The following factors were considered in the analysis: length, age, diameter, slope, material, upstream depth, downstream depth, basin and zone. Based in the data set used, the authors concluded that the age is the most important factor to predict deterioration. The different methods used also ranked the length as one of the most important factors to predict failure. The other factors' ranking varied depending on the method that was used (Carvalho et al., 2018).

Davies et al. (2001) presented a review of factors influencing pipe deterioration of rigid sewer pipes. The authors classified the factors in three categories, as presented in Table 2.4

Table 2.4 Factors by Davies et al (2001) that influence structural deterioration and collapse of rigid sewer pipes

Construction factors	- Installation methods - Standard of workmanship - Sewer size - Sewer depth - Bedding material and type	- Sewer pipe material - Joint type and material - Pipe section length - Connections
Local external factors	- Surface use - Surface loading - Surface type - Traffic characteristics - Water main burst/leakage - Ground movement	- Maintenance of other buried services - Groundwater level - Infiltration/Exfiltration - Soil/backfill type - Root interference
Other factors	- Sewage characteristics - Use of inappropriate maintenance method	- Asset age - Sediment level - Surcharge

Fenner & Sweeting (1999) used a two-stage hierarchical model to conclude about how to distinguish the parts of the sewer system that needs more attention. With the use of a two-stage hierarchical model (GIS analysis and Bayesian model), the authors concluded in their study, using information of UK networks, that some of the characteristics of the pipes that are more prone to failure include long lengths, small diameters, shallow depths, slack to moderate gradients and foul sewers.

Hawari et al. (2017) with the use of integrated fuzzy analytical network process (FANP) and Monte Carlo simulation techniques developed a condition assessment model for pressurised and gravity sewer pipes. In this analysis, factors affecting the pipes deterioration were reviewed (pipe material, depth, length, age, diameter, bedding factor and street category). The authors concluded that age, followed by length were the factors with the most impact on deterioration. On the other hand, other factors like depth, diameter, and groundwater were identified as moderately sensitive.

3 Research Design

3.1 Objective

The objective of this research is to identify the influence of different characteristics on the failure probability of sewer pipes.

3.2 Research questions

In order to achieve this objective, the following main research question has been formulated:

"What is the influence of different characteristics on the probability of failure of the sewer pipes?"

To help answer this question, the following sub-questions have been developed:

1. *What defects can lead to sewer structural failure?*
2. *What physical characteristics make sewer pipes more prone to fail/deteriorate?*

3.3 Scope

To achieve the research objective, analyses of the sewer inspections records of the Dutch municipalities of Breda and Almere were carried out.

As mentioned in chapter 2, decision making regarding sewer assets is still based on intuition, for which decision making for maintenance and management, lacks argumentation.

Considering the important role risk-based decisions play on the optimisation and prioritisation of any work, an assessment of the influences of characteristics on the probability of failure of the sewer pipes is proposed.

In order to tackle the managing situation of the aging sewer systems in Europe, frameworks and instructions were built to assess the condition of the components of the drainage systems, and to provide a guideline procedure to assure the quality requirements that these assets need (NEN, 2015a). From 2004, the European Standards EN 13508-1 Investigation and assessment of drain and sewer systems outside buildings -Part 1, and EN 13508-2 Research and assessment of the external sewers - Part 2: Coding system for visual inspection, became the technical norms for the assessment and management of the sewer systems of the member countries of the European Union. In The Netherlands, the NEN 3398 and NEN 3399 are further elaborations of the above-mentioned standards, respectively, concerning the Dutch situation (flat and low lands, the existent sewer networks and the method used in the NPR 3220 (1994) which was the guideline for the management of the outdoor drainage that was previously used) (NEN, 2015a). Considering this, only the inspections that were recorded from 2004 up to date will be analysed. Previous inspections will not be contemplated.

Unfortunately, not many administrations keep a complete record of the pipes that failed or collapsed. This hinders the assessment of existing sewers, the implementation and development of predictive models, and the evaluation of their effects in maintenance policy (Wirahadikusumah et al., 2001). This was the case in both Breda and Almere, as there were no enough records of collapses in either of them to carry a complete statistical analysis.

Neglecting prior failure events can have disastrous consequences (Eiseführ et al., 2010) and, as explained in sections 1.1 and 2.5, loss of watertightness is considered a prior failure to collapse, since it induces vulnerability to the pipes and potentially causes its collapse. Therefore, the failure to be studied in this thesis is defined as the loss of watertightness.

Watertightness considers that no event of exfiltration nor infiltration occurs in any degree. Exfiltration refers to when water leaves the pipe during periods of hydraulic surcharge, while infiltration causes inflow of groundwater and soil particles into the pipe (Gokhale & Graham, 2004). However, loss of watertightness, is not measured nor registered by municipalities. For this reason, the defects that may be prone to cause this are reviewed and assessed. These defects were identified in section 2.5, Table 2.2.

For all these reasons, the present research uses the defects that induce loss of watertightness as a proxy for collapse. Hence, pipe failure is defined to occur when the pipe 'is not watertight' and the defects that might cause loss of watertighness are considered a proxy for loss of watertightness, as illustrated by Figure 3.1. A proxy is a way of measuring an objective of interest or attribute, and are used when it is difficult to select a natural attribute, or event that can be easily counted or physically quantified to measure the objective, in this case a failure of sewer pipes (Keeney & Gregory, 2005).

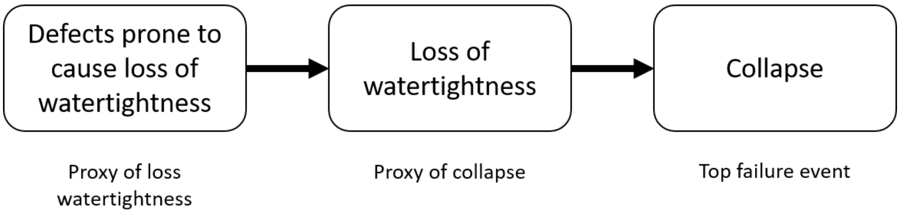


Figure 3.1 Proxy approach for the failure analysis

4 Methodology

The research approach used in this study to answer the research questions, is illustrated in Figure 4.1. Further explanation of each step is provided below.

	Activity	Output
1. Data collection	1.1 Literature review →	Sub-question 1: defects that lead to structural failure (loss of watertightness)
	1.2 Data gathering	
	1.2.1 Data processing and cleansing	
2. Data analysis	2.1 Descriptive statistics	
	2.1 Survival analysis with proposed methods	
3. Data results	3.1 Descriptive statistics	
	3.2 Results analysis →	Sub-question 2: Pipe characteristics that make it more prone to failure
	3.3 Discussion, conclusions and recommendation →	Research question

Figure 4.1 Research approach

4.1 Data collection

The aim of this step is to collect the data and information required to do the analysis.

4.1.1 Requirements for case study selection

In order to select the case studies to be used during the analysis, some requirements were stablished beforehand:

- Sewer network managed by the municipal authorities
- Sufficient number of inspections (at least 10 years of inspections). In case of using Dutch cases, the majority of inspections are expected since 2004 that the new standards (NEN 3398 and NEN 3399) started to apply
- The selected municipalities require to have inspections of more than 50% of the total length of their gravity-flow sewer system network.
- Double inspections are considered an advantage, but are not a compulsory requirement.

The case studies selected were initially chosen due to the already stablished contact between the municipalities and the Sanitary Engineering department from TU Delft. Three municipalitie s were contacted before reviewing if they satisfied all the requirements. Only Breda and Almere were selected.

The selected municipalities do not have enough records of collapses to carry out a complete statistical analysis. For this reason, a proxy of the failure was considered (see section 3.3 for further explanation).

4.1.2 Failure proxy

Due to the lack of records of collapse in the studied cases, a prior failure that may lead to this event was selected to be studied. Loss-of-watertightness, as found in the literature, induces vulnerability to the pipes that can cause collapse events. Nevertheless, as it was explained in section 3.3, this failure is not measured, reason why the defects that potentially cause this to happen to the pipes were reviewed and selected based on the NEN 3399 coding. The review of this defects was done in the literature review, section 2.5.

With this step can be answered the sub-question 1: *What defects can lead to sewer structural failure?*

4.1.3 Data gathering

Visual inspection data and reports were requested to Breda and Almere. This information was provided as inspection files that come in a format '.RIB' and '.RIBX', readable with the software *Kikker*, a Geographical Information System (GIS) for the management of sewer systems developed by Riodesk (Riodesk, n.d.).

*Kikke*r allows to locate the sewers, collect information from the visual inspections, and investigate the sewer conditions, among some more functions. This software is based on the European Standard EN 13508-2, therefore, information extracted about the pipes, manholes and inspections can be interpreted based in this standard (Riodesk, n.d.).

All information from gravity flow sewer pipes regarding the pipes, the manholes and the interpretation of the inspections was extracted from Kikker in formats '.csv' and in '.shp' (for location).

The '.shp' files were used to locate the pipes and create maps with the help of ArcGIS.

The '.cvs' file were loaded in MATLAB to process, select and clean the data to be analysed. These steps are hereby explained:

1. Load-data set: Load information extracted from *Kikker* (pipes, manholes, inspections) in format '.csv' into MATLAB.
2. Process-data: this step is to processes the original files obtained from *Kikker* and extract and organize what is relevant for the research. To do so, the information is converted into a '.mat' file, and organised in tables, so it is easier to further use in MATLAB.

   The extracted information is organised in three tables, one with the information about the pipes, one of the manholes and one about the inspection results. The naming of the variables provided by the municipalities is similar or in some cases the same, which makes it easier to process in MATLAB.

   The pipes table has the following information: pipe id, initial manhole, final manhole, installation year, system type, shape, initial invert level, final invert level, height [mm], width [mm], length [m], material, street name, soil type, above ground material. The number of pipes that are processed in Breda are 42078, and in Almere are 25490, including those that have more than one inspection.

   The manholes table has information about: manhole id, invert level, latitude, longitude. The total amount of manholes processed from Breda's dataset are 45115 manholes, and from Almere's are 20863.

   The inspections table has the following information: file id, inspection id, inspection date, initial manhole id, final manhole id, pipe id, axial begin location [m], axial final location [m], defect type, condition class, first characteristic, second characteristic. The amount of inspection files received from Breda are 773 and from Almere are 688. Each inspection file has several inspection ids, which correspond to the different examined pipes.

3. Selected-Data: This step is for selecting the information about pipes and inspections that will be analysed. All information is translated from Dutch to English.

   For the Breda dataset, information about pipes that are not gravity sewer pipes is removed. The number of pipes in this step are 32227 in Breda. The pipes received from Almere are all gravity sewer pipes for which this amount is the same as the previous step.

   For the selected inspections, only those that were recorded from 2004 are considered, since then started the implementation of the EN 13508-1 (NEN 3398). The number of selected inspection files are 579 in Breda and 628 in Almere.

4. Clean-Data: This step it to remove double counting on the data, eliminate inconsistencies, and deals with unreliable data.

   In the pipes table, those that lack some information, or is not realistic, have this characteristic replaced with 'NaN'. This allows to analyse the other characteristics of the pipe, but ignore those that are not correct. This step was required for some reported invert levels, for around 163 pipes' installation dates from Breda and 2041 from Almere, and for 19260 pipes' above ground materials from Almere that are reported as 'unknown'. Furthermore, if the pipes were reported as circular shape, but have a width different from the height, they are corrected and classified as 'semi-elliptical'.
   In Almere there were some manholes with incorrect coordinates (outside the country), and some lines were connecting these manholes to the urban area and were being reported as pipes. These lines (pipes) were removed from the data.

   Breda provided some pipes without inspections. In this step, only those pipes that have a supporting inspection are left and cleaned. A total of 32226 pipes from Breda's data base are left in this step and 22239 from Almere. These pipes include those that have more than one inspection. If counted only as unique pipes (regardless of the number of inspections), for Breda the inspected pipes that were studied are 19166 and for Almere 21346.

   In the cleaned-inspections table, double counting was reviewed. Those inspections, with the same pipes, same data, but different file id, were counted only once. The total amount of inspected files for Breda are 561 and for Almere 612.

   Another table was generated in this step: Merged inspections. This is for reporting the occurrence of defect type per pipe only once. For instance, if a pipe has reported two observations of BAB (cracks), one of BAF (surface damage), three of BAJ (displaced joint) and one BBA (roots), the table shows that this particular pipe showed evidence of BAB, BAF, BAJ and BBA. This allows to classify in an easier way those pipes that had reported defects that may lead to the occurrence of loss of watertightness.

4.2 Data analysis

Once the data was collected and gathered, it was possible to identify the explanatory variables that were available in the datasets. The characteristics that were selected for the analysis are: pipe material, pipe shape, pipe diameter, pipe length, sewer system types and above ground materials.

First, an analysis of descriptive statistics was carried out about the information available from the datasets, of the municipalities, once selected and cleaned. This included analysis regarding the networks, their pipes' characteristics (age, installation years, amount per material, etc.), the influence of the defects under study and the location of the defected pipes.

Next, a survival analysis was carried out to infer the influence of the different characteristics on the probability of occurrence of a defect (that cause loss of watertightness). This analysis was done with two different methods: a non-parametric and a semi-parametric survival model. These methods are explained below.

This survival analysis considered the defects identified in Table 2.2 that potentially cause loss of watertightness, which are: Cracks (BAB), Break (BAC), Defective connection (BAH) , Intruding sealing material (BAI), Displaced joint (BAJ), Porous pipe (concrete only) (BAN), Soil visible through defect (BAO), Void visible through defect (BAP), Infiltration (BBF) and Exfiltration (BBG).

As explained before, these defects are used as a proxy for loss of watertightness, which at the same time is used as proxy for collapse. Based on this, the analysis considered the study of the influence of the different characteristics per defect, as well as for the aggregation of these defects. The later means, that any pipe that had at least one of the aforementioned defects was selected as defective and analysed.

4.2.1 Descriptive statistics

The goal of this section is to identify the amount of data that is available, and the data limitations of the main characteristic of the networks under study. This is applied to the factors that are measured and are reported in the inspections datasets which are: pipes' materials, diameters, length, shape, above ground material, and sewer system type. Also, the different installed km in each decade per variable were analysed, in order to identify differences in the ages, preferred techniques or characteristic of the elements of each variable.

This step is also for reviewing the amount of data available per studied defect and to locate the areas of interest.

4.2.2 Survival analysis

In order to identify the influence of the characteristics on the probabilities of defect occurrence, and the characteristics with the highest influence, a non-parametric estimator of survival function is proposed, which considers left truncation and right censoring. Results are complemented and compared with the analysis of the Cox proportional hazard model. These methods are explained in this section.

4.2.2.1 Non- parametric estimator of survival function

Survival analysis allows to describe, measure and analyse events in order to predict about an individual's survival as well as 'time-to-event' (Liu, 2012).

Survival function is the probability of an individual surviving beyond time x, meaning that the event under study might be experienced by the individual after time x. This function is defined as:

$$S(x) = Pr(X > x) \qquad (2)$$

The survival function is the complement of the cumulative distribution function, when X is a continuous random variable: $S(x) = 1 - F(x)$, where $F(x) = \Pr\ (X \leq x)$ (Klein & Moeschberger, 2003).

Survival analysis consists of parametric, semiparametric and non-parametric models (Klein & Moeschberger, 2003). In the literature, different survival function estimators may be found. One of the most known non-parametric survival estimators is the Kaplan-Meier or the Product Limit estimator, of which the resulting estimate is a step function that has observed event times (Diez, n.d.; Klein & Moeschberger, 2003).

Other estimator is the Nelson-Aalen estimator of the cumulative hazard, which compared to the Kaplan-Meier has better sample size performance (Klein & Moeschberger, 2003). As this estimator is based only on right censored data, Pan & Chappell (1998) proposed and extension of it to consider left-truncated data, the Extended Nelson Estimator (ENE).

Using the ENE, and its derivative the Extended Survival Estimator (ESE), Carrión et al (2010) evaluated failure probabilities of pipes from a water supply network. The authors used these estimators in order to be able to accommodate the right censoring and left truncation of the data, which is common in pipes data sets. Based on this, and considering that sewer networks also have left truncated and right censored data, the use of these extended estimators seems adequate for the analysis of this research.

Given a data set n of left truncated and right censored observations $\{(x_i, y_i, \delta_i)|\ i = 1, 2, \dots, n\}$, where x_i represents the entry time at which each element of the data set enter observation, y_i is the time-to-failure or censuring time of the i-th observation and δ_i is the censoring indicator that takes value 1 when there is a failure and 0 otherwise. The cumulative hazard function can be estimated as the summation for every failure time $y_i \leq t$ of the ration between the number of failed pipes at time y_i (denoted as $d_{(y_i)}$) and the number of individuals at risk or under observation at the same time (denoted as $r_{(yi)}$) (Carrión et al., 2010; Trotter, 2017). The ENE is expressed as:

$$ENE = \tilde{\Lambda}(t) = \sum_{i=1}^{n} \frac{1_{\{y_i \leq t, \delta_i = 1\}}}{\sum_{j=1}^{n} 1_{\{x_j \leq y_i \leq y_j\}}} = \sum_{y_i \leq t} \frac{d_{(y_i)}}{r_{(y_i)}} \qquad (3)$$

Based on equation (3) it is possible to derive the ESE (Carrión et al., 2010; Klein & Moeschberger, 2003; Trotter, 2017) as follows:

$$ESE = \tilde{S}(t) = e^{-\tilde{\Lambda}(t)} = e^{-ENE} \qquad (4)$$

Considering this information, in order to assess the influence of the pipes' characteristics, these estimators are applied and plotted using the dataset of the case studies. To accomplish this, MATLAB is employed to generate scripts that can process and analyse the already organized data. The results of this assessment are presented in Chapter 6. The advantage of using these method relies on the fact that the influence can be identified graphically without making any assumption on their behaviour (Trotter, 2017).

Once the data is in place to use the aforementioned estimators in MATLAB, some considerations have to be made before modelling. These estimators consider the pipes' age, which is estimated with the entry time, in this case that refers to the installation year of the pipes, and the end time, which is equivalent to the time-to-event (time-to-failure in case of occurrence of defect or time-to-end-of-study in case of right censoring). Differently from the water supply systems, which have information about the occurrence of events or failures, sewer systems only have information about the condition of the pipes at the time of inspection (Scheidegger et al., 2015). Due to this, there is no available information to estimate precisely the time that defects occurred. Therefore, to estimate the hazard age, or survival age an assumption must be made, that the time-to-event is the time of inspection. Although, the exact prediction of time-to-event might not be obtained with the dataset of the case studies, an estimation of the effect of the pipe's characteristics on the probability of occurrence of a defect can be found.

Furthermore, this assumption requires to check those pipes that have more than one inspection. This is done in order to make sure that no replacement has been done without updating the installation year. This action is carried out in MATLAB, by comparing the pipe id, the installation date and the inspection dates. If the same pipe has different inspections dates, but show the same installation year, it is assumed that no replacement has been done.

The analysis of the non-parametric estimator is performed per defect (that may cause loss of watertightness) and for the aggregation of all of them. This analysis is done for all pipes of the two networks and for each or the characteristics under study.

4.2.2.2 Cox Proportional hazard model

Cox is used to evaluate the different characteristics that may affect the outcomes of groups of time-to-event through the hazard function (Klein & Moeschberger, 2003). This model is a semiparametric model that assumes the hazard rate $h(t \mid z)$ at time t for an individual with risk vector z (p x 1 vector of a set of predictors $z_1, z_2 \dots, z_k$), is proportional to an unknown baseline hazard function h_0 (Klein & Moeschberger, 2003; W. Pan & Chappell, 2002), and is formulated as follows :

$$h(t \mid z) = h_0(t)\, e^{z\beta} \tag{5}$$

Where β is a column vector of regression coefficient such that β_k is a measure of the effect of k predictor or covariate over the instantaneous probability of failure (Carrión et al., 2010; George, Seals, & Aban, 2014; W. Pan & Chappell, 2002). Moreover, $h_0(t)$ is an arbitrary baseline hazard rate, and is the non-parametric part of the model. This baseline hazard can be interpreted as the hazard function for the population of subjects with $z = 0$. The parametric part of the model is $z\beta$ (Klein & Moeschberger, 2003; Zhang, 2005).

The key hypothesis of this model is the proportionality on the hazard rate, where the baseline hazard function depends on the time, but the covariates do not (Carrión et al., 2010).

In other words, the Cox model assumes that if we look at two individuals with covariate values z and z^*, the ratio between the hazard rate is a constant, which explains why the hazard rates are proportional (Klein & Moeschberger, 2003) :

$$\frac{h(t \mid z)}{h(t \mid z^*)} = \frac{h_0(t)\exp[\sum_{k=1}^{p} \beta_k z_k]}{h_0(t)\exp[\sum_{k=1}^{p} \beta_k z_k^*]} = exp\left[\sum_{k=1}^{p} \beta_k (z_k - z_k^*)\right] \tag{6}$$

The proportional hazard model can also be interpreted as the relative risk associated with one unit increase in z_k while the value of another covariate is being held fix, then,

$$RR = \frac{h(t \mid z_k + 1)}{h(t \mid z_k)} = \frac{h_0(t) e^{\beta_k (z_k+1)}}{h_0(t) e^{\beta_k (z_k)}} = \frac{e^{\beta_k (z_k)} e^{\beta_k}}{e^{\beta_k (z_k)}} = e^{\beta_k} \tag{7}$$

Namely, this means that e^{β_k} is the risk ratio (RR) related to one unit increase in z_k (Zhang, 2005).

In order to estimate the relative risk, and inference about β must be made. The inference of β is based on a partial (or conditional) likelihood, which corresponds to the product of partial likelihoods estimated for each failure time (Klein & Moeschberger, 2003).

Let $t_1 < t_2 < \cdots < t_D$ denote the ordered times of events, $z_{(i)k}$ be the *k-th* covariate associated the individual whose failure times is t_i, and $R(t_i)$ designate the risk set or individual still under study prior to time t_i. The partial likelihood can be estimated as follows (Carrión et al., 2010; Klein & Moeschberger, 2003):

$$L(\beta) = \prod_{i=1}^{D} \frac{\exp[\sum_{k=1}^{p} \beta_k z_{(i)k}]}{\sum_{j \in R(t_i)} \exp[\sum_{k=1}^{p} \beta_k z_{jk}]} \tag{8}$$

Once inferred the β, the risk ratio can be obtained. Being $\exp(\beta_k)$ the risk ratio for a one unit increase in z_k, when RR>1 ($\beta > 0$) increasing values of z_k are associated with increased risk and shorter survival times. On the contrary, for predictors z_k with RR<1 ($\beta < 0$) increasing values of z_k are associated with reduced risk and longer survival times (Vittinghoff & Glidden, 2012). In other words, the risk ratio explains the influence of the covariate on the occurrence of the event. This can be expressed in the percentage risk reduction, or risk increase, as follows:

For RR<1 → (1-RR) • 100%

For RR>1 → (RR-1) • 100%

Among the different advantages that the Cox model has, one is that it is possible to take into account subjects that were not exactly observed for the same period of time and even if the event under study did not take place at the end of the investigation. A second advantage is the fact that the continuous variables do not require to be discretise (Bugnard, Ducrot, & Calavas, 1994). A third advantage is that there is no need to assume a specific form of the baseline hazard function h_0 to be able to evaluate the impact of the covariates in the hazard function (Røstum, 2000). Despite all these advantages, the use of this model is very restricted by its proportionality hazard condition (Bugnard et al., 1994).

For this study, the analysis of this model was done with MATLAB and its function *coxphfit*, which allows to estimate the β coefficients. This function considers right censoring for the data, but not left truncation. Nevertheless, one of the inputs of the function is 'time-to-event', which has been determined for this research starting from 2004 (similar to the ESE analysis). With this, the database is characterised with left truncation, and is implemented in the analysis. The MATLAB function returns the β per covariate, as well as the loglikelihood and other statistic information of β like the standard errors, z-value, the p-value, among some others.

To obtain the risk ratio for all the covariables in MATLAB, the baseline used is the mean of the observation of predictor variables, so the hazard rate at z is $h(t|\, z) = h_0(t)\exp(\beta * (z - mean(z)))$. This does not affect the coefficient estimate.

The risk ratio can also be expressed as the function of several covariates. Being this the case, it means that the risk ratio explains the increase of one unit in z_k given that the other covariates remain constant. Mathematically, this means:

$$RR = \frac{h(t \mid z_k + 1)}{h(t \mid z_k)} = \frac{h_0(t)e^{\beta_1(z_1+1)+\beta_2(z_2)+\cdots+\beta_j(z_j)}}{h_0(t)e^{\beta_1(z_1)+\beta_2(z_2)+\cdots+\beta_j(z_j)}} = e^{\beta_1} \qquad (9)$$

Considering this expression, univariate interpretations of the risk ratio were done, starting with the estimation of RR based on the sewer system type and then adding one by one the rest of the covariates under study (materials, shape, diameter and length) per municipality, like this:

- Sewer system type
- Sewer system type + materials
- Sewer system type + materials + diameter
- Sewer system type + materials + diameter + length
- Sewer system type + materials + diameter + length + shape

Once the risk ratios are obtained and interpreted, it must be validated if it is appropriate to use the Cox PH model for the different covariates of this study in each municipality. To do so, a check of the proportional hazard assumption was done using graphical validation methods. One validation method was done using the survival graphs obtained with the ESE function explained in the previous section (4.2.2.1) and comparing them in their version $-\ln(-\ln ESE)$ over the different covariates and their states (Kleinbaum & Klein, 2013) for the two municipalities. The different curves should be approximately parallel and should not intersect, although it is noted that in early observed time point a bit of crossing could be due to noise in the survival estimates and not particularly to the non-accomplishment of the proportionality (George et al., 2014).

A second graphical approach of the Cox model to assess the proportional statement is based on the observed vs the expected plot (Kleinbaum & Klein, 2013). This assessment is done using the graph obtained with the Cox hazard function and with the ENE function explained in the previous section (4.2.2.1).

5 Case studies

5.1 Breda

Breda is a city located in the south of the Netherlands, in the province North Brabant. It became officially a city in 1252.

The municipality has an area of 128.68 km^2 and a population estimate of 183,456 (Wikipedia, 2018b).

According to the Municipal Sewer Plan (GRP, in Dutch Gemeentelijk Rioleringsplan), the construction of the first underground sewer started in 1863, with the construction of masonry arched canals that used to discharge waste and rainwater to the port area. It was only in the 1960’s that a wastewater treatment plant was built and in 1976 that started the construction of separate drainage system for the storm water and the wastewater (Gemeente Breda, 2009).

As explained before, there was an expansion of the sewers in the Netherlands in 1950’s, and Breda was no exception. Figure 5.1 presents the decades of construction of the combined water, foulwater and stormwater sewers. The combined water sewers installed in 1950’s and 1960’s, with an average life expectancy of 60-80 years, are theoretically estimated by the municipality to be the first to be replaced in the coming decade, expecting a replacement volume of approximately 15 km/yr (Gemeente Breda, 2013). As it can be seen for the stormwater sewers, their construction has taken place mostly in the last three decades, for which they are considered relatively young. Although separating the foul water and storm flow is a costly plan, the municipality continues decoupling the pipes, depending mainly on the pace of urban renewal (about 1% area per year), or wherever old pipes require replacements new separate pipes area installed. Unfortunately, separating the water flows on existing private land is costly and complicated, not only technically speaking, but also it can be socially objected. For these reasons the municipality is implementing this in a slow pace, whenever suitable opportunities arise (Gemeente Breda, 2009).

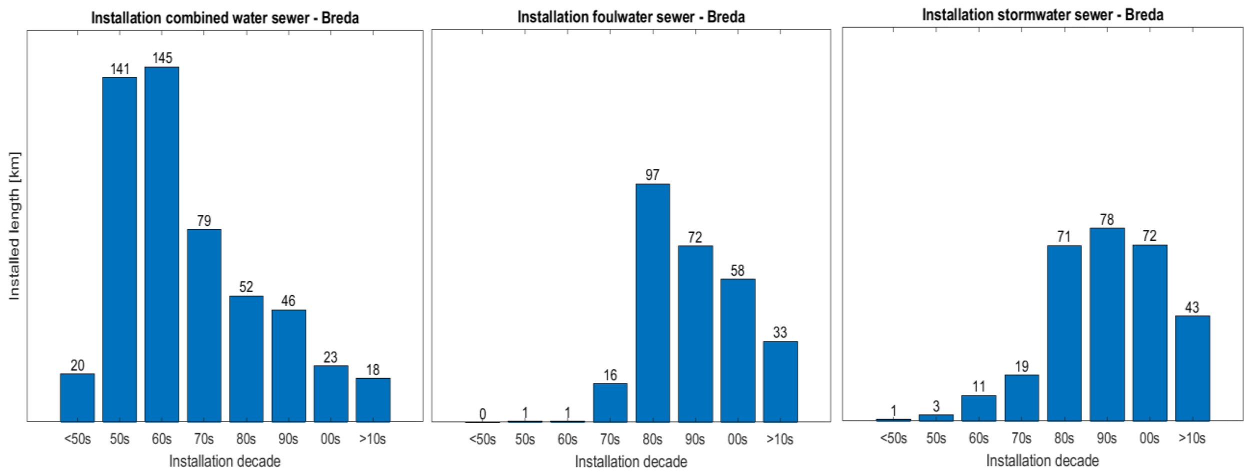


Figure 5.1 Installed km of combined water, foulwater and stormwater pipes every decade in Breda

Sand is the predominant soil type in the municipality. The location of the gravity flow sewer pipes that have been inspected are presented in Figure 5.2. In this figure combined, storm water and foulwater pipes are presented within the area of Breda.

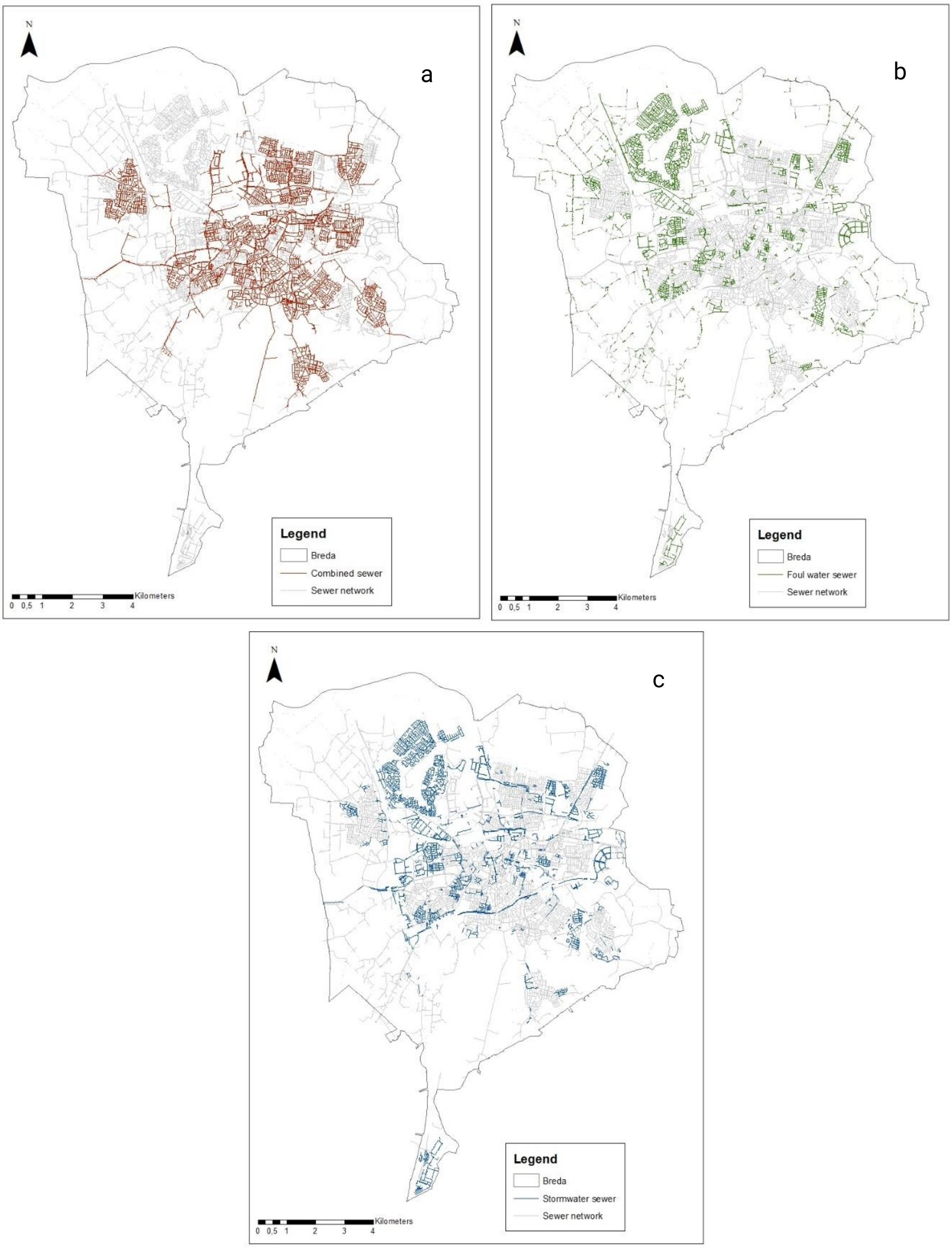


Figure 5.2 Gravity flow sewer pipes in Breda
(a: combined sewer, b: foulwater sewer, c: stormwater sewer) (own illustration)

More than 1382 km of underground pipelines are in Breda, of which approximately 1100 km are gravity sewers (Gemeente Breda, 2013). Table 5.1 presents the summary of structural elements present in the Breda sewer's system (Gemeente Breda, 2009).

Table 5.1 Structural elements in Breda's sewer network

Number of manholes (inspection chamber)	Approx. 25,000 pieces
Length foulwater sewer	Approx. 280 km
Length stormwater sewer	Approx. 315 km
Length combined sewer	Approx. 531 km
Length pressure drainage (drukriolering)	Approx. 133 km
Length pressure pipes (persleidingen)	Approx. 44 km
Length infiltration pipes (drainageleidingen)	Approx.28 km
Number of rainwater discharge points	Approx. 175
Number of pumping stations	580

Of the approximately 1100 km of gravity sewer, nearly 12,500 pipes (about 600 km) of pipes have been inspected since 1993 (about 55%), which serves the municipality to obtain an estimation of the condition index. Of these inspected pipes, nearly 25% (3057 pipes) percent has more than 1 inspection (about 127 km). Figure 5.3 presents the location of the pipes inspected more than once.

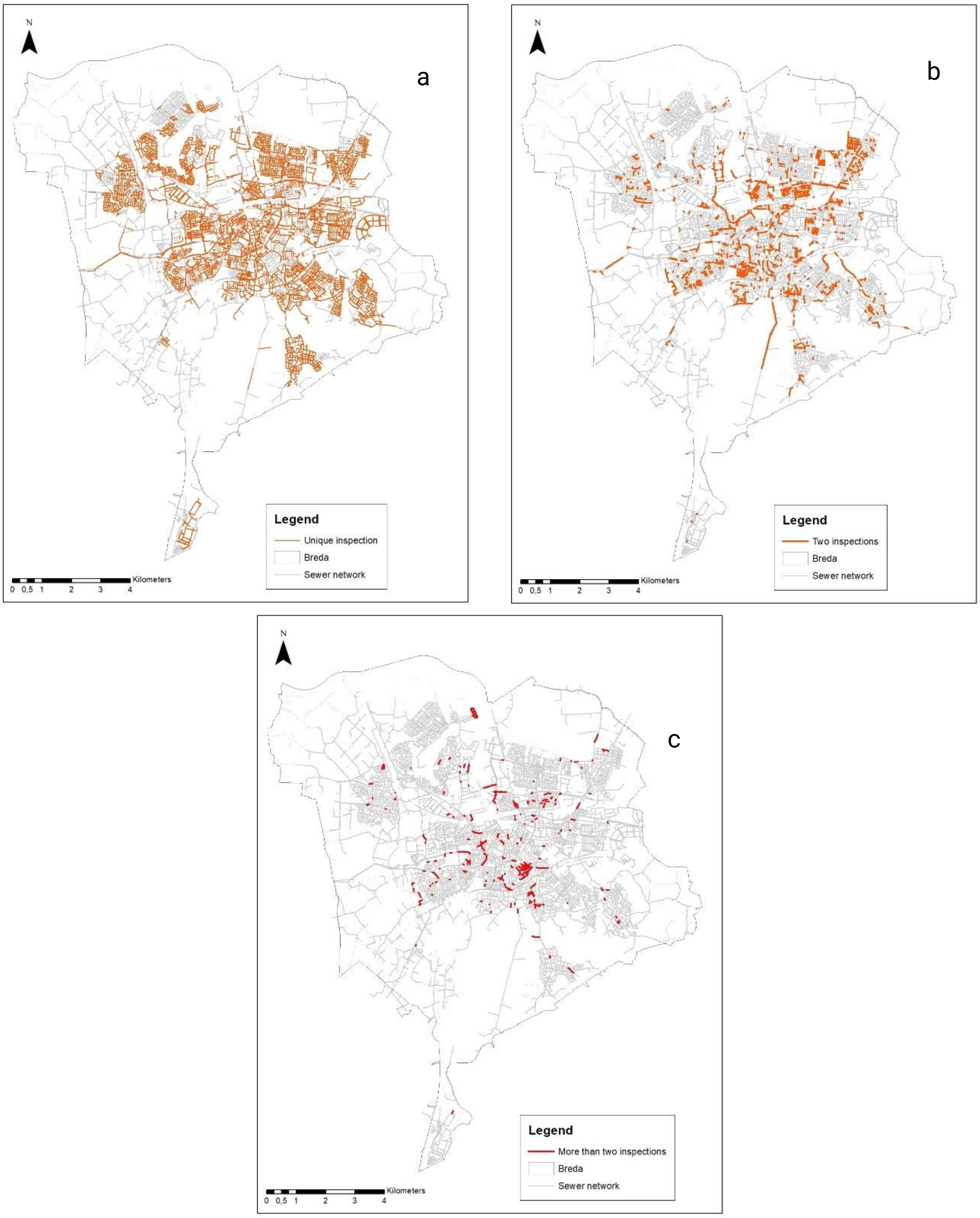


Figure 5.3 Location of gravity sewer pipes with different number of inspections in Breda (a: pipes with only one inspection, b: pipes with two inspections, c: pipes with more than two inspections) (own illustration)

5.2 Almere

Almere is a city located in in the province Flevoland in The Netherlands. Almere is a planned city, that was built on a polder, reclaimed from the sea between 1959 and 1968 (Gemeente Almere, n.d.). It has a total area of 24.77 km^2 and 205,596 inhabitants (July 2018) (Gemeente Almere, n.d.; Wikipedia, 2018a).

The oldest sewers in Almere date from 1976. Due to the fact that the city is young, the sewer system has been installed since the construction of the city separating the foulwater flows from the stormwater flows. Therefore, all household and industrial foulwater is discharged separately from the stormwater (Gemeente Almere, 2011). The foulwater is eventually transported to be treated at the WWTP, which is a responsibility of the Water Board. Stormwater is directly discharged locally to the surface water (Gemeente Almere, 2011).

Although the sewer system is young (about 40 years), its estimated lifespan of about 60 years is reduced due to the constant occurrence of subsidence (settlements). This is caused mainly by a strongly varying soil where soft layers of clay and peat soil alternate with firm sand ridges (Gemeente Almere et al., 2017). As a consequence, pipes connections might get loose, or foulwater may not be able to flow in the desired direction under free flow, causing possible blockages of the pipes. Stormwater sewers suffer less the effect of subsidence, as relatively clean water flows through then and the chance of blockages is therefore less (Gemeente Almere et al., 2017).

Figure 5.4 presents the amount of km installed of foulwater and stormwater pipes in the last decades.

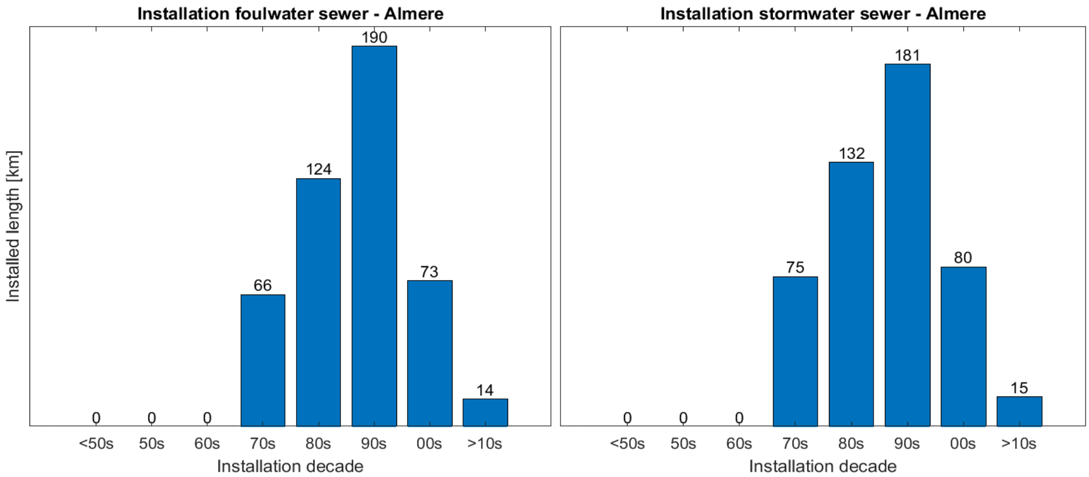


Figure 5.4 Installed km of foulwater and stormwater pipes every decade in Almere

Of the approximately 1800 km of sewer network, 1100 km are gravity sewer. The location of the gravity sewer pipes that are being assessed in this research are presented in Figure 5.5. The summary of the main structural elements of the network in Almere are presented in Table 5.2.

Table 5.2 Structural elements in Almere's sewer network

Number of manholes (inspection chamber)	25,000
Length foulwater sewer	Approx. 546 km
Length stormwater sewer	Approx. 553 km
Length combined water sewer	Approx. 295 m
Length pressure drainage (drukriolering)	Approx. 133 km
Length pressure pipes (persleidingen)	Approx. 36 km
Length infiltration pipes (drainageleidingen)	Approx.1800 km
Number of pumping stations	Approx. 300

Figure 5.5 Gravity flow sewer pipes in Almere
(a: foulwater sewer, b: stormwater sewer) (own illustration)

Of the gravity pipes, approximately 984 km (89% of the total length of foul water and stormwater sewers), have been inspected since 1994. Inspections are assigned every 12 and 36 years since the installation of the pipe (Gemeente Almere, 2011). There is approximately 14 % of the gravity pipes that have been inspected more than once. These pipes are illustrated in Figure 5.6. In the analysed inspection files, only one pipe registered more than two inspections, this pipe is not illustrated.

Figure 5.6 Location of gravity sewer pipes with different number of inspections in Almere
(a: pipes with only one inspection, b: pipes with two inspections) (own illustration)

6 Results

6.1 Descriptive statistics

The data available per case study was analysed.

The number of defects identified in the different visual inspections per municipality are illustrated in Figure 6.1. This analysis was based on the inspections after 2004. Those defects that are in green in the plot, are those that were identified as prone to cause loss of watertightness.

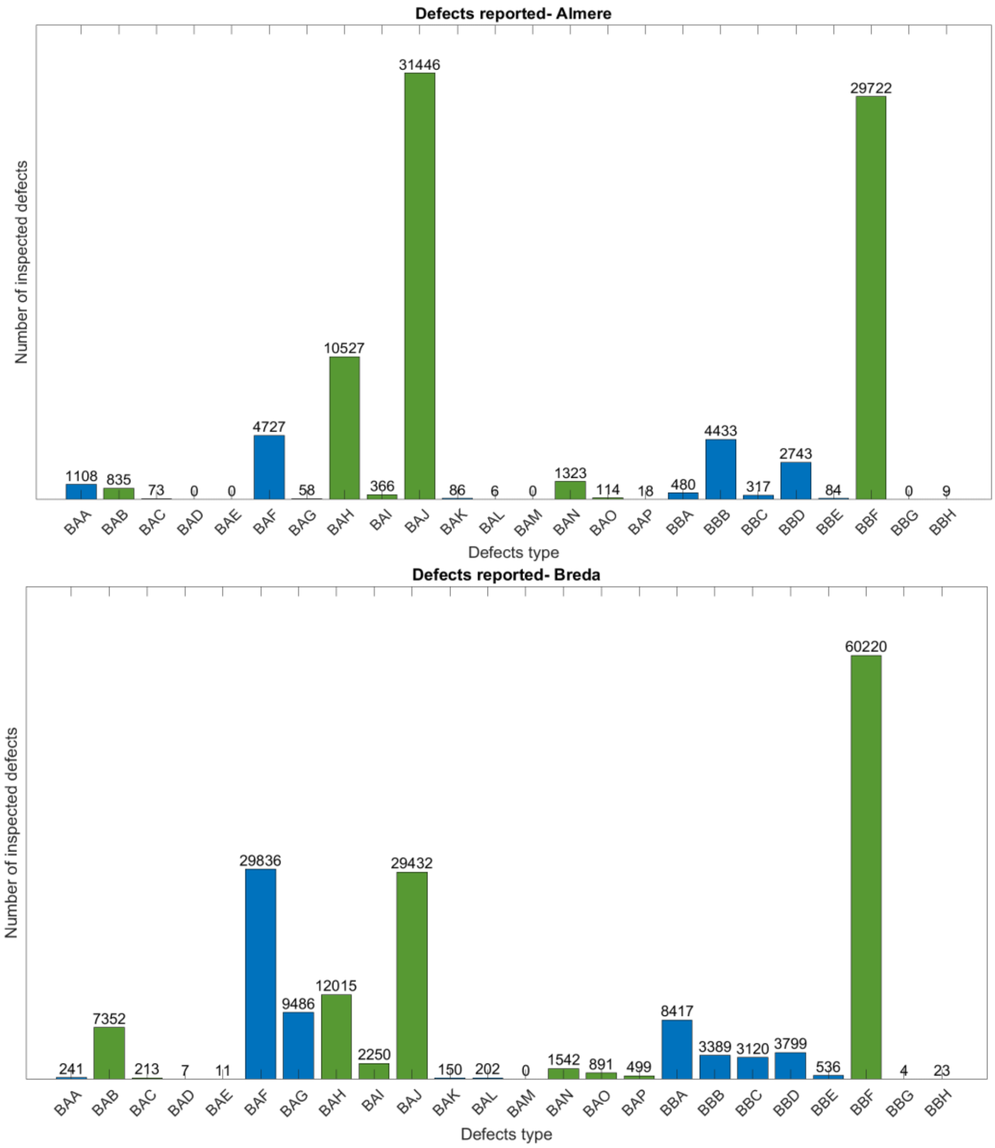


Figure 6.1 Defects reported in Almere and Breda

The comparison of the two municipalities and the records of the defects that may cause loss of watertightness in the studied pipes, are summarised in Table 6.1.

As it may be seen in Figure 6.1 in Almere the defect that has more records since 2004 on the pipes that were studied is displaced joint (BAJ) with 31446 reports, followed by infiltration (BBF) (29722 reports) and defective connection (BAH) (10527 reports). Defect exfiltration (BBG) considered as part of the defects under study was never reported in Almere. The reason behind this may be because pipes are cleaned and emptied before doing any inspection, and with the

CCTV it is not possible to see if exfiltration is occurring or not. Therefore, this defect will not be considered in the study. The remaining defects had the following records of events (in ascending order): Void visible through defect (BAP) (18 records), break (BAC) (73 records), soil visible through defect (BAO) (114 records), intruding sealing material (BAI) (366 records), cracks (BAB) (835 events), and Porous Pipe (BAN) (1323 records).

Table 6.1 Records of defects under study

Defects	Almere	Breda
BAB	835	7352
BAC	73	213
BAH	10527	12015
BAI	366	2250
BAJ	31446	29432
BAN	1323	1542
BAO	114	891
BAP	18	499
BBF	29722	60220
BBG	0	4

As for the case of Breda, infiltration (BBF) is the most reported defect since 2004 (60220 events), followed by surface damage (BAF) (29836 records), Displaced joint (BAJ) (29432 events) and defective connection (BAH) (12015 records). Surface damage (BAF) is not one of the defects under study for potential cause of loss of watertightness, for which is not further reviewed.

Similar to Almere, in Breda defect exfiltration (BBG) was only reported 4 times. Therefore, this defect will not be studied, as there are not enough records of this event to conclude objectively. Of the other defects under study, break (BAC) is the next one to have less records (213), followed by void visible through defect (BAP) with 499 records of events, and soil visible through defect (BAO) with 891 events. The remaining defects under study had the following number of records: 1542 `for porous pipe (BAN), 2250 for intruding sealing material (BAI), and 7352 for cracks (BAB).

Table 6.2 presents the number of pipes per sewer type that were assessed in the analysis.

Table 6.2 Pipes that were analysed per municipality

Type	Breda		Almere	
	L [km]	N [-]	L [km]	N [-]
Foulwater sewer	153	3712	467	10380
Stormwater sewer	163	4117	483	10952
Combined sewer	457	11337	0.295	14
Total	773	19166	950	21346

There are only 295 m of combined sewer in Almere. As it is not significant enough to compare with the other types (only 14 pipes transport combined water), this sewer system type will not be considered in the survival analysis of Almere.

As for the other two systems, it can be said that in Almere the studied length of foulwater and stormwater sewers is similar.

In the case of Breda, 59% of the studied network are combined water pipes. The separated sewers, foulwater and stormwater, have a similar length, corresponding to 20% of the network for the foulwater pipes and 21% the stormwater pipes.

Further review on the materials (Figure 6.2), it was possible to identify that the majority of pipes that were analysed in the Breda's network are concrete (12714 pipes) followed by PVC (5846 pipes), and that the sum of other pipe materials corresponds to 3% of the total amount of studied pipes. Only concrete, lined concrete, reinforced concrete, and PVC will be analysed with the survival models for Breda, as there is not enough information about the other materials to conclude objectively.

As for Almere, about 10505 pipes of the total network are made of concrete (mainly the storm water pipes) ,10635 are PVC (foulwater sewer pipes), and the sum of the rest of the materials is about 2% of the total amount of studied pipes.

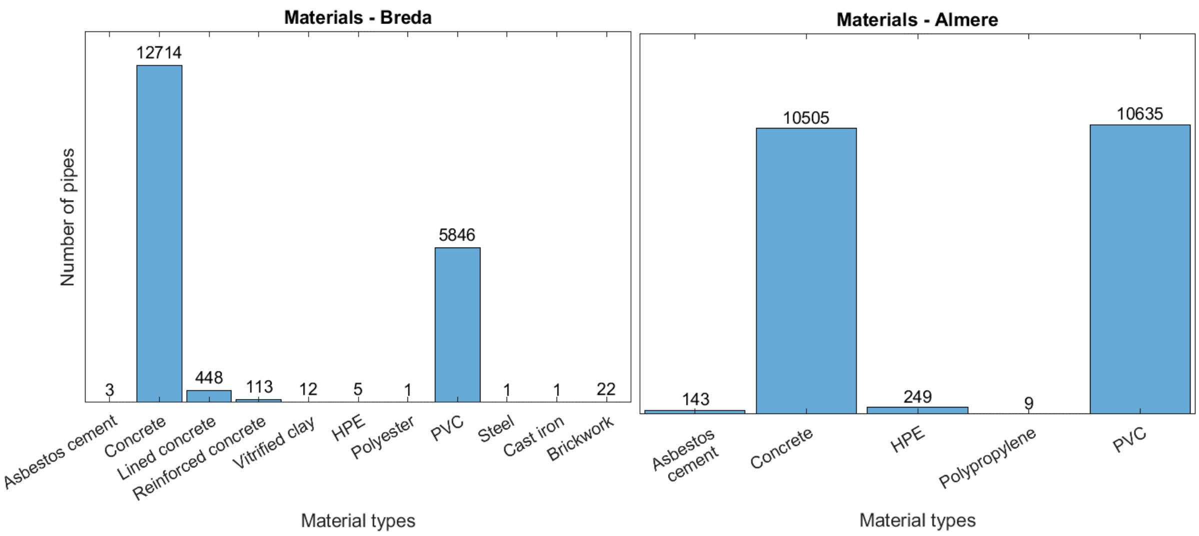


Figure 6.2 Number of analysed pipes per material per municipality

Similarly, the different pipe shapes were checked in the two municipalities.

Figure 6.3 illustrates the pipe's shapes in the municipality of Breda. The circular shape is the most common one (17856 pipes), followed by the egg-shaped (1259 pipes).

As for the case of Almere, all pipes from the dataset are registered as circular.

Regarding the above ground materials of the pipes, the results are presented in Table 6.3 for Breda and Almere

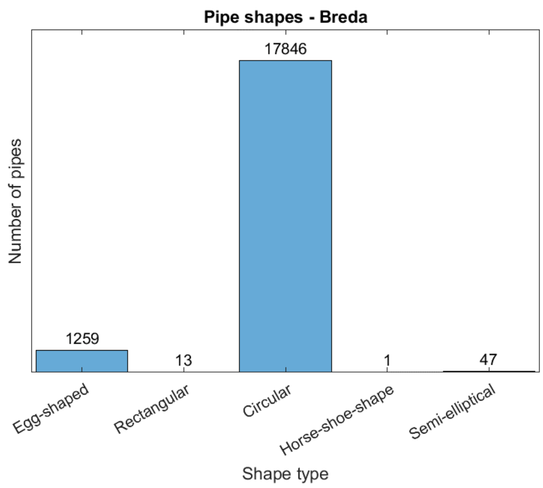


Figure 6.3 Number of analysed pipes per shape

Table 6.3 Above ground material per municipality

Material	Breda	Almere
	N [-]	N [-]
Pavement	10,432	-
Asphalt	3,780	2991
Floor tiles	2,402	847
Green field	2,176	-
Unpaved road	363	1250
Concrete	14	21
Crushed stone	-	36

The most common above ground material reported in the municipality of Breda, for the studied pipes, is pavement, followed by asphalt, floor tiles and green fields.

In the case of Almere Asphalt is the above ground material with more reports in the inspections. This variable, nevertheless, does not have many reports in this municipality. In the studied inspected pipes, 16396 had the above-ground material reported as 'unknown'. Therefore this characteristic is not significant in the analysis of Almere, as there is not enough information to conclude on its influence on the occurrence of defects.

Furthermore, for the continuous variables of the pipes (diameter and length), ranges were stablished to discretise the variables and assess, in a like manner, the number of pipes with such characteristics.

Results of Figure 6.4, show that the majority of pipes in Breda (18488 pipes) have a diameter between 250 and 500 mm, followed by diameters between 22 and 249 mm (8171 pipes).

In the case of Almere, the majority of pipes also have a diameter between 250 and 500 mm (19164).

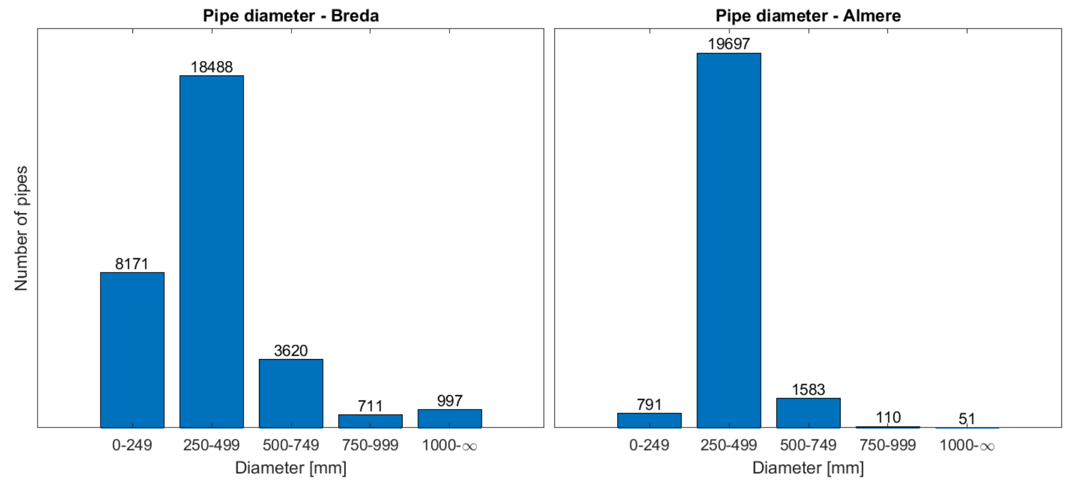


Figure 6.4 Number of pipes per diameter per municipality

Likewise, the length of the pipes was grouped and discretised for the two networks. Figure 6.5 illustrates the number of pipes per ranges of length for Breda and Almere.

The majority of studied pipes in Breda have lengths between 20 and 50 m (12735 pipes), followed by 8088 pipes with lengths between 50 and 100 m.

Similarly, in Almere, the majority of the studied pipes have lengths in the same ranges, with 9418 pipes with lengths between 50 and 100 m, and 8692 pipes with lengths between 20 and 50 m.

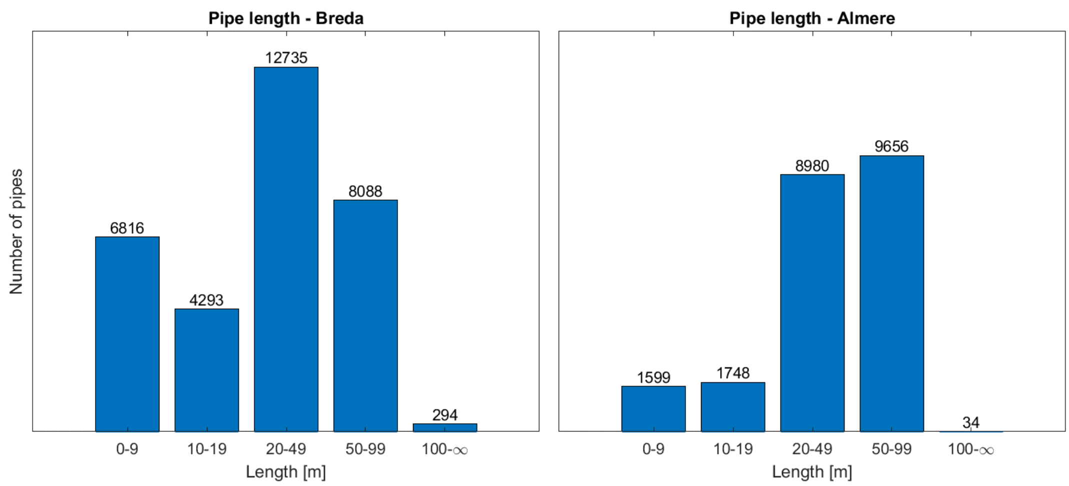


Figure 6.5 Number of pipes per length per municipality

The number of installed km per each element of the variables were also revised per decades, considering the variables under study. Results are shown for Breda in Figure 6.6 and for Almere in Figure 6.7.

In Almere's case, all elements have similar number of elements installed in each decade, which might be explained because the city is relatively new. On the other hand, Breda, reflects big differences between the elements in the type of sewer, the material and the pipe shape. Figure 6.6 evidences the preferred type of sewer until the 70's (combined), the most commonly used material, at least until the 90's (concrete), and that egg-shape pipes were mainly installed in the 50's, but with circular shape being in all decades the most commonly used shape.

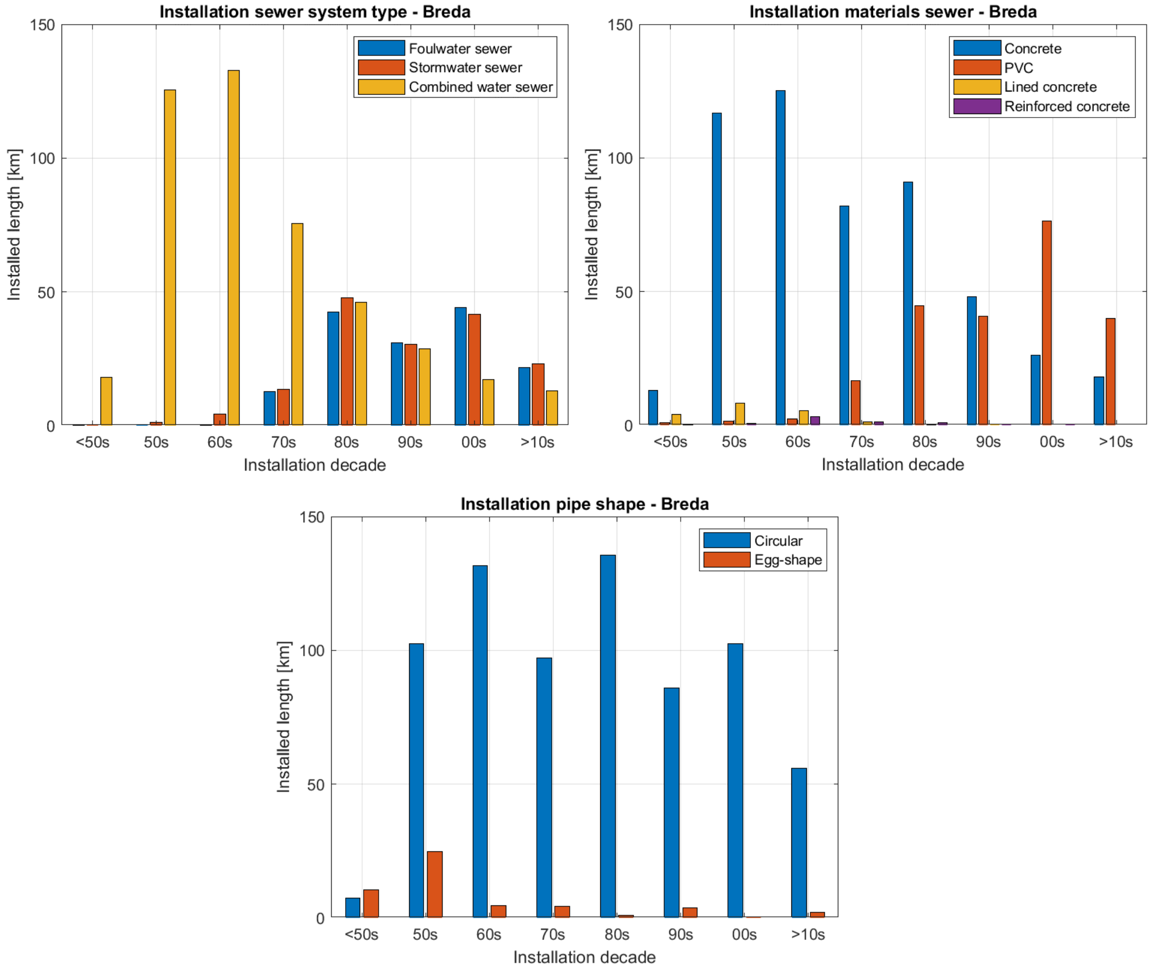


Figure 6.6 Installed length [km] per decade per element of the variables - Breda

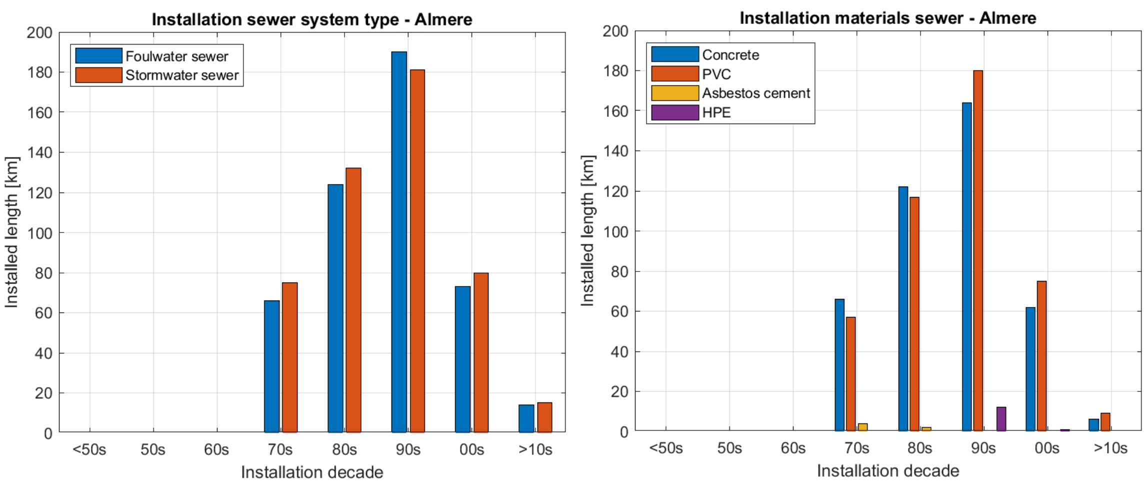


Figure 6.7 Installed length [km] per decade per element of the variables - Almere

6.2 Non-parametric survival analysis

First, a survival analysis for the occurrence of the any of the studied defect that may cause loss of watertightness to the pipes was carried out per municipality. Results are illustrated in Figure 6.8. These curves represent the probability that the pipes have no defects that may cause loss of watertightness at some determined age.

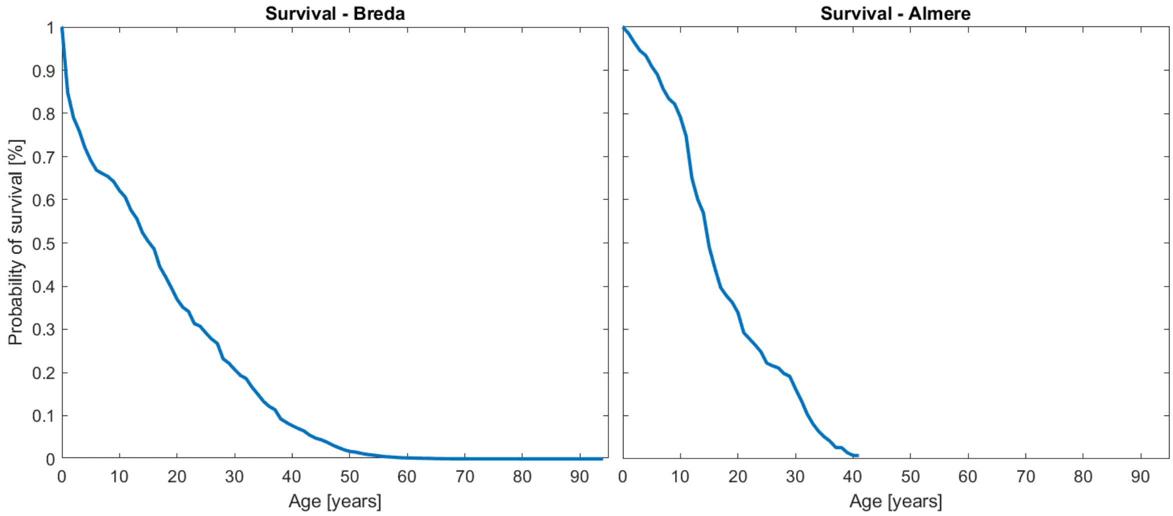


Figure 6.8 Non-parametric survival estimate for aggregate defects

As can be seen in Figure 6.8, for Breda the median survival time is 15 years, meaning that 50% of the pipes have not defects that may cause the loss of watertightness past 15 years. The curve shows an almost immediate sign of deterioration, with a steep slope during the first 6 years. By the time the pipes are 20 years old, they will have a 37% probability of still being watertight. Also, the graph estimated that by the time the pipes are 60 years old, almost all would have at least one defect that may potentially cause the loss of watertightness.

In Almere's case, the slope is also steep, meaning defects that cause loss of watertightness occur early on the pipes' lifespan. It is important to notice that Almere's sewer system is younger than Breda's, being the oldest pipe installed about 43 years old. The median survival probability for Almere is about 14.4 years, similar to Breda. There is a 32% of probability that the pipes are watertight at the age of 20. By the age of 40 most of the network pipes would have at least one defect that may cause them the loss of watertightness.

This analysis was based on the result of aggregating the defects that are under study. To see the effect of each defect on the aggregate curve, a survival analysis assessment was performed to each of the defects and compared to the aggregate one. This analysis is illustrated per municipality in Figure 6.9. For both municipalities, displaced joints (BAJ), defective connection (BAH) and infiltration (BBF) showed a faster reduction of the probability of survival, compared to the other defects.

In the case of Breda, displaced joint (BAJ) shows the strongest effect in the loss of watertightness, which is reflected on the resemblance to the aggregate defects curve. Furthermore, for this municipality, beside the already mentioned defects, the presence of cracks (BAB) also shows relevant deterioration.

Almere's analysis, shows that the defects that potentially cause more loss of watertightness are displaced joint (BAJ) and infiltration (BBF), with a very similar behaviour. These defects are followed in effect by defective connection (BAH) and porous pipes (BAN).

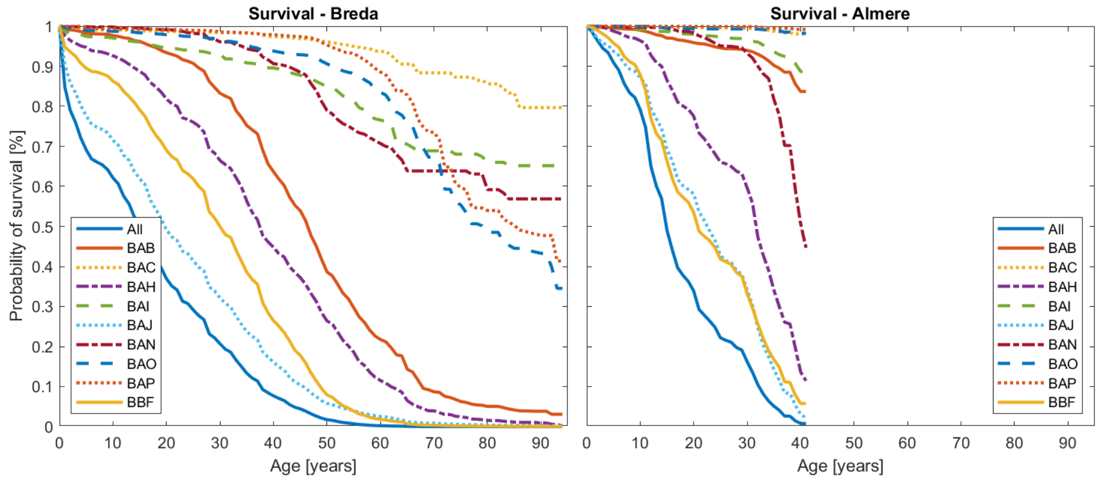


Figure 6.9 Non-parametric survival estimate for all studied defects compared to aggregate curve

6.2.1 The system type

The analysis of the survival estimator regarding the sewer system types are presented in this section for the two municipalities.

- **<u>Breda</u>**

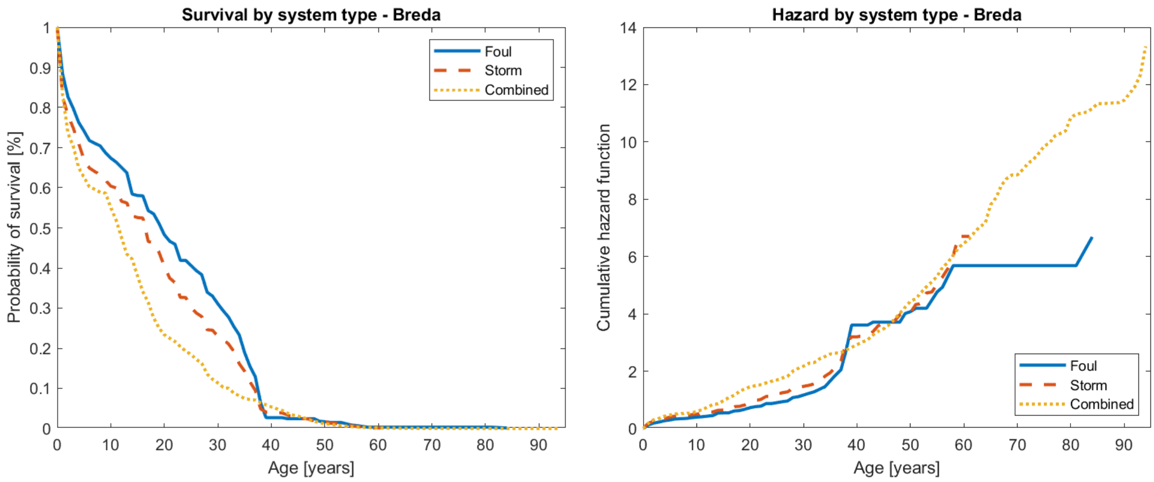


Figure 6.10 Survival probability ESE and cumulative hazard ENE by system type for Breda's sewer

In the case of Breda's network, the combined sewer has a lower survival probability that the foul and stormwater sewers, and the foul water has higher survival than the stormwater sewer. At the age of 10, the probability that no defects that cause loss of watertightness have occurred is 55%, 60% and 67% for the combined, storm and foul water sewers respectively. By the time the sewer pipes have survived 30 years, only 11% of the combined sewer are still defectless as well as is the case for 23% and 31% for the stormwater and the foul water sewers respectively.

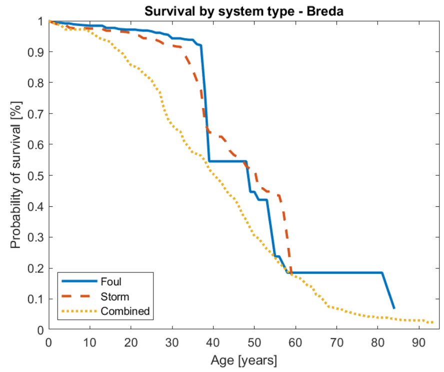
The three curves cross at approximately 25% of probability of survival. After, the curves seem to overlap, with a very low probability (lower than 3%) at approximately 60 years. In the cumulative hazard function curve, it can be seen that after that point, the combined sewer shows a higher risk of defect occurrence, than the other two. By the age of 40 years most pipes are showing that they have at least suffered one defect that may cause the loss of watertight.

To understand the influence of the sewer systems on the loss of watertightness, each of the different defects under study were analysed and are presented for Breda in Table 6.4.

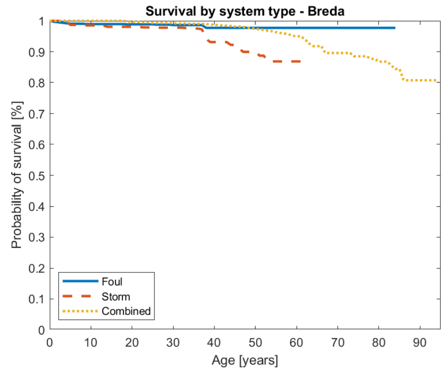
Table 6.4 Comparison of the probabilities of survival influenced by sewer type per defect (Breda)

Survival probability by sewer type per defect (Breda)

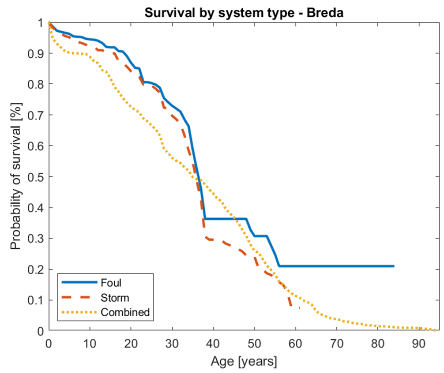
BAB: Crack



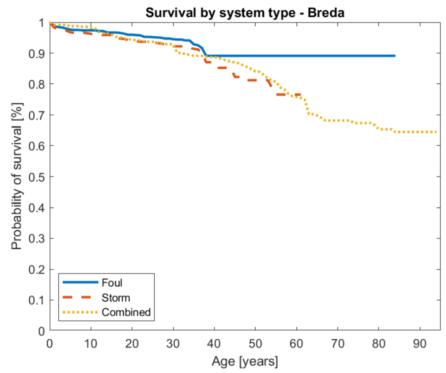
BAC: Break



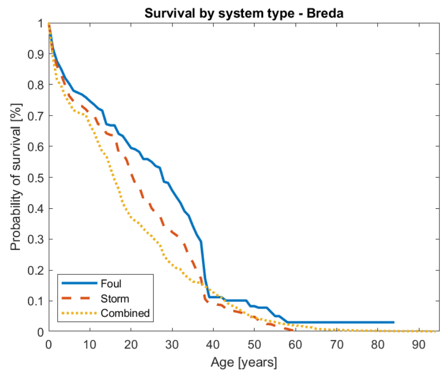
BAH: Defective connection



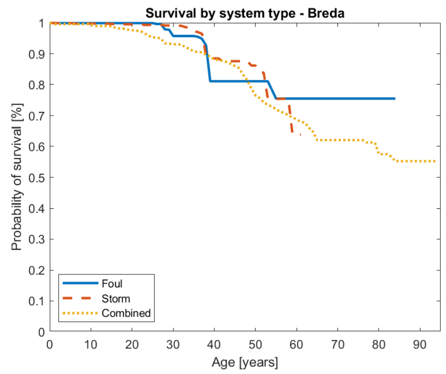
BAI: Intruding sealing material



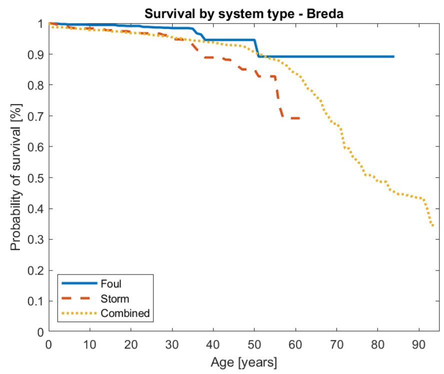
BAJ: Displaced joint



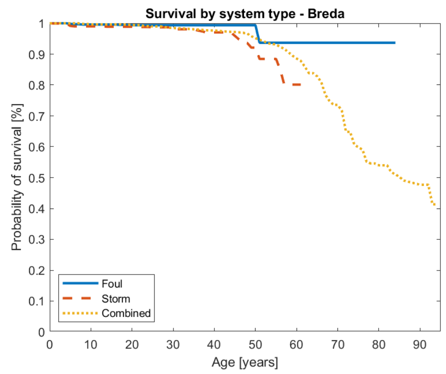
BAN: Porous pipe (Concrete only)

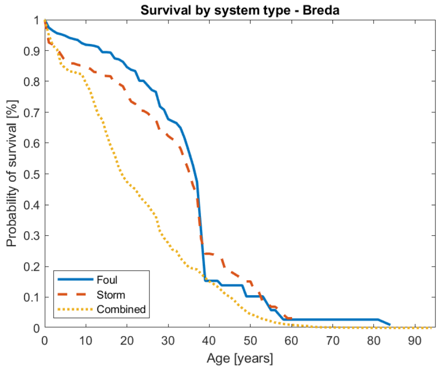


BAO: Soil visible through defect



BAP: Void visible through defect



Survival probability by sewer type per defect (Breda)
BBF: Infiltration


As it can be seen in the different graphs (Table 6.4), the structural defects where the influence of the type of system is more significant on the survival probability are displaced joint (BAJ), infiltration (BBF), defective connections (BAH) and cracks (BAB).

More evidence of infiltration (BBF) was reported on the combined sewer, which have a lower probability of survival with respect to the foul and storm pipes.

For the displaced joints (BAJ), the median survival times is 27 years for foul sewers, 19 years for stormwater and 15 years for combined. For a survival of 60 years, which is the minimal lifespan estimated by the municipality, the survival probability is very close to zero for the three system types. In a like manner, for defective connection (BAH) the median is 36, 35 and 34 years for foul, storm and combined sewer respectively. For this defect, combined sewer shows a lower survival probability up until 35-36 years, where the foul and storm curves show a steeper curve and show lower probabilities than the combined.

- **Almere**

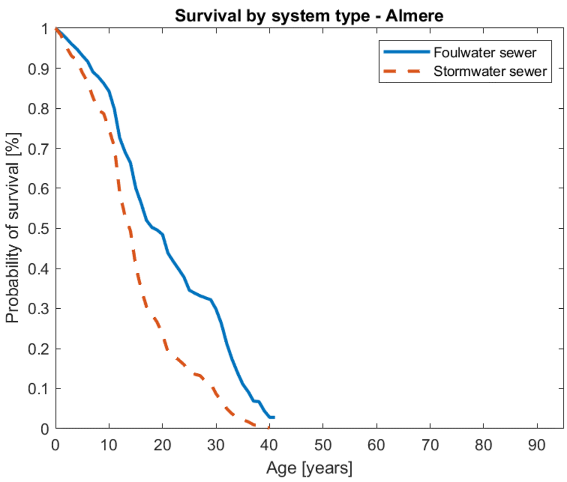


Figure 6.11 Survival probability ESE by system type for Almere's sewer

In the case of the municipality of Almere, the curves show that the foul sewer pipes have a higher survival probability than the stormwater pipes. This means that the stormwater pipes have a higher probability of occurrence of defect that may cause loss of watertightness. As it can be seen the median survival year is 17 years for foul sewers and 12 years for stormwater sewers. Furthermore, survival probability for 20 years is about 48% for foul sewers and 20% for storm sewers.

The analysis on how the sewer system type influences the probability of occurrence per each different defect was also carried out. The comparing graphs can be found in Appendix B.3.

From the defect graphs it is also inferred that defective connection (BAH), displaced joints (BAJ), porous pipes (concrete only) (BAN) and infiltration (BBF) are the defects that have more effect on the loss of water tightness when influenced by the sewer type in Almere. Similar to what was observed in Breda, in Almere also the foulwater sewer has higher survival probabilities than the stormwater sewer in all the reviewed defects.

6.2.2 The pipes' materials

The analysis of the survival estimator regarding the pipes' materials are presented in this section for the two municipalities.

- **Breda**

The ESE analysis with the subgroup of materials of Breda's sewer pipes are shown in Figure 6.12.

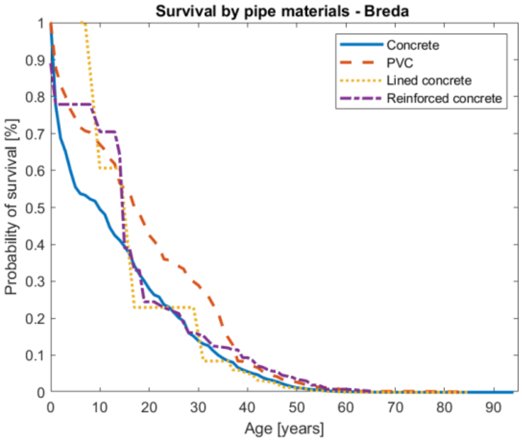


Figure 6.12 Survival probability ESE by materials for Breda's sewer

Comparing concrete and PVC for Breda, concrete has a higher risk of failure because the curve decreases faster. This is also the case for reinforced concrete and lined concrete. For concrete, 28% of the pipes survive past 20 years without losing the water tightness, as for PVC this amount is 42%. The median survival time for concrete pipes is 9.7 years while for PVC is 17 years. Lined concrete and reinforced concrete show a similar survival behaviour, with a median of approximately 14.4 years for lined concrete and of 14.6 for reinforced. As observed in the cumulative hazard curve (see appendix A.1), lined concrete is the one with higher risk of failure, compared to the concrete, reinforced concrete and PVC.

Based on the analysis per defect (see appendix A.4 for the graphs), cracks (BAB), defective connection (BAH), infiltration (BBF) and displaced joints (BAJ) have more effect on the survival probabilities, being the later the one to show a more immediate deterioration per material. PVC pipes show less effect of displaced joint (BAJ) compared to the concrete pipes. As for the case of infiltration (BBF), also concrete pipes are more affected, showing a steep slope in the first 10 years. Reinforced concrete does not show much effect on their survival probability due to cracks (BAB). Defective connection (BAH) affects concrete and PVC similarly up until the latter is about 50 years that the probabilities of the of survival do not decrease in the same speed as the ones from concrete.

The variability of the probabilities of survival influenced by materials are the highest compared with other characteristics. This is the case for the aggregate defects, and for defects cracks (BAB), displaced joint (BAJ), intruding sealing material (BAI) and soil visible through defect (BAO). This suggest that this characteristic has high influence on the probability of occurrence of defects that may cause loss of watertightness.

- **Almere**

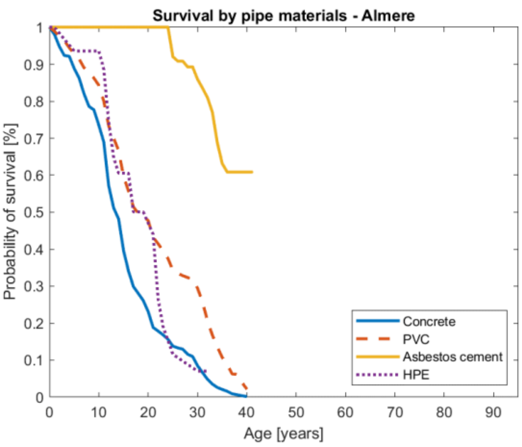


Figure 6.13 Survival probability ESE by materials for Almere's sewer

In the analysis of Almere, the survival curves per material are illustrated in Figure 6.13. Although there are only a few inspected pipes of asbestos cement (143), these showed the higher survival probability.

Considering the materials which are majority in the network (concrete: 10505 pipes and PVC: 10635 pipes), concrete shows a lower probability of survival than PVC. The median survival for concrete is 18.2 years, while for PVC is 17 years. Both these materials, show a survival probability of almost 0% approximately at 40 year, meaning that at 40 years almost all pipes in Almere had had at least one of the defects that may cause loss of watertightness.

Hard polyethylene (HPE), shows a similar behaviour to PVC up to a survival probability of 42% (21 years), where the slope gets steeper and the survival probability decreases fast.

Regarding the defects that have more effect are displaced joint (BAJ), defective connection (BAH) and infiltration (BBF). Displaced joint (BAJ) affects more the concrete, PVC and HPE, showing the first two with a probability close to 0% at 40 years. Infiltration (BBF) shows at 40 years, a survival probability for concrete of almost 0%, for PVC of about 25%, for HPE of 50% and for asbestos cement of approximately 73%.

The survival probabilities influenced by materials vary widely, compared to the influence of other characteristics. This was specially observed for the curves of aggregate defects and for defects like defective connection (BAH) and infiltration (BBF).

6.2.3 Pipe shape

Almere's pipes are all reported as circular. Only the pipe shapes of Breda are analysed:

- **Breda**

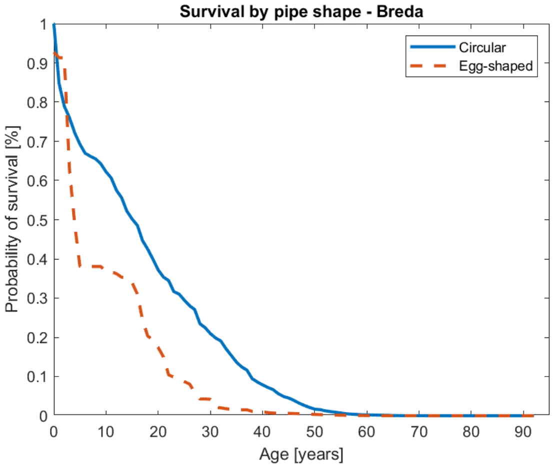


Figure 6.14 Survival probability ESE by pipe shape for Breda's sewer

Circular shape is the most common shape found in Breda's network, with a median probability of 15.1 years. Past 53 years the survival probability for circular pipes is approximately 1%. Egg-shaped pipes show the lowest survival tendency, with a median of 3.9 years and a survival probability of 10% past 22.7 years. This means that the egg-shaped pipes have a higher tendency to have defects that will potentially cause the loss of watertightness than the circular shapes.

In all the reviewed defects, the egg-shaped pipes show the lowest probability of survival. Displaced joint (BAJ) seems to be the defect that affects more immediate the deterioration of the circular shaped pipes. As for the egg-shaped pipes, they seem affected by infiltration (BBF), where a big step can be observed in the first years, that may be related to lack of inspection of this type of pipes. Results for each defect are presented in appendix A.5.

6.2.4 Pipe diameter

The analysis of the survival estimator regarding the pipes' diameter is presented in this section for the two municipalities.

- **Breda**

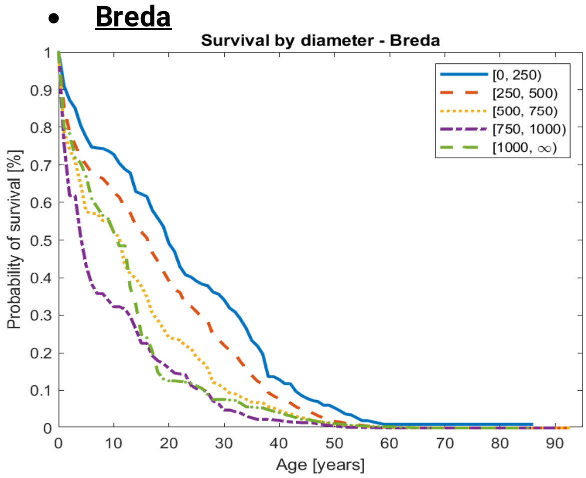


Figure 6.15 Survival probability ESE by pipe diameter [mm] for Breda's sewer

As it can be seen in Figure 6.15, there is a tendency where the smaller the diameter the higher the survival probabilities. This means that the smaller the diameter, less chances that a defect that may cause loss of watertightness will occur. Only the pipes with diameter of more than 1 m do not follow this tendency, in Breda's case.

When analysing each particular defect under study, this tendency is not evident for all defect. In fact, only this tendency is observable for defects BAJ (displaced joint), BBF (infiltration) and for defect BAH (defective connection) only up to 40 years. These defects are the ones with more effect on the aggregate curve of defects.

With the exception of pipes with diameters between 0 and 250 mm and larger than 1000 mm, the opposite tendency is observed for defects cracks (BAB), break (BAC), porous pipes (BAN) and void visible through defect (BAP). Meaning that for these defects pipes with diameter 250-500 have a higher probability of failure than those with a diameter between 750 and 1000 mm.

- **Almere**

Similar to Breda, in Almere, the results of the analysis of the diameters show a tendency of lower probability of failure when the diameters are smaller. For the range of pipes with a diameter larger than 1000 mm this tendency is not met. Nevertheless, it has to be taken into account that only 51 pipes where in this range of diameters.

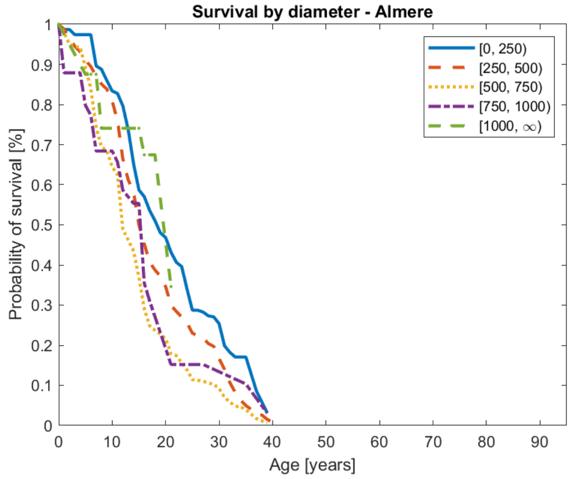


Figure 6.16 Survival probability ESE by pipe diameter [mm] for Almere's sewer

Diameters between 0 and 250 and between 250 and 500 mm showed a higher probability of survival, compare to diameters between 500 and 750 mm, and between 750 and 1000 mm. Diameters between 750 and 1000 mm start with the lowest survival probability up until a probability of 68% (7 years), where the lowest survival probability is observed for diameters between 500 and 750. Also, diameters equal or bigger than 1000 mm do not follow the tendency.

The median probability for the different ranges of diameter is 17.5 years for diameters [0,250), 14.6 years for [250,500), 11.6 years for [500,750), 14.5 years for [750,1000) and 18.6 for pipes with diameter bigger or equal to 1000 mm.

When reviewing the influence of the ranges of diameters in each defect, the aforementioned tendency is easily observed in defects displaced joint (BAJ) and intruding sealing material (BAI). In the defect defective connection (BAH), the tendency applies for diameters between 0 and 750 mm.

6.2.5 Pipe length

The analysis of the survival estimator regarding the pipes' length is presented in this section for the two municipalities.

- **Breda**

In Breda, it can be observed for the length of pipes, that those pipes with a shorter length present higher probability of surviving, or that no defect that will cause loss of watertightness will occur, than those of long length. Although it might be noticed that this tendency is not proportional during all the years and that the pipes with length between 10 and 20 m do not follow the tendency. The median for lengths between 0 and 10 m is 19.1 years, between 10 and 20 is 12.5 years, 20 to 50 is 15.4 years, 50 to 100 is 14.1 years, and for those equal or longer than 100 m the median is 5.5 years.

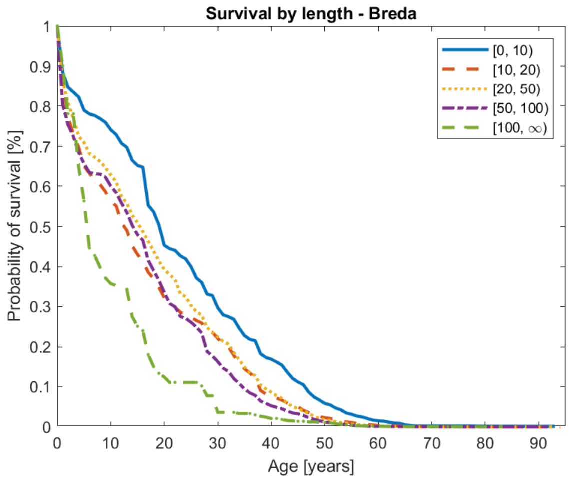


Figure 6.17 Survival probability ESE by pipe length [m] for Breda's sewer

In the analysis per defect, this tendency is easy to observe in defects like defective connection (BAH), porous pipes (BAN) and infiltration (BBF). In displaced joint (BAJ) the tendency is met except for pipes with lengths between 10 and 20 m (at least in some ranges of years). Similar behaviour, although not always proportional is observed in defect soil visible through defect (BAO) and void visible through defect (BAP).

- **<u>Almere</u>**

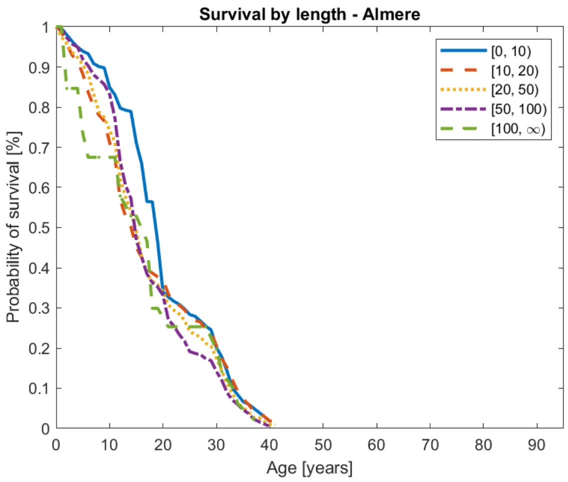


Figure 6.18 Survival probability ESE by pipe length [m] for Almere's sewer

In Almere's case, it can be observed that the range of length that has more probability of survival is 0 to 10 m, which is the shortest, and the one that has lower probability of survival is one of the largest (50 to 100 m). The tendency observed in Breda, were the lower the length, the higher the probability of survival is observed in Figure 6.18 only in some ranges of age, especially after 20 years, where it is easier to observe. The median probability for the lengths is Almere are, 18.2 years between 0 and 10 m, 13.2 years between 10 and 20m, 14.1 years between 20 and 50, 14 years between 50 and 100 m, and 18.6 for equal or bigger than 100m (only 34 records).

In the analysis per defect it is observed that the tendency occurs in defects defective connection (BAH) (although only for lengths between 0 and 100 m), displaced joint (BAJ) and porous pipes (BAN).

6.2.6 Above ground material

Only the results of Breda are presented here, as Almere's files do not have enough reports of the above ground material. Nevertheless, the analysis of Almere with the available data can be found in Appendix B.7.

- **Breda**

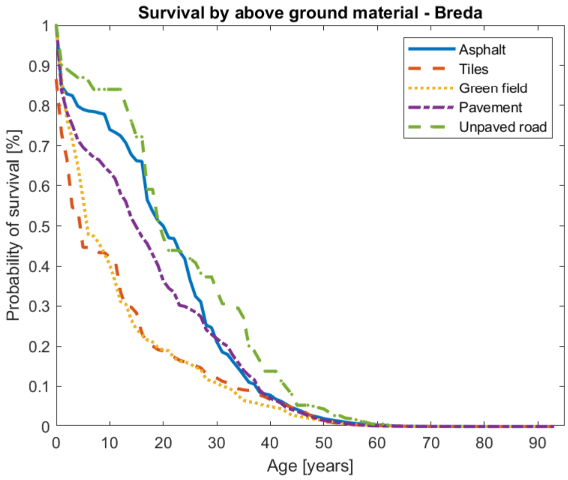


Figure 6.19 Survival probability ESE by the pipes' above ground material for Breda's sewer

As shown in Figure 6.19 , tiles and green field show a similar survival probability, which is lower than those of the other reviewed materials at least before 60 years of age, with a median of 3.9 years for floor tiles and of 5.8 years for green field. All materials show a rapid deterioration during the first years. The median of asphalt, pavement and unpaved roads are respectively, 20 years, 15 years and 19.3 years.

When reviewing the influence of these materials in each defect that may cause loss of watertightness, same order of the probabilities is observed in defects displaced joint (BAJ) and infiltration (BBF). When cracks (BAB) occur, pavement shows the lowest probability of survival followed by floor tiles.

6.3 Cox proportional hazard function

Results of the risk ratio per variable, for the two municipalities, are presented in Table 6.6. The states or subgroups of each variable are identified with a letter, as explained in Table 6.5.

Table 6.5 Explanatory variables and notation in risk ratio analysis

Variables	ID's	States	ID's
Sewer system type [-]	SYS	Foulwater sewer	a
		Stormwater sewer	b
		Combined sewer	c
Materials [-]	MAT	Concrete	d
		PVC	e
		Others	f
Diameter [mm]	DIA	Diameter	g
Length [m]	LEN	Length	h
Shapes [-]	SHA	Circular	i
		Others	j

Above ground material was not analysed with this method, as the two municipalities did not have many elements in common, and Almere had only a few reports for it which were not significant.

Table 6.6 Risk ratio of explanatory variables towards the occurrence of defects prone to cause loss of watertightness in sewer pipes

Municipality	Variables	Risk Ratio									
		SYS			MAT			DIA	LEN	SHA	
		a	b	c	d	e	f	i	j	g	h
Almere	SYS	1.9723	3.6379	--							
	SYS + MAT	2.0047	3.6752	--	0.3408	0.3429	0.0705				
	SYS + MAT +DIA	2.0003	3.6634	--	0.3466	0.3429	0.0718	1.000**			
	SYS + MAT + DIA + LEN	1.9182	3.5265	--	0.3546	0.3514	0.0740	1.000**	1.0048	--	--
Breda*	SYS	0.8483*	0.8194*	0.2102*							
	SYS + MAT	0.3267*	0.4321*	0.1189*	1.7263*	2.8318*	1.9286*				
	SYS + MAT +DIA	0.3203*	0.4243*	0.1163*	1.7296*	2.8588*	1.8709*	1.0000*			
	SYS + MAT + DIA + LEN	0.2389*	0.3285*	0.0904*	1.7584*	3.0341*	1.6580*	1.0000*	1.0064		
	SYS + MAT + DIA + LEN + SHA	0.2656*	0.3554*	0.1026*	1.3230*	2.0966*	1.3026*	0.9998*	1.0065	1.3517*	0.5669*

**** Breda does not meet the proportional hazard assumption of Cox proportional hazard model. These results are inaccurate***

***** Diameter in Almere does not meet the proportional hazard assumption of Cox PH model***

As mentioned before, the risk or hazard is the occurrence of defects that may cause the pipes to lose watertightness. In Table 6.6 it is possible to observe variance of the risk whenever a new covariate is assessed. This is due to confounding among the risk variables considered.

In the case of the municipality of Almere, results show that the risk ratio of the foulwater sewer with respect to the stormwater sewer is 0.54. The risk increases with respect to the variable sewer system type, 91% when is foulwater sewer and 252% when is stormwater sewer. When considering the materials, the risk reduces 66% when the material is concrete, and a similar value when the material of the pipes is a PVC. Further on, it may be said that an increase of 1 mm of diameter does not add significantly to the risk. On the other hand, increasing the pipe's length by 1 m increases the risk by 0.48%.

Results also show that the sewer system type is the characteristic with more influence on the failure probabilities for Almere, followed by length. This is observed by how much the risk ratio varies when these variables are added to the model.

These values were validated for the municipality of Almere. The graphical validation of $-\ln(-\ln ESE)$ shows for Almere that sewer system and materials meet the proportionality assumption of the Cox model, as the curves are approximately parallel. Further on, the hazard function results obtained with Cox for Almere were compared graphically, for each covariate, to results obtained with ENE, showing similarity and proportionality (observed vs expected). Figure 6.20 shows the evaluation of the $-\ln(-\ln ESE)$ of the sewer system type. Figure 6.21 shows the comparison of the hazards obtained with Cox and ENE. The rest of the graphical validation plots can be found in Appendix C.

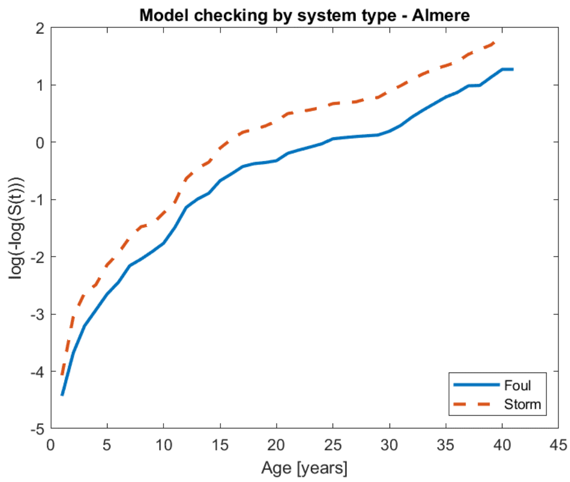


Figure 6.20 Graphical validation log (-log ESE) for sewer system type Almere

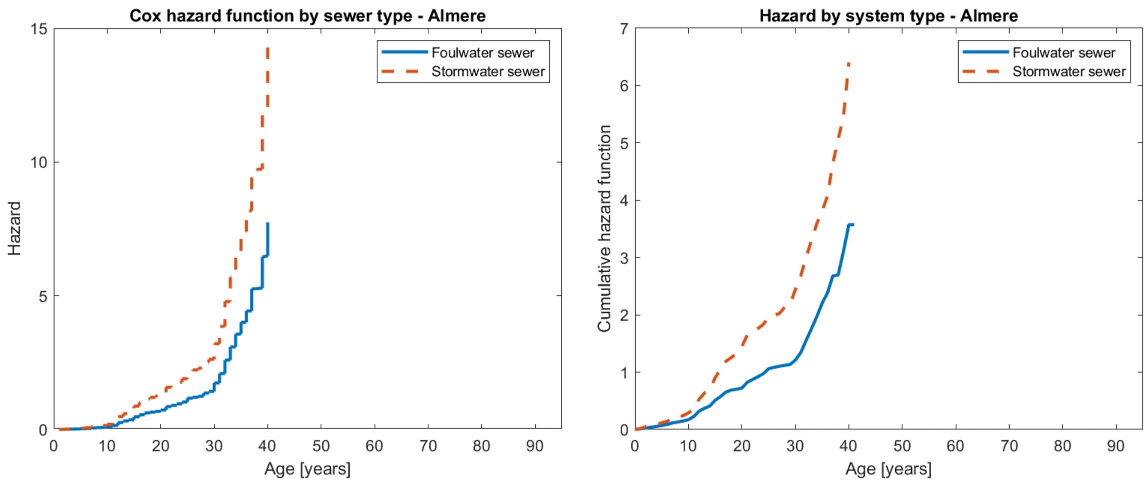


Figure 6.21 Graphical validation 'Observed vs expected' for sewer system type - Almere

Validation results showed than in Almere only the diameter does not meet the proportional hazard assumption.

In the case of the municipality of Breda, results presented in Table 6.6 show a different behaviour compared to Almere. Risk reduces 16% when the sewer system is foulwater, 18% when is stormwater and 79% when is combined water. When evaluating the materials, in Breda instead of reducing the risk, it increases. The risk increases 73% when the material is concrete, 183% when it is PVC and 93% when is other material. An increase of 1 mm of diameter, does not change the risk, while when increasing 1 m of length the risk increases 0.64%. Finally, the risk increased 35% times when the shape is circular, or reduces by 43% when it is other shape. For this municipality, results show that the characteristic that influences the most the probability of failure is the material, as it may be observed on how much the risk ratio changes when this value is incorporated in the analysis.

Nevertheless, it is very important to notice that when validating the results of Breda, both graphical methods indicate that the Cox proportional model is **not** appropriate. In the case of the $-\ln(-\ln ESE)$ validation, all variables showed crossed curves. Also, the observed and the expected values differ. When a hazard was expected to be the lowest, the graphs showed it as the highest. This is the case illustrated for Breda's sewer system type in Figure 6.22, where combined sewer shows the lowest hazard with Cox and the highest when obtained with ENE. The rest of the validation plots can be found in Appendix C.

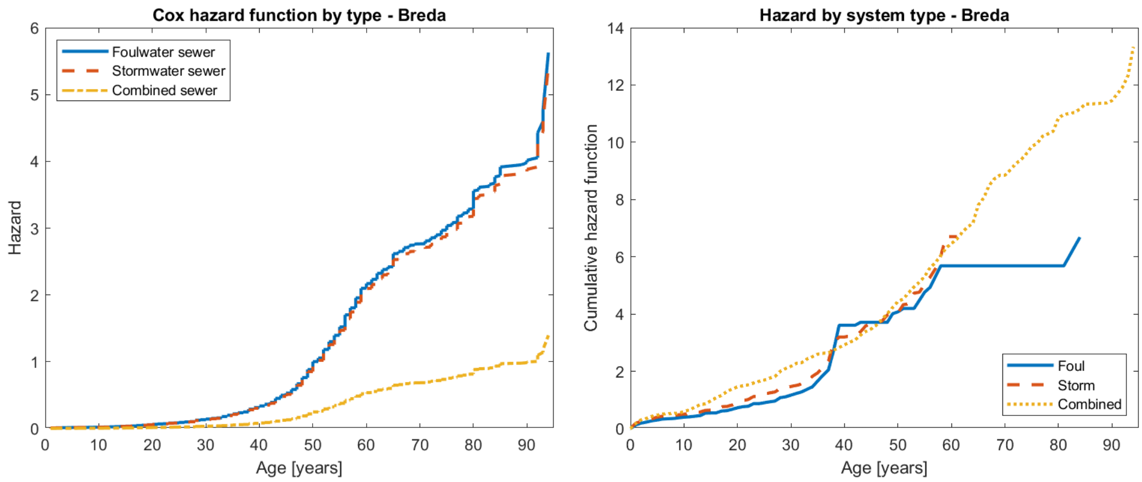


Figure 6.22 Graphical validation 'Observed vs expected' for sewer system type- Breda

7 Discussion

7.1 Data quality and availability

The amount of data available is always a limitation regarding the estimation of failure probabilities. Specially if looking to estimate sewer failures with higher consequences like collapse, blockages, or leakages, there is not enough information to investigate them. This may also be related to the fact that many municipalities are risk aversive, and they implement replacement strategies more frequent that they are really required (van Riel et al., 2014). This is why it was necessary to use a proxy failure to do the analysis of this study. Although a proxy is not an ideal measurement, they are very handy when natural attributes, in this case records of collapses, are not available. The disadvantage of using this proxy is that other possible causes of collapse (non-related to loss of watertightness) are left out of the analysis.

The reliability of the findings depends strongly on the data used. This research was carried out only using data from visual inspections, which already adds subjectivity to the results. As stated by Dirksen & Clemens (2008), the interpretation of the sewer inspection footage is subjective and highly conditioned by the inspector's opinion. Adding to this, and as mentioned in the literature review, the visual inspections are not always consistent, with a 25% of probability of a defect not observed although present (false negative), and a 4% probability of a defect observed although not present (false positive) (Dirksen et al., 2013).

Also, bias is added to the results due to the fact that sewer inspection frequency is very low and because of that in each inspection one has only information on the time of the inspection and not on the time of the events. As the time of the event is essential to run the survival models, it was required to make an assumption that the time of event was equivalent to the time of inspection. This assumption works for this study, as it is not being used to predict future failures but to identify the influence of the pipe's characteristics on the probability of failure. Nevertheless, in case of considering to predict more precisely time-to-failure events in sewers, more information or data might be required.

Moreover, in the analysis only information about inspections from 2004 were considered, as from this year a new standard was introduced. In Almere's case, all received inspections were after this date, but in Breda's case at least 11 years of inspections were discarded for this reason. Although the previous standard and the current NEN 3399 have similarities, the way the sewer pipes were assessed differs. The current standard uses a 23 defects classification (mentioned in Table 2.1), while the previous standard assessed the pipes on 18 different condition aspects which were classified in 3 groups: leaks tightness, stability and flow gradient. However, some of these condition aspects can be related to some of the defects of the new standard, for which some transformations can be considered in case this data is required for further studies, or to avoid discarding it.

Additionally, in section 4.2.2.1 an assumption was made about considering that no pipes were replaced if the installation date was the same for inspections at different times. Nevertheless, it must be mentioned that municipalities do not always inform about replacements or do not update them on time. This may create a bias that Scheidegger, Scholten, Maurer, & Reichert (2013) call "Absence of replaced pipe data". This underrepresents the dataset of the pipes that fail more often and reduces the possibilities of identifying the most representative characteristics that lead to failure.

Finally, some particular information in the dataset of the municipalities had to be removed to avoid errors. As an example, it was observed that some of Almere's files reported some coordinates inversely, meaning latitude was longitude and vice versa. Although this was easy to identify, other data errors might be harder to spot, like height and width, or even year of installation or of replacement. This example of human error indicates that data is also affected by that factor, which creates uncertainty to the results.

7.2 Methods

The non-parametric model that was implemented considers the right censoring and the left truncation that is common in failure data. Cox proportional model, on the other hand, only considers right censoring. Nevertheless, when implementing the MATLAB function *coxphfit* to estimate the β coefficients, the input that was used as the time-to-event vector was organised in a similar way as how the ESE model examines the number of individuals at risk at the time-to-event, so that left truncation was considered for the Cox model as well.

The ESE model is a non-parametric model, and therefore reflects what is found in the databases and does not assume a survival behaviour. However, it is important to notice that this model is commonly used for water supply networks and not for sewer system. This is mainly to the limitation on failure data exact time-of-event on sewer systems mentioned before. Nevertheless, and for the objective of this research, this method was applicable for sewer systems, as the intention was to estimate the influence of the characteristics on the probability of failures and not to predict future failure events.

Also, the ESE model favours older pipes. In other words, those pipes that are older and are present in the inspection records, are there because they have survived up to the inspection date and therefore have more years to report their behaviour. This includes characteristics like asbestos cement pipes, and others. Records of pipes with similar characteristics that failed before the study were not provided and therefore survival bias is added to the results, reducing the real failure estimation of the particular characteristics.

With respect to the Cox proportional hazard model, its use is restricted to the assumption of proportionality. This assumption was met with the data from Almere, but in the case of Breda it was not. The reason behind this is related to the age of the sewer network and the ages of installation of the different elements per variable.

When making the analysis of the cumulative hazard function with ENE, each element of the variables was analysed on their own and later compared to the others. In the case of the Cox model, all elements are analysed together. So, the difference of the ages of the pipes do not reflect old installation techniques, or preferences, but merely suggests that some pipes have survived longer. To illustrate this, Figure 6.6 in section 6.1, shows the installed length in km of the different sewer types in Breda, where combined sewers not only double the number of pipes of foulwater and stormwater, but also shows how the installation preferences vary over the decades. Similar results can be observed in the installation length per material and shapes (see Figure 6.6). This suggest that there is a time component in these variables, which suggest that the Cox model cannot be applied. This is because this model assumes that only the baseline hazard $h_0(t)$ is a function of time, while the z_k or predictor variables must be time-independent. In case of considering the Cox model for further studies with this data, the Cox extended model could be implemented as it allows for the analysis of time-dependent variables.

7.3 Pipe defects and the failure

Although the failure proxy that was defined for this research does not indicate that the pipe is not functional, it shows a condition which can trigger several consequences including collapse, pollution, settlement, among others. This should be considered when making decisions about pipe replacement, repair, or maintenance, and also when making decisions about inspection strategies.

As explained before, when watertightness is lost, infiltration and exfiltration might occur. Infiltration and exfiltration have as some of their main consequences the washing of soil surrounding the pipe and allowing the formation of voids that might affect the pipe's stability. In the case of infiltration, when it occurs it reduces the designed hydraulic capacity of the pipes due to the additional flow that enters the system, as well as for introducing washed soil that may cause sedimentation and reduction of flow velocity, besides the additional cost that this extra flow implies in the operation of the wastewater treatment plant.

Infiltration and exfiltration are reported in the inspections as operational defects, identified with the codes BBF and BBG respectively. It is assumed that if they were reported in the inspections is because their evidence was very clear. Nevertheless, as the pipes are inspected after they are emptied and cleaned, it is difficult to evidence exfiltration. Therefore, both municipalities present little records of the occurrence of this defect, almost null. Hence, results based on this defect are not considered significant. Also, this opens a discussion if other structural defects are not seen or overlap when infiltration is registered. If it was the case where the overlapping defects are some of the ones under observation for loss of watertightness, then their real implications may not be revealed for the model. If the case was that the defect that is allowing infiltration is another one apart from the identified ones, then this type of defect is being underestimated if not ignored, as well as its possible consequences. Therefore, and to avoid assumptions, future spatial correlation studies wherever infiltration is identified should be at least considered. This analysis could provide managers with more precise information about the structural defects that are allowing infiltration (and possibly exfiltration) to occur in their networks, and could be used as guidance to improve inspections and replacement strategies.

In this thesis, the loss of watertightness is analysed using the aggregate information about the defects under study, and by analysing each defect independently. Of the aggregate curve per municipality, it is possible to conclude that Breda shows a higher probability that defects that cause loss of watertightness will occur on the first 10 years. Nevertheless, when the pipes are past 20 years, the survival probability for the two municipalities is not that different, approximately 38% for Breda and 35% for Almere. This probability remains similar up to 30 years, after which Almere's drops almost to 0% by the time the pipes are 40 years, while in Breda it is close to 8%. The probability of survival is almost 0% for Breda past 60 years. This indicates that some of these defects have more negative effect on Almere's network and make it more prone to lose the watertightness.

For both municipalities, it was observed the incidence of each defect on the survival probability obtained with the aggregation of defects (See Figure 6.9). Both locations showed that the defects that have more effect on the curve are displaced joint (BAJ), infiltration (BBF) and defective connection (BAH). In Breda's case, also cracks (BAB) showed a high effect. Questions may rise regarding why these defects occur and why are they so common in these networks. Type of soil, construction techniques, traffic loads, trees, vicinity to a construction place, improper selection of joint materials and others, could be traced spatially (and some temporarily) to find what could be causing these defects to happen. Also using the information of the influence of each variable or characteristic of the pipes on each of these defects, can guide managers on where to look for damage or occurrence of these particular defects.

When comparing the occurrence of the most prominent defects, it was observed that displaced joint (BAJ) happens more early in Breda, at least during the first 30 years. After that, Almere shows a faster reduction of the survival probability between 30 and 40 years, going from a probability of survival of 35% to almost 3%. While in Breda for the same years, the probability goes from 31% to 17%. As mentioned in the case study description, section 5.2, in Almere there is a constant occurrence of subsidence mainly because of the type of soil. This may explain the sudden drop of survival probability of this municipality when this defect occurs.

Infiltration (BBF) in Almere has a similar, almost equal, behaviour as displaced joint (BAJ). This might indicate some correlation. Further spatial analysis, could indicate if this is the case or not. Also, infiltration (BBF) in Almere shows a fast decrease on the probability after 10 years, compared to Breda, which may be influence by the just mentioned occurrence of subsidence.

In the case of defective connection (BAH), Almere and Breda behave similarly up until approximately 30 years, after which Almere shows a much faster deterioration, observed in a steeper curve. Moreover, in Almere the defect porous pipes (only concrete pipes) (BAN), shows little failure events up to 30 years (95% survival probability approximately), after which the probability drops fast, and by the time pipes are past 40 years the probability of survival is 50%. Porous pipes (BAN) may be affected more by chemical conditions. For which some studies can be conducted regarding the accelerated deterioration of the pipes after they are 30 years, in order to identify if there is any component that is affecting these pipes in particular. Further on, this defect should also be considered by managers whenever inspecting concrete pipes that have more than 30 years, or whenever repair or replacement strategies are being considered for pipes of these characteristics.

7.4 Pipe characteristics

Although there are several factor and/or characteristics that might influence the pipes structural deterioration and failure, as the ones mention by Davies et al. (2001) (see Table 2.4), there were only six considered in this research (sewer system type, material, shape, diameter, length and above ground material). The reason behind this choice was the availability of information about these potentially explanatory variables in the dataset of the visual inspections provided by Breda and Almere.

For a more complete assessment of the failure influential factors, other sources of information will be required, as may be construction reports, reports of joint type and material selection, local external factors like traffic load, maintenance information of other buried services, groundwater level, type of vegetation and possible root interference, among some others. Unfortunately, asset managers do not always have access to all the information, and therefore it is important to see what analysis and results can be obtained from that information that they normally have at hand.

Based on this, analyses of the influences of different characteristics were carried out. Results obtained with the ESE model, showed that in both municipalities the foulwater sewer has a higher probability of survival than the stormwater sewer. This is positive regarding the environmental consequences that a leakage of foulwater could have over the surrounding area of the pipe, compared to the less polluting effect produced by a stormwater leak. Nevertheless, in Breda's network, the sewer system type that presented the lowest probability of survival is the combined water sewer, so the risk of environmental damage due to leakage of wastewater is still high for that municipality. It is important to notice that the combined sewer has the majority of pipes in this municipality, for which they are inspected more often than the other types. Additionally, because this type has more pipes, and also older pipes (see Figure 6.6), the chances that more failure events (or in this case, defect that may cause loss of watertightness) are reported is higher than for the other system types. These two reasons create a data bias, that managers should consider if using the influence of this characteristic on the pipe's failure in any decision.

In the case of the municipality of Breda, the ESE results of the sewer system type show that by the time the pipes are 40 years approximately, the probability that no defect that causes loss of watertightness has occurred to any of the three systems, is almost null. This is also the case for Almere's system types, where past 42 years the probability of survival is almost 0%.

Almere's system type behaviour is correlated to the materials. Most of the foulwater sewer of Almere is in PVC, while the stormwater system is concrete. When analysing the materials, concrete shows a lower probability of survival compared to PVC and to other materials in this municipality. Same relation found for the sewer system types. In Breda's case this correlation is not that easy to spot. This is mainly because this network is older and therefore construction preferences of the system, selected materials and shapes have changed throughout the decades.

In a like manner for Breda, concrete pipes have a higher probability that defects that may cause loss of watertightness will occur to them compared to PVC pipes.

The failure probabilities when assessed with the influence of the materials, show the bigger evolution over time of all the studied characteristics for the two municipalities. Which suggests that this is the studied characteristic that may make sewer pipes more prone to fail.

For the characteristic shape, it was only analysed in Breda, as all studied pipes from Almere were reported as circular. It was observed that the egg-shaped pipes have a lower probability of survival than the circular shaped. Nevertheless, it was observed in Figure 6.6, that circular shaped pipes are not only the majority type of shape in Breda's network but some are also older than the egg-shape type. Therefore, this may lead to some bias of the result.

Both municipalities showed in their analysis of the ESE model that the smaller the diameter, the higher the survival probability (no defects that cause loss of watertightness will occur). This tendency was not observed in all the studied defects but mainly in the ones that have more incidence (displaced joint (BAJ), infiltration (BBF), and defective connection (BAH)). The opposite tendency was observed for diameters between 250 and 1000 mm for Breda and between 0 to 1000 mm for Almere, when defects like cracks (BAB), break (BAC) or porous pipes (BAN) occur. This indicates that the conclusion obtained with the aggregate curve and with the defects with more incidence is opposite to what is found in the literature, that normally bigger pipes tend to structurally fail less than smaller ones. However, displaced joint (BAJ), and defective connection (BAH) although classified as structural failures, refer more to the separation of its parts, whereas BAC (break) and BAB (crack), and BAN (porous pipes) have incidence in the structure as it is. This might suggest that the tendency found in the literature is met for those defects that have structural consequences, while for those that interrupt the continuous flow the tendency is the opposite to what is found in the literature. The reason why this may be is because displaced joints (BAJ) and defective connections (BAH) are more evident on a pipe with smaller diameters.

When analysing the length of the pipes, in the aggregate curves as well as in all defects, for both municipalities, it is observed a tendency that shorter lengths have a higher survival probability than longer ones. Translated into loss of watertightness, the shorter the pipe, the lower the probability that more defects that can cause loss of watertightness will affect them. This coincides with what is found in the literature, longer pipes have a higher probability of failure than shorter pipes.

Finally, the above ground materials influence results were only informed for Breda as Almere has little records, making this characteristic insignificant for that municipality. Results show that defects that may cause loss of watertightness have a higher probability of occurring were there are floor tiles and green fields. Vegetation on green field, and their roots, may have some incidence in the displacement of joints (BAJ), and on infiltration (BBF). Also, cracks (BAB) occur more for pipes that have above them pavement and floor tiles, this may suggest a road or an urban area. This characteristic could be complemented with spatial correlated analysis, and some complementary reports, like traffic load, type of vegetation, and other factors that will link it more with the characteristics of the pipes (like diameter, length, material, shape).

When considering the results obtained with the Cox proportional model, Breda's results contradict the ones obtained with ESE. This is mainly because Breda's data is not appropriate to be used with the Cox proportional model as is time dependent and therefore does not meet the proportionality assumption of the model. On the contrary, Almere's results with Cox show similarities with what was found with ESE. In Almere's case, results show that the sewer system type, followed by the length, are the characteristics that influence most the probabilities of failure of the pipes. This conclusion is based on the variation of the risk ratio once these characteristics where added.

7.5 Role on asset management

In order to improve the means to implement proactive approaches, the obtained probabilities of failure (or of defect occurrence that may cause loss of watertightness) can be considered in the risk-based inspection and maintenance strategies. These strategies can optimise and prioritise the areas where more attention is required, in order to avoid failure.

Longer inspection intervals, reduce the maintenance cost but may increase the failure rate. On the contrary, when the inspection intervals are shorter, the maintenance cost might increase but the failure rate reduces (Khan et al., 2004). This is where the influences of the characteristics on the probabilities of failure can be used as a tool to identify those sewer pipes that require more attention and prioritisation of the inspection intervals, in order to avoid future loss of watertightness and possible collapse.

Further on, as the results are based on different defects, those that occur more frequently and also have more effect on the loss of watertightness should be considered in the maintenance strategies, to seek for possible causes, and for possible ways of reducing their occurrence.

Adding to this, the renovation plans for the pipes of the municipalities are estimated for every 60 years. Considering this, and the results obtained in the analysis, it I expected that the sewer pipes in Breda will not be watertight at least for 3 years (probability of survival is close to 0% past 57 years), compared to Almere where it is expected that the pipes will be not be watertight for at least 18 years (probability of survival is close to 0% past 42 years).This should be considered in their maintenance plans or renovation plans.

Nevertheless, if this is known, and also influential characteristics are identified, the pipes that have higher risk because they are not watertight, could be included in the risk-based inspection strategies, and be monitored to avoid possible failure before the renovation takes place.

8 Conclusion

This section concludes on the main research question that reads:

What is the influence of different characteristics on the probability of failure in the sewer pipes?

The analysis is based on reports of visual inspections, which adds subjectivity to the results.

Of the studied defects that may cause loss of watertightness, it was concluded that displaced joint (BAJ), infiltration (BBF) and defective connection (BAH) are the defects that have the largest incidence on the failure rate for both Almere and Breda. Although Breda's network was also highly affected by cracks (BAB), and Almere's by porous pipes (BAN).

Using the aggregate information of defects on the ESE model, it was observed that for both municipalities the median survival probability that the pipes will not have defects that will cause them to lose watertightness is past 14 years. By the time the pipes in Almere are 40 years old, almost all will have experienced a defect that may cause loss of watertightness, and in Breda's case this is approximately when the pipes are 57 years old.

The characteristics under study were chosen as their information was available in the dataset of the visual inspections provided by the municipalities.

According to the findings, the probabilities of failure vary with respect to the characteristics and their elements. The influence of the evaluated characteristics is reflected on how much the failure probability evolve over time. For the ESE model, the material was the characteristic that showed the most influence on the failure probability for both municipalities, followed by length and diameter.

Moreover, some observations were derived from the characteristics of the two municipalities: Breda's combined water sewers are more prone to have defects that may cause loss of watertightness than foulwater or stormwater sewers, and the latter has a higher probability of failure than foul sewer. Nevertheless, it must be considered that combined pipes are the majority of pipes in the network and because of that are inspected more often. This could add some bias to the result interpretation. In the case of Almere, stormwater sewers showed that they have a higher probability of failure than foulwater sewers.

Concrete and PVC are the most commonly used materials in both municipalities, and concrete pipes have a higher probability of occurrence of defects that cause loss of watertightness than PVC pipes.

The characteristic shape was only assessed for Breda, where results showed that egg-shape pipes have a lower probability of surviving than circular shape pipes. These results may be affected by some bias, as there is a big difference in the dates and amount of installed circular pipes and egg-shaped pipes.

Also, for both municipalities, when the pipes' diameter is smaller, the probabilities that the defects that cause loss of watertightness will occur is lower than when the diameters are larger. Nevertheless, this tendency was only met for the aggregate defects and the most influential defects (Displaced joint (BAJ), infiltration (BBF), and defective connection (BAH)). For other defects, with more evident structural damage on the pipe, like crack (BAB), break (BAC) or porous pipe (BAN), results showed the opposite tendency, larger diameters with a lower probability of defect occurrence (higher survival probability) than those of smaller diameters.

In the case of the influence of the length, it was observed for both municipalities that the probability that pipes will have defects that causes loss of watertightness is lower for shorter lengths than for longer ones. This was observed for the aggregate defects and each defect independently.

Regarding the above ground materials, only the results of Breda were considered, as Almere had little information about this characteristic. Pipes that have green fields and floor tiles above them, have a higher probability of having defects that cause loss of watertightness than those that have asphalt or pavement. Infiltration (BBF) and displaced joint (BAJ) were most influenced by green fields.

On the other hand, the results obtained with Cox proportional hazard model showed similarly to the ESE model, that for Breda the material is the variable that influences the most the occurrence of defects that may cause loss of watertightness, while in the case of Almere, sewer system type, followed by length showed the most influence, followed by materials. Nevertheless, Breda’s data did not seem appropriate to be used with this model, which may be explained by the differences observed over time in the installed materials, shapes and systems types. This suggest a time component on these variables, making them time dependent and hence unfit to accomplish Cox’s proportionality assumption.

To summarise, the pipe’s characteristics that influence more negatively the probability of failure are combined sewers, egg-shaped pipes, concrete, bigger diameters, longer pipes, and green fields and floor tiles above the pipes.

These influences can be considered in risk-based inspection and maintenance strategies, which optimise and prioritise the areas where attention is required, and where reducing the inspection intervals can help to avoid future loss of watertightness and possible collapses.

9 Recommendations

Based on the discussion and conclusion, some recommendations for future research are given:

- In order not to discard information from the inspections, a similar study could be carried out with the data obtained with inspections before 2004 where the previous standard was used (only for the case of Breda). This may require some adaptations or transformations to find similarities of the previous standard with the current one, to identify the studied defects that may cause loss of watertightness. Results should be analysed together with the ones obtained in this study, and see how the influences of the characteristics on the probabilities of failure vary if more years of data are considered.
- Moreover, a similar study can be addressed for the same defects but considering their condition classes (from 1 to 5). This will allow to identify the influences of the characteristics also in each condition state per defect.
- A research regarding the possible consequences due to the occurrence of the different identified defects can be considered. This will allow to estimate the expected cost with the already obtained probabilities of failure, and can be considered for future risk-based decisions of maintenance or inspections.
- A spatial correlation analysis could be implemented wherever infiltration (BBF) and exfiltration (BBG) defects are identified. This could help to identify the structural defects that are allowing leaks to occur. In this way, overlapping defects of the visual inspection is avoided and also those defects that have more incidence on the occurrence of infiltration and exfiltration can be pointed out to see what maintenance strategies could help reducing them.
- A spatial location analysis could also be considered for those defects that occur more often and have more incidence on the loss of watertightness. This could help to identify the causes of these defects and to consider possible solutions.
- In order to see if the above ground material is an explanatory variable that is worth considering in future research, first a spatial analysis can also be considered with the defects.
- Knowing that Breda's characteristics are time dependent and therefore do not meet the proportionality assumption of the Cox proportional hazard model, future analysis could be done using the extended Cox model, which allows for time dependent variables.

Adding to this, some recommendations for the municipalities:

- Information about replacement data should be handled with care. Having this data provides better information about the real condition of the networks. Past and present inspections records should be saved as it helps to estimate the maintenance strategies.
- By increasing the frequency of the inspections, accuracy of the probabilities of failure is improved and more objective decision regarding the maintenance, inspections, replacement, and management in general of the sewer can be made.
- Almere's network showed an accelerated reduction of the probability of survival past 30 years when the defect porous pipes (BAN) occurs. Identification of what could be causing this can prevent further damage of some of their pipes.

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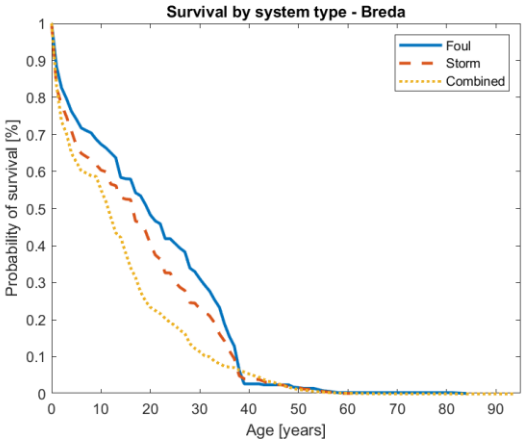
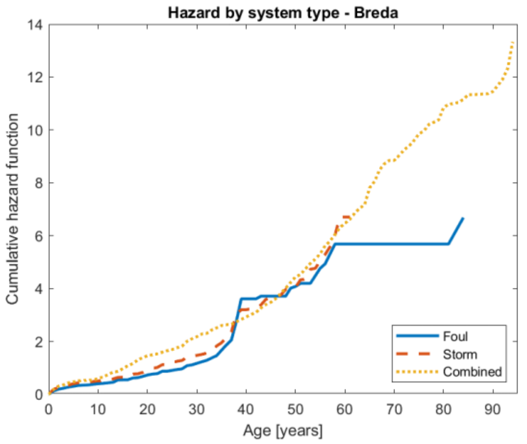
Appendices

Appendix A: Non-parametric survival analysis Breda

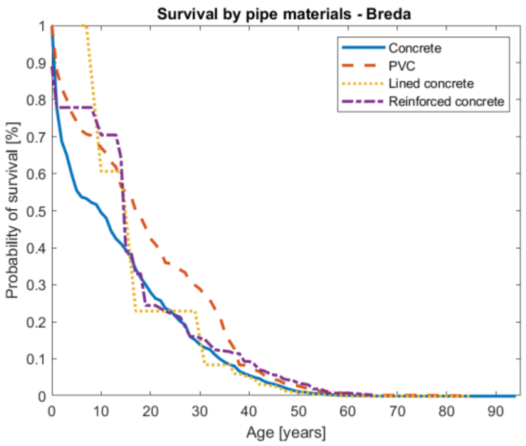
A.1 Aggregate defects. Survival analysis and hazard function

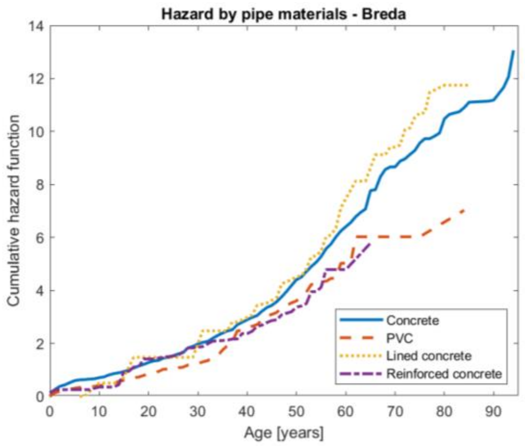
- Sewer system type



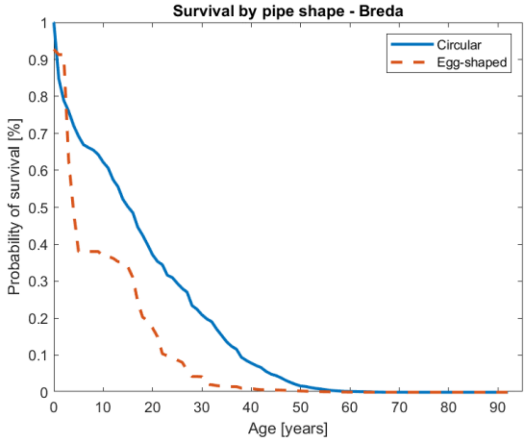


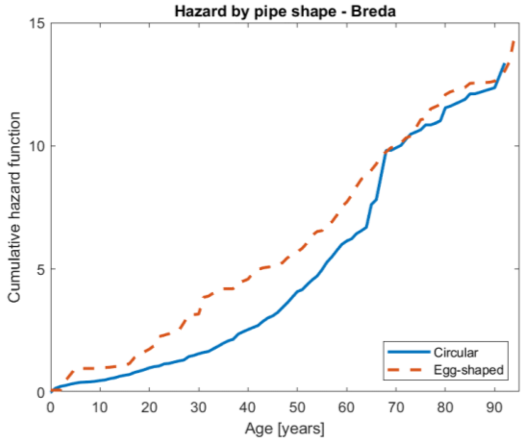
- Materials



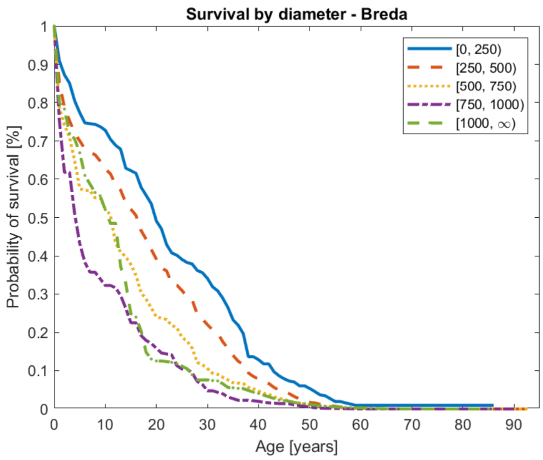


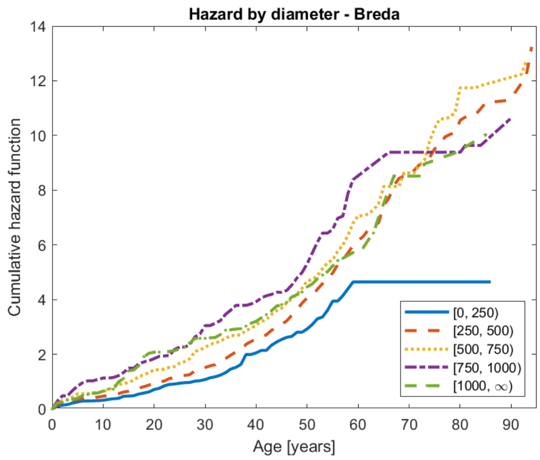
- Shape



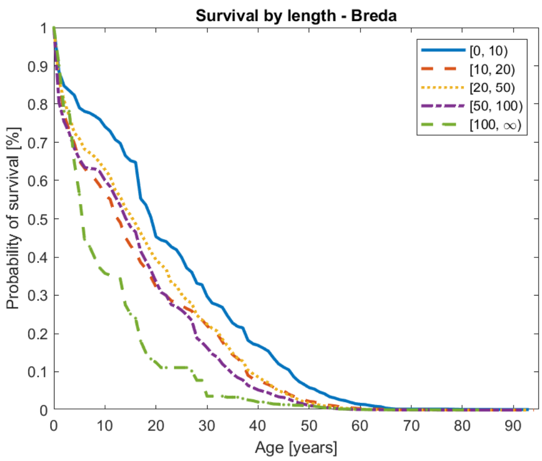


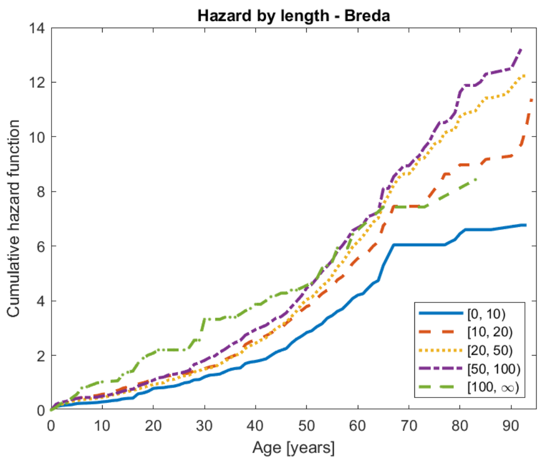
- Diameter



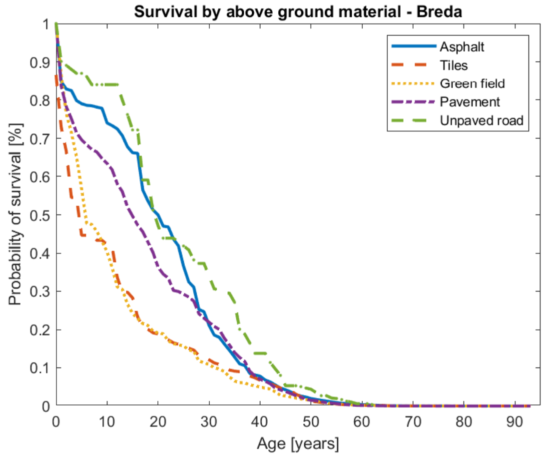


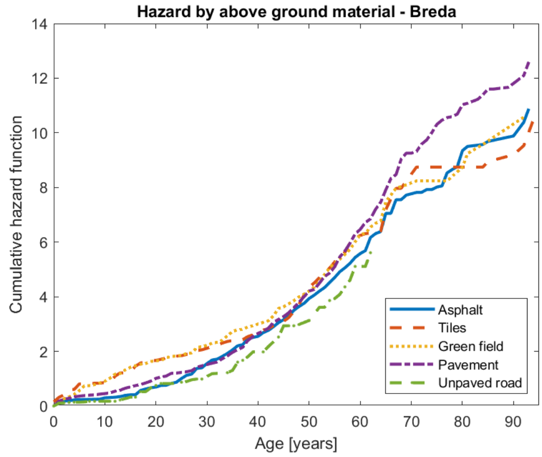
- Length





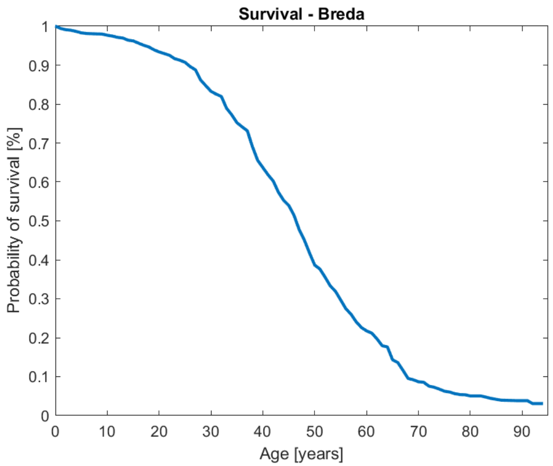
- Above ground material





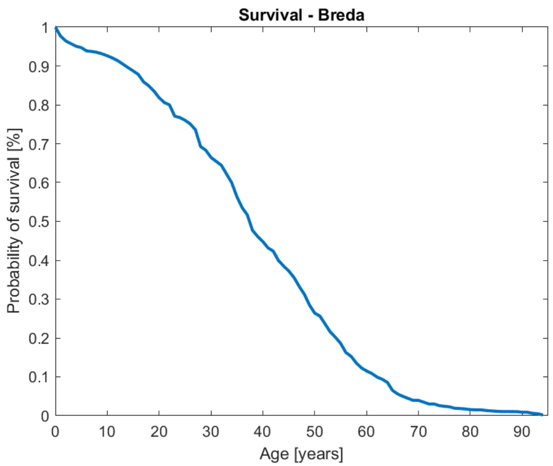
A.2 Survival probability per defect- Breda

BAB: Crack

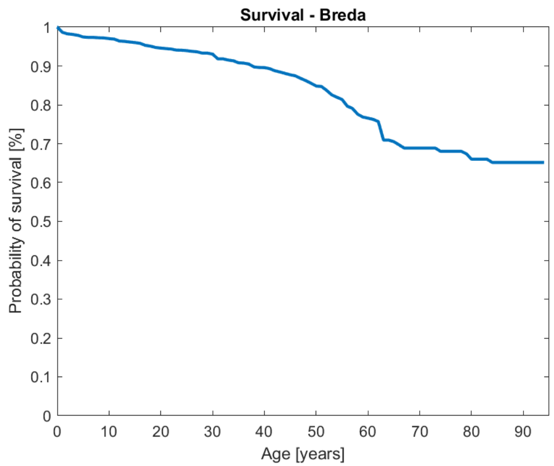


BAC: Break

BAH: Defective connection

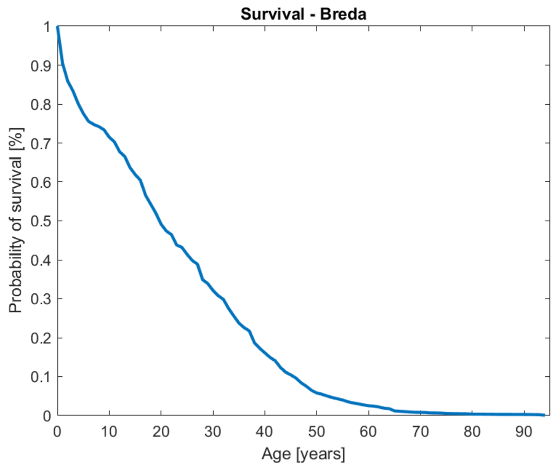


BAI: Intruding sealing material

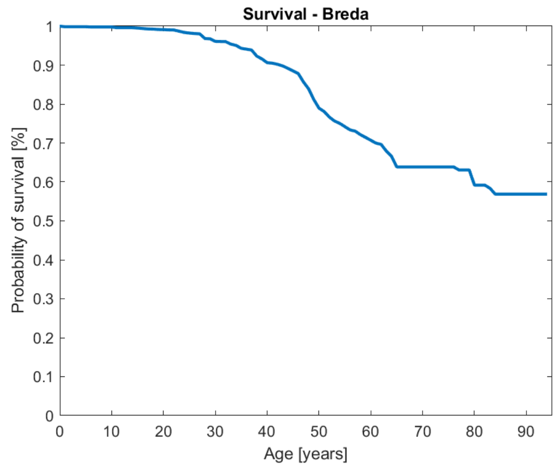


(continue) A.2 Survival probability per defect - Breda

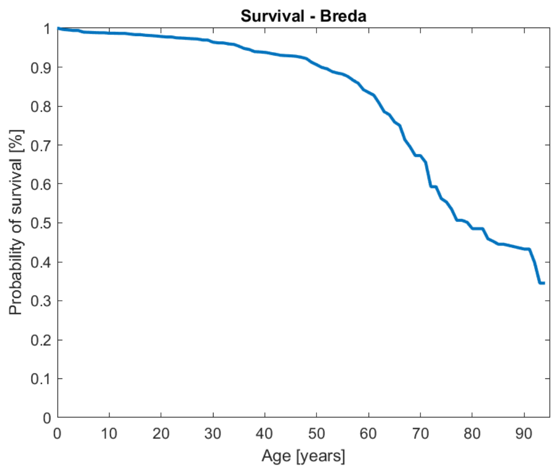
BAJ: Displaced joint



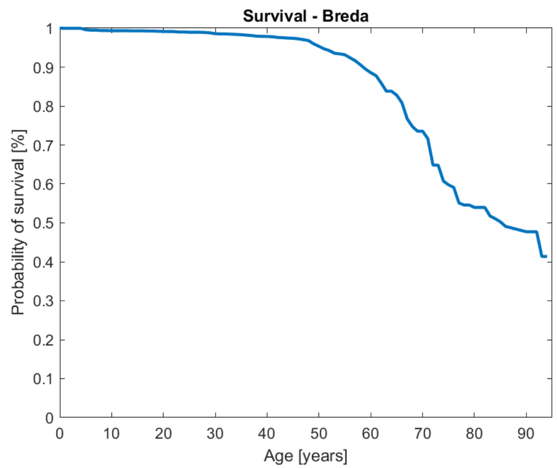
BAN: Porous pipe (Concrete only)



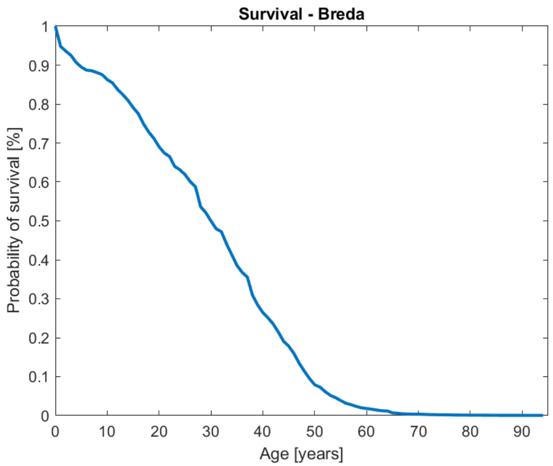
BAO: Soil visible through defect



BAP: Void visible through defect

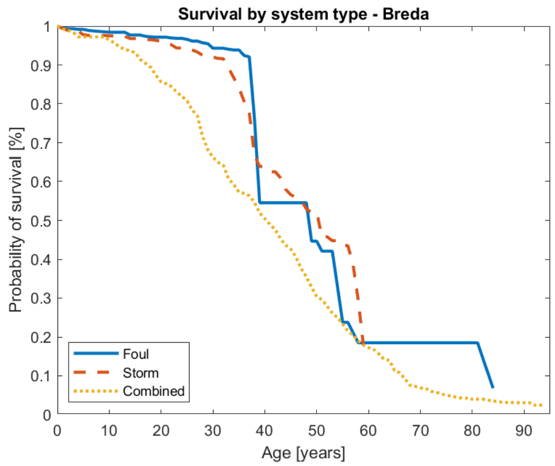


(continue) A.2 Survival probability per defect - Breda

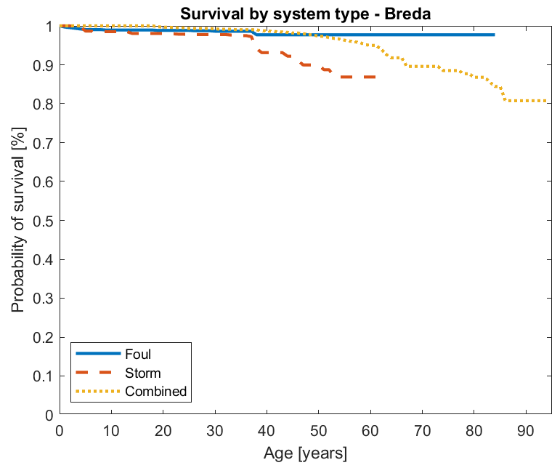
BBF: Infiltration	
	

A.3 Survival by sewer type per defect - Breda

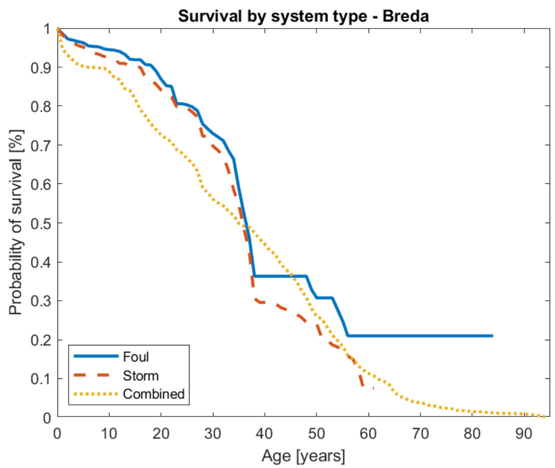
BAB: Crack



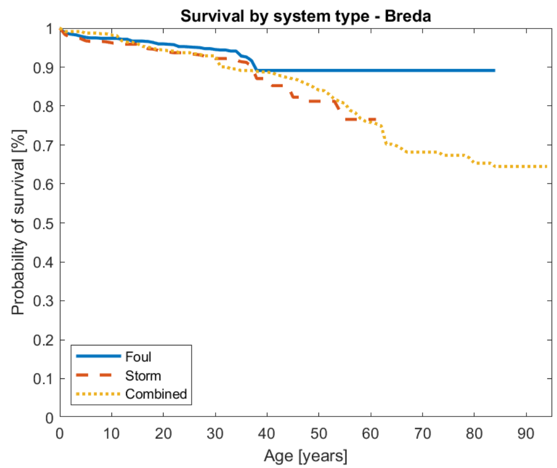
BAC: Break



BAH: Defective connection

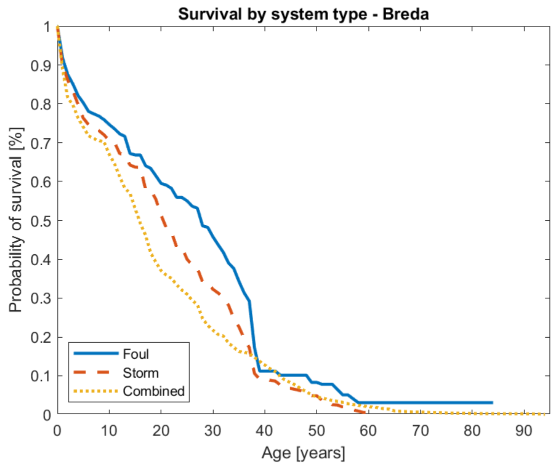


BAI: Intruding sealing material

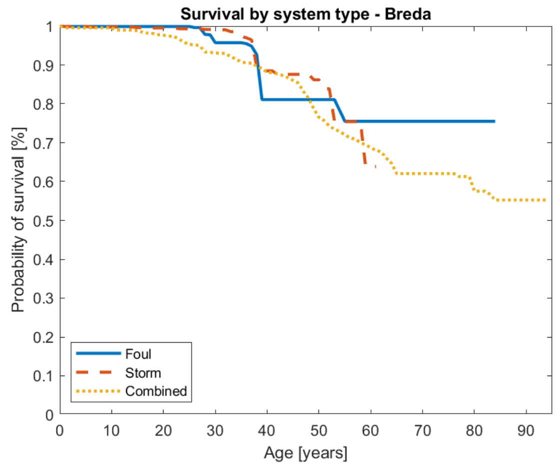


(continue) A.3 Survival by sewer type per defect - Breda

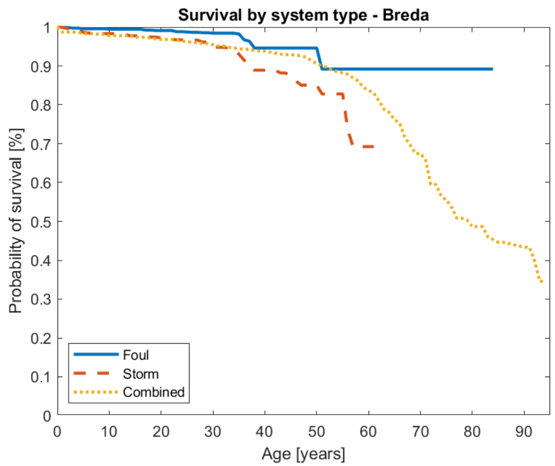
BAJ: Displaced joint



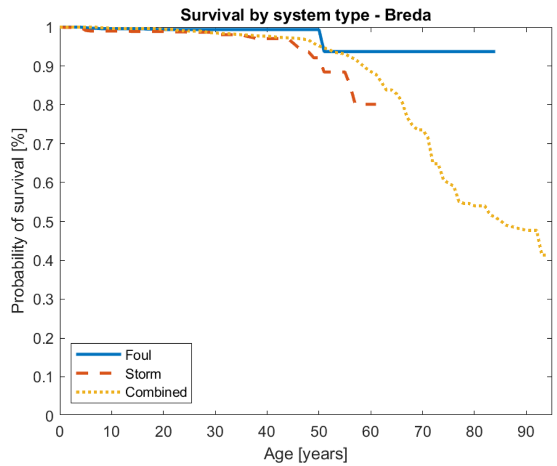
BAN: Porous pipe (Concrete only)



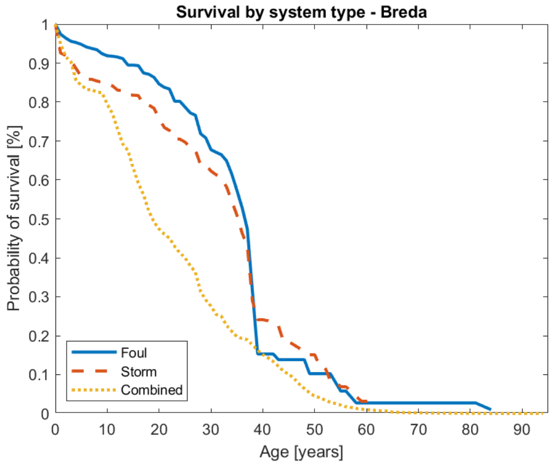
BAO: Soil visible through defect



BAP: Void visible through defect

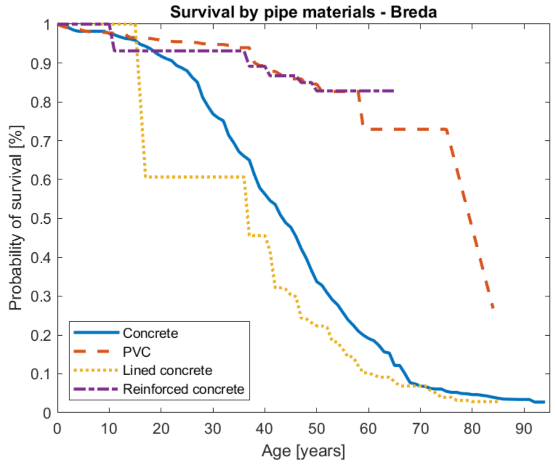


(continue) A.3 Survival by sewer type per defect - Breda

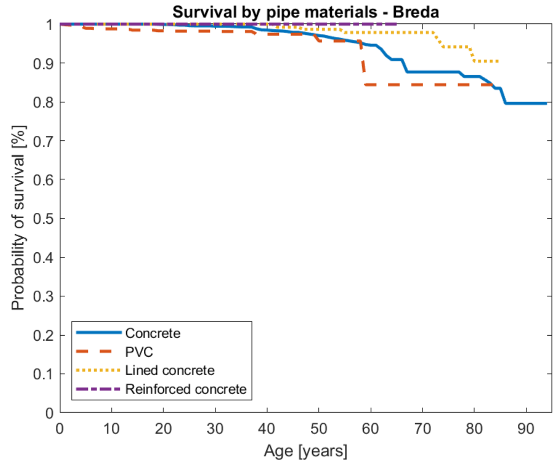
BBF: Infiltration	
	

A.4 Survival by material per defect - Breda

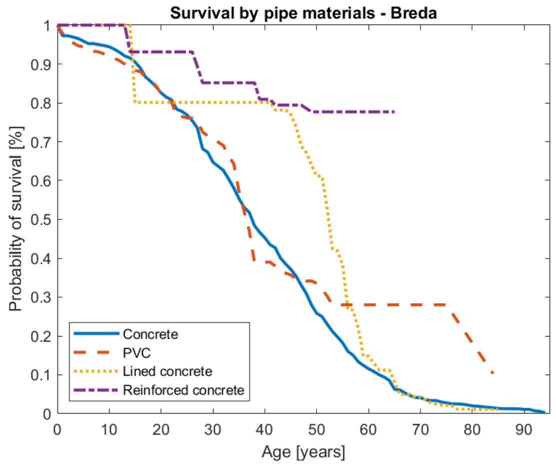
BAB: Crack



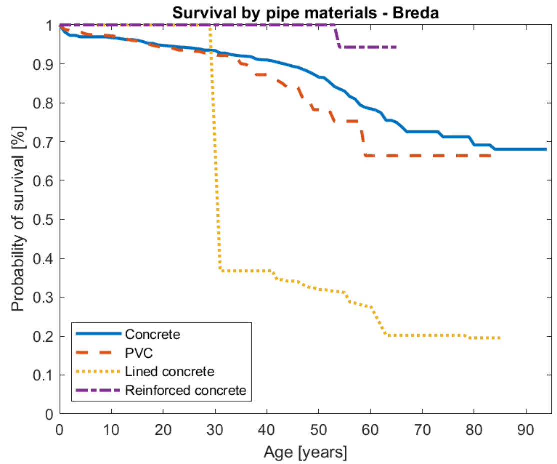
BAC: Break



BAH: Defective connection

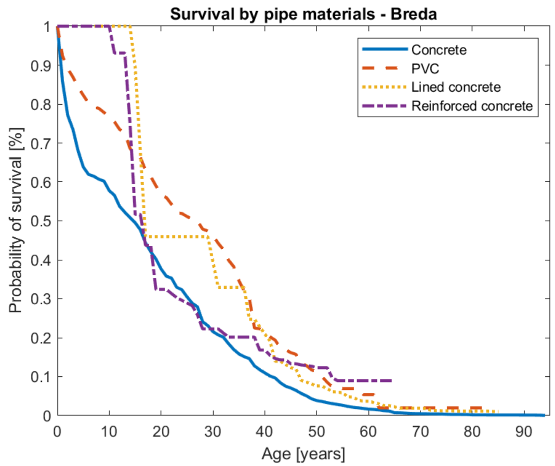


BAI: Intruding sealing material

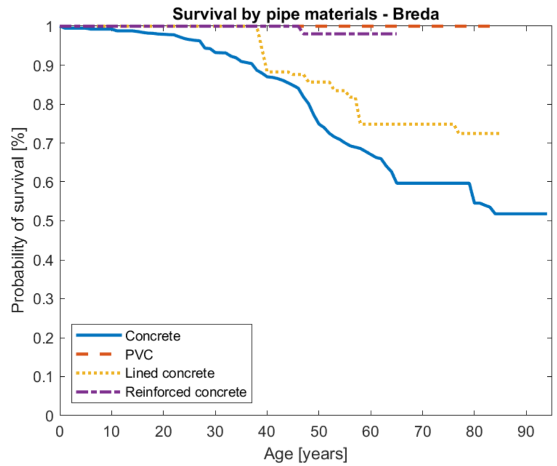


(continue) A.4 Survival by material per defect - Breda

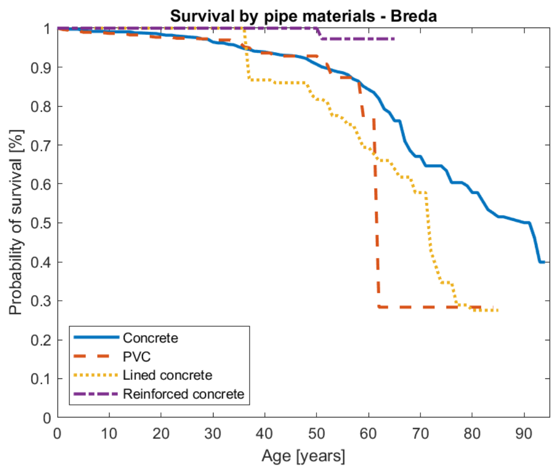
BAJ: Displaced joint



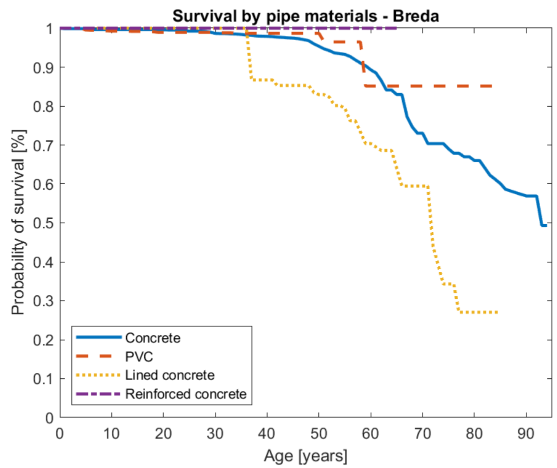
BAN: Porous pipe (Concrete only)



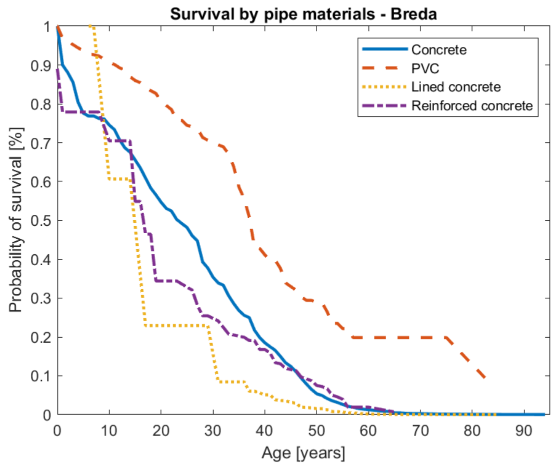
BAO: Soil visible through defect



BAP: Void visible through defect

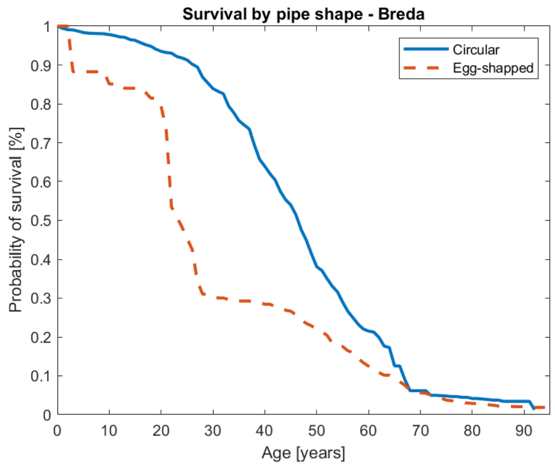


(continue) A.4 Survival by material per defect - Breda

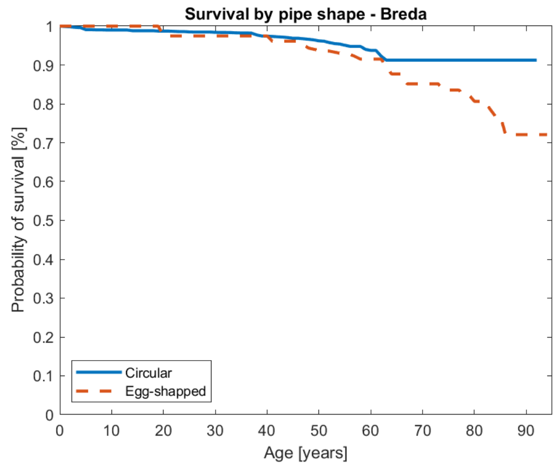
BBF: Infiltration	
	

A.5 Survival by pipe shape per defect – Breda

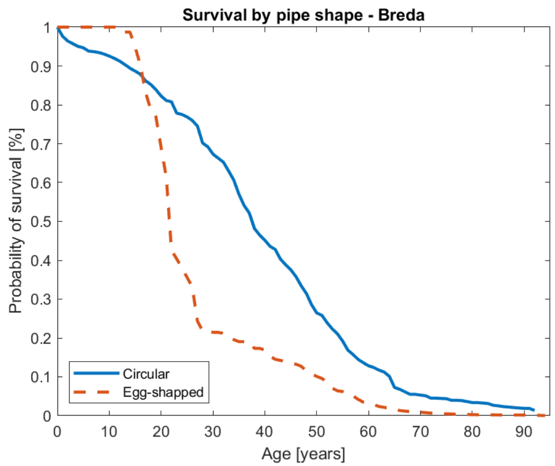
BAB: Crack



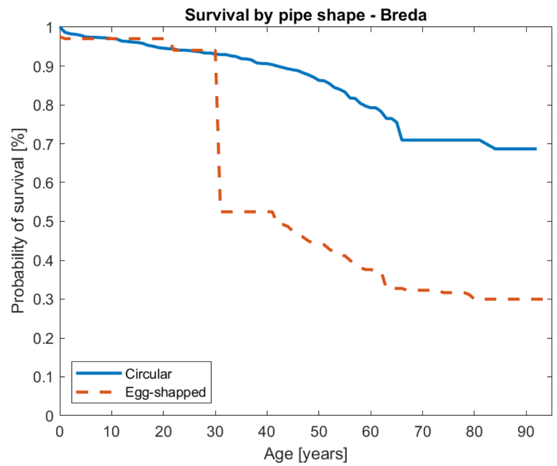
BAC: Break



BAH: Defective connection

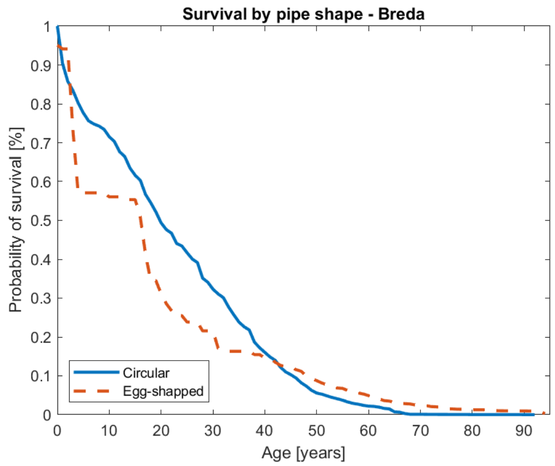


BAI: Intruding sealing material

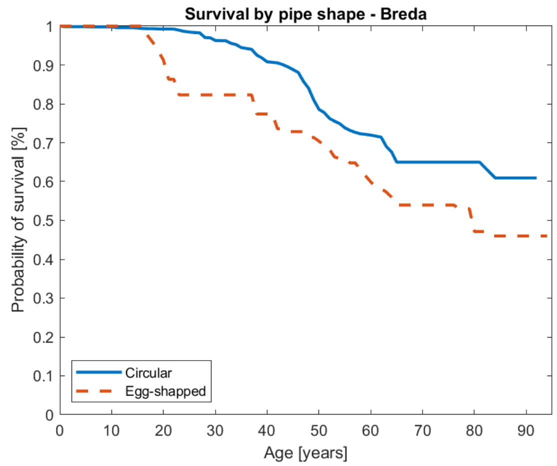


(continue) A.5 Survival by pipe shape per defect - Breda

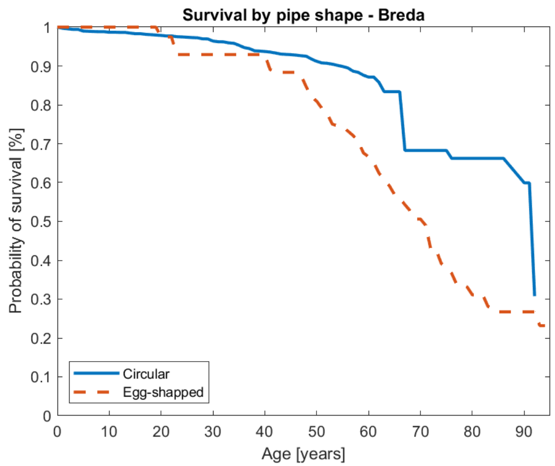
BAJ: Displaced joint



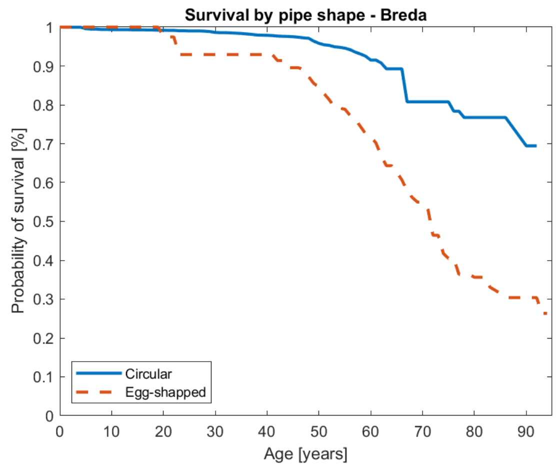
BAN: Porous pipe (Concrete only)



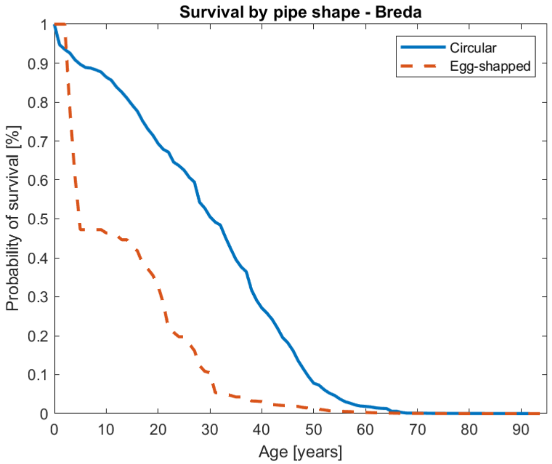
BAO: Soil visible through defect



BAP: Void visible through defect

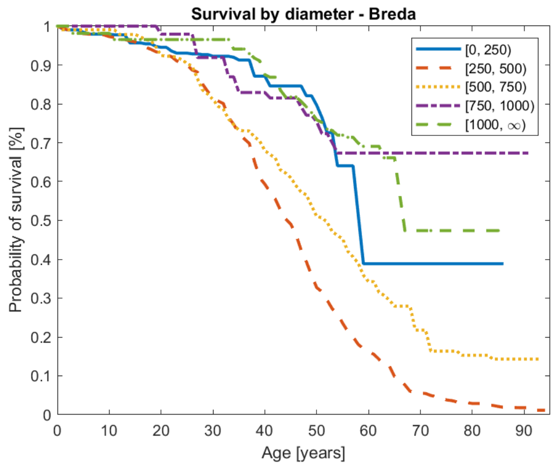


(continue) A.5 Survival by pipe shape per defect – Breda

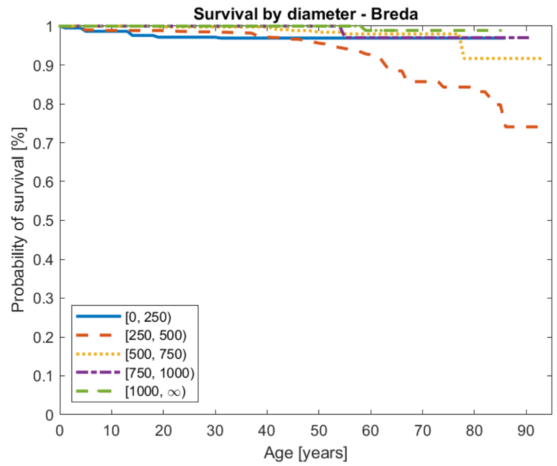
BBF: Infiltration	
	

A.6 Survival by pipe diameter per defect – Breda

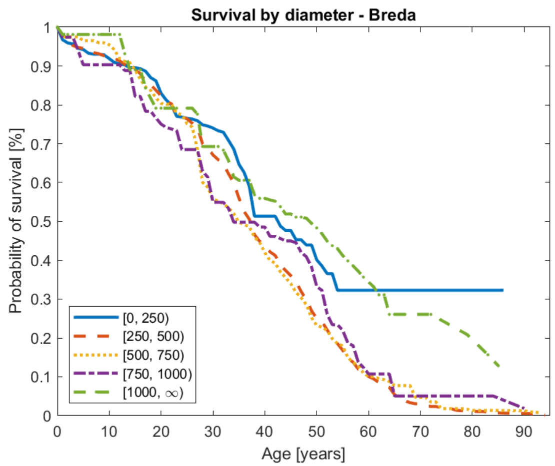
BAB: Crack



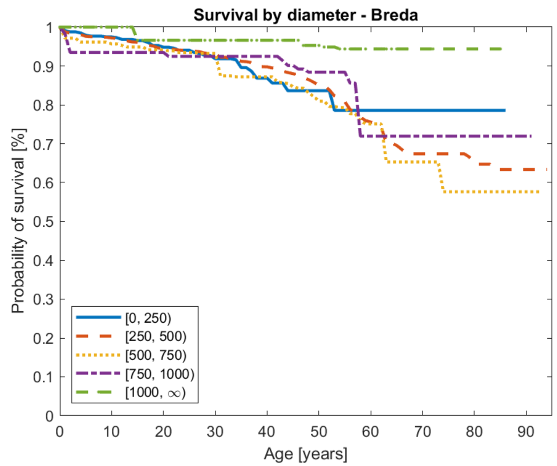
BAC: Break



BAH: Defective connection

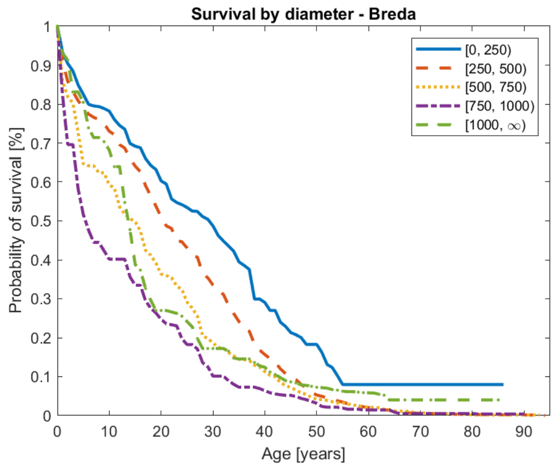


BAI: Intruding sealing material

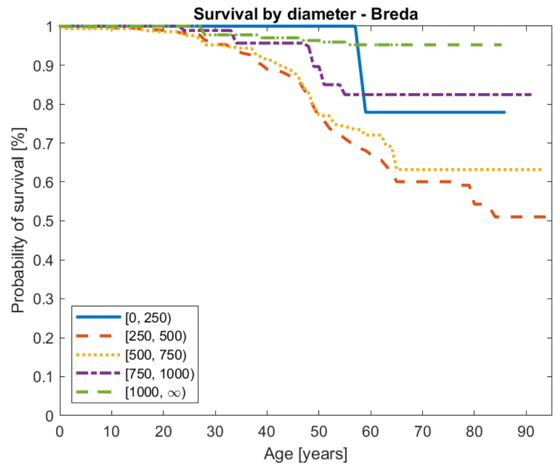


(continue) A.6 Survival by pipe diameter per defect – Breda

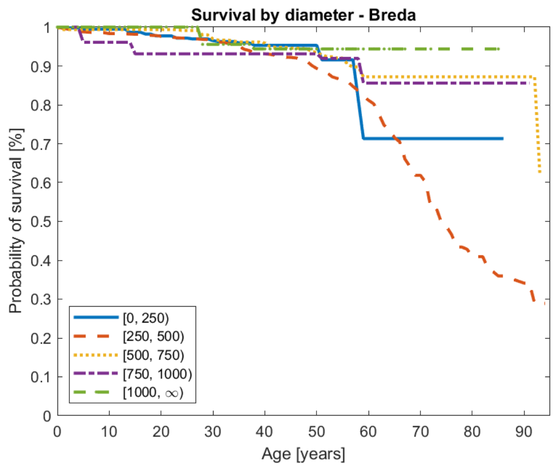
BAJ: Displaced joint



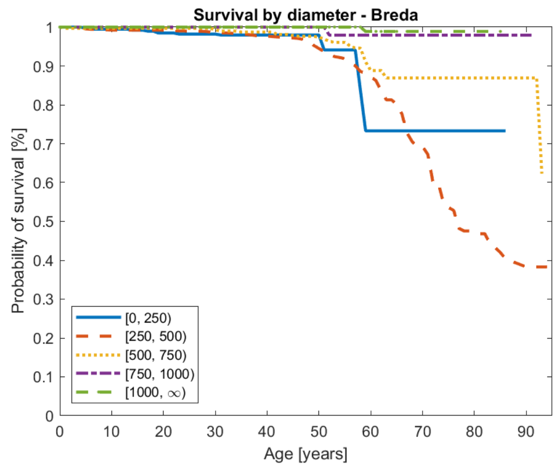
BAN: Porous pipe (Concrete only)



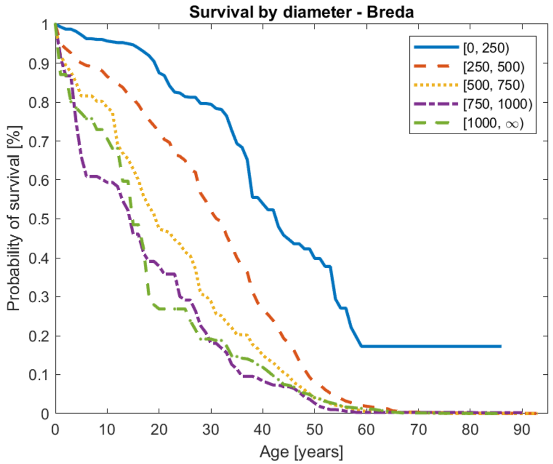
BAO: Soil visible through defect



BAP: Void visible through defect

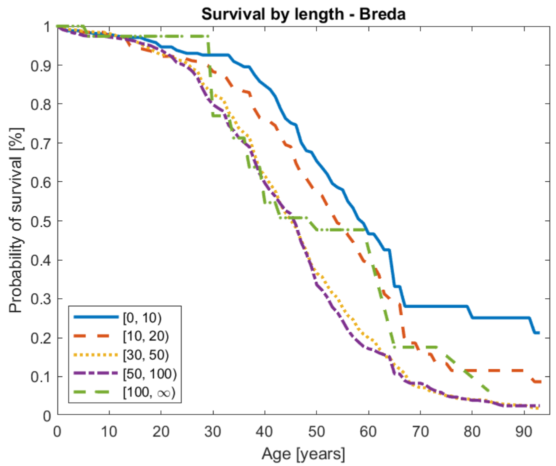


(continue) A.6 Survival by pipe diameter per defect – Breda

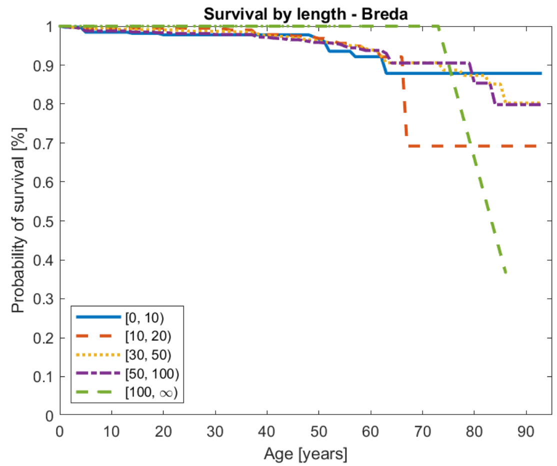
BBF: Infiltration	
	

A.7 Survival by pipe length per defect – Breda

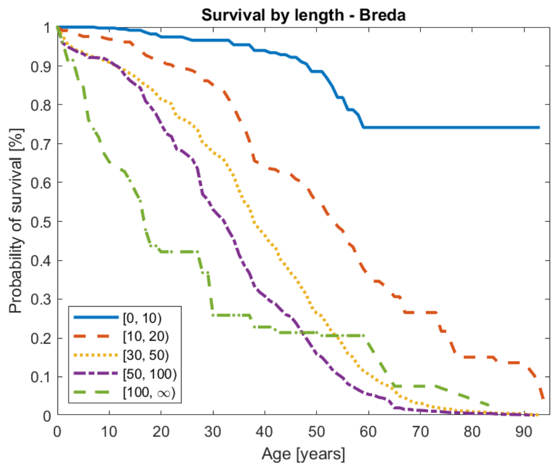
BAB: Crack



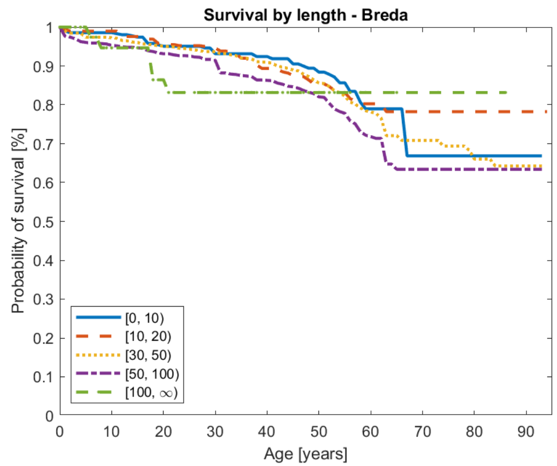
BAC: Break



BAH: Defective connection

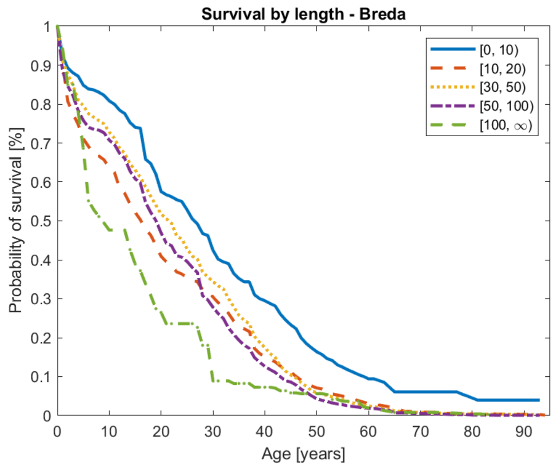


BAI: Intruding sealing material

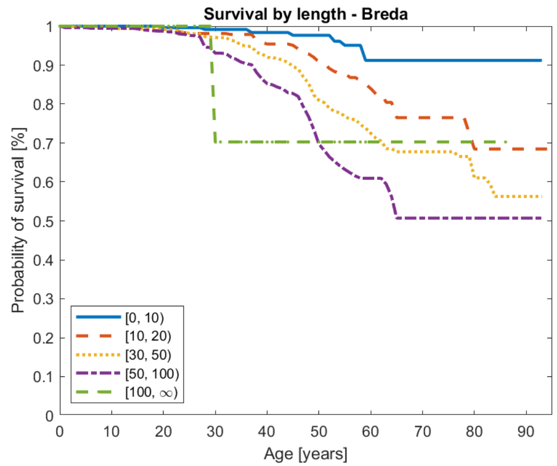


(continue) A.7 Survival by pipe length per defect - Breda

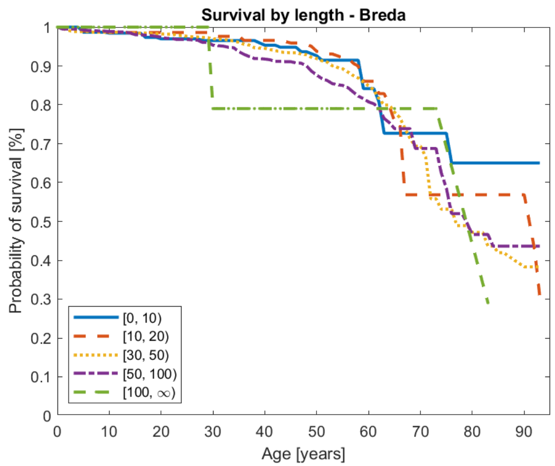
BAJ: Displaced joint



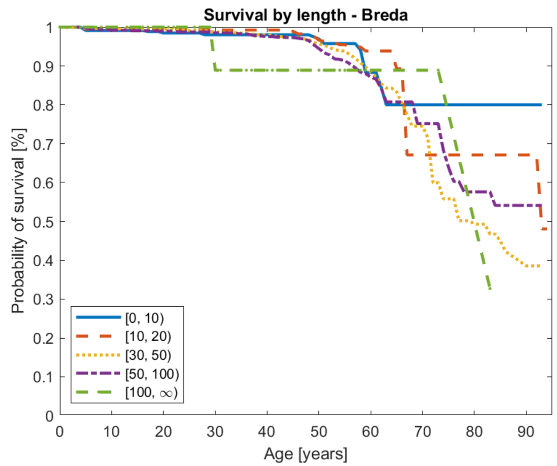
BAN: Porous pipe (Concrete only)



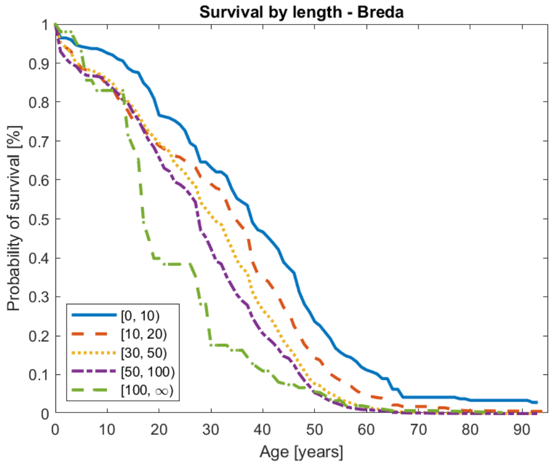
BAO: Soil visible through defect



BAP: Void visible through defect

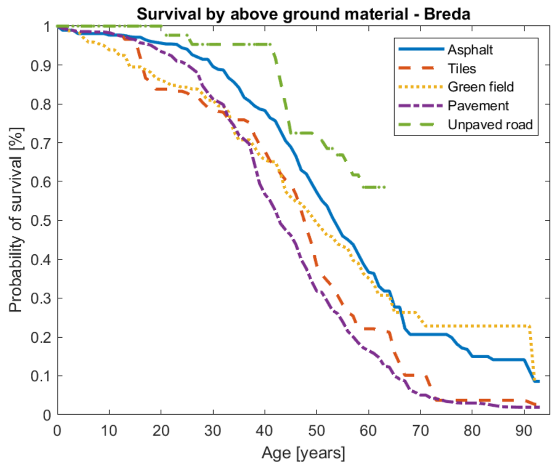


(continue) A.7 Survival by pipe length per defect - Breda

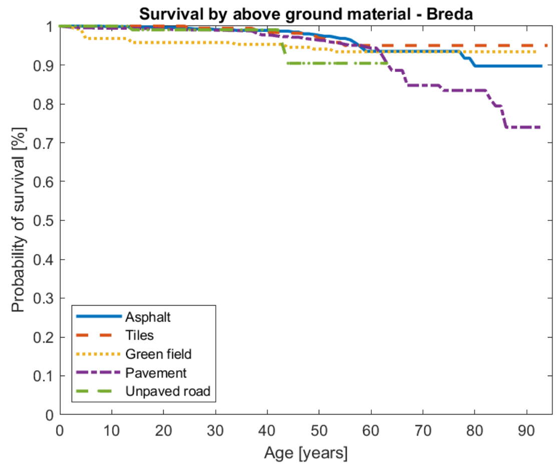
BBF: Infiltration	
	

A.8 Survival by above ground materials per defect – Breda

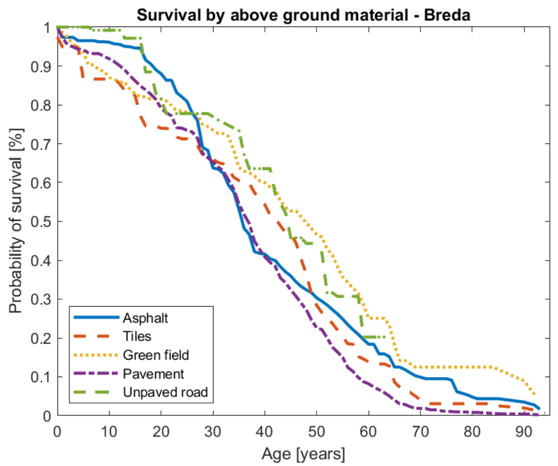
BAB: Crack



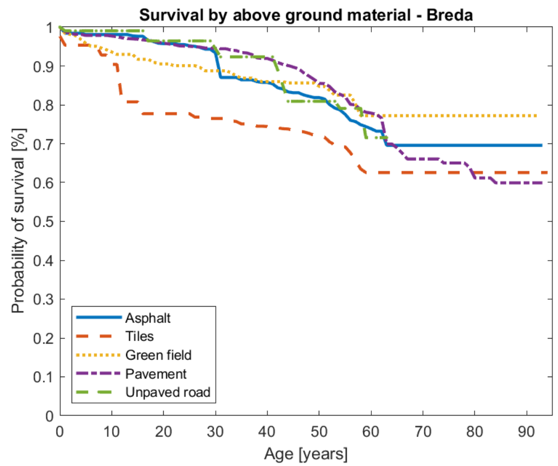
BAC: Break



BAH: Defective connection

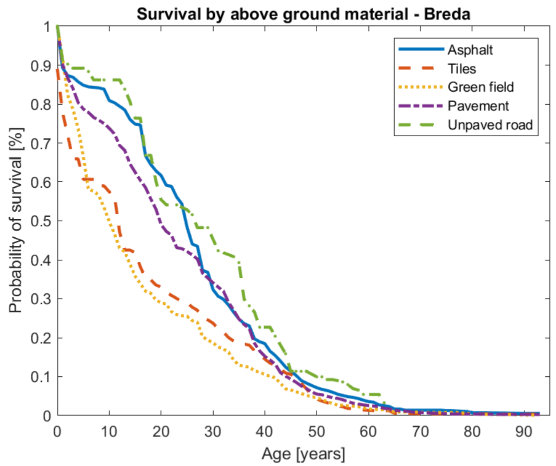


BAI: Intruding sealing material

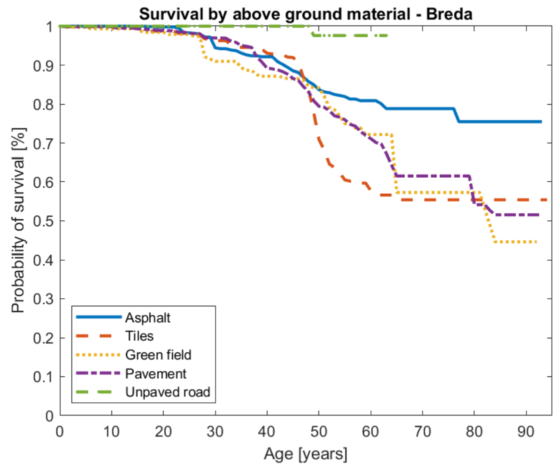


(continue) A.8 Survival by above ground materials per defect - Breda

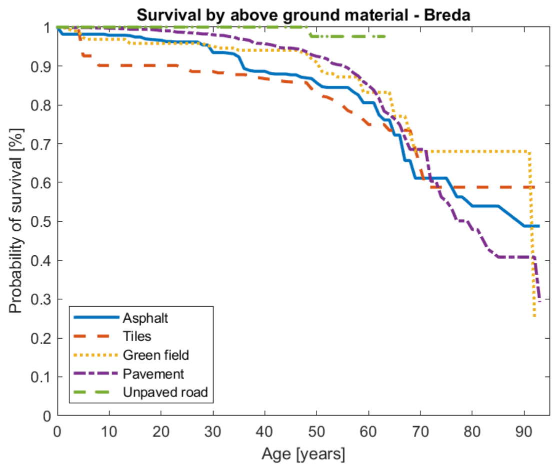
BAJ: Displaced joint



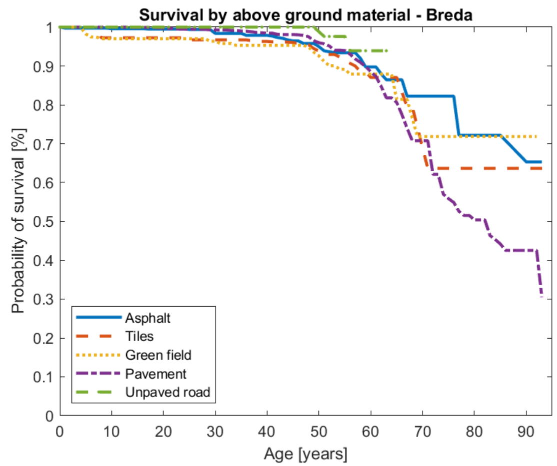
BAN: Porous pipe (Concrete only)



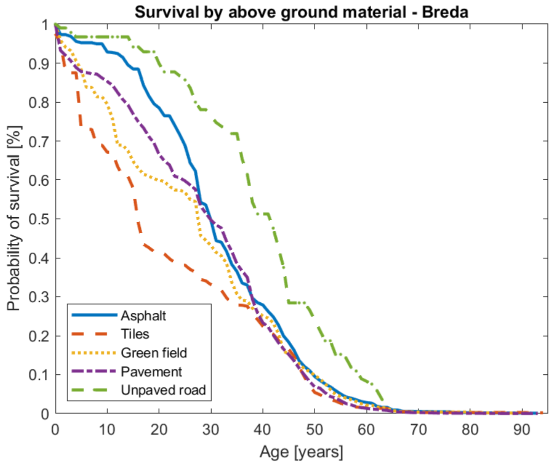
BAO: Soil visible through defect



BAP: Void visible through defect



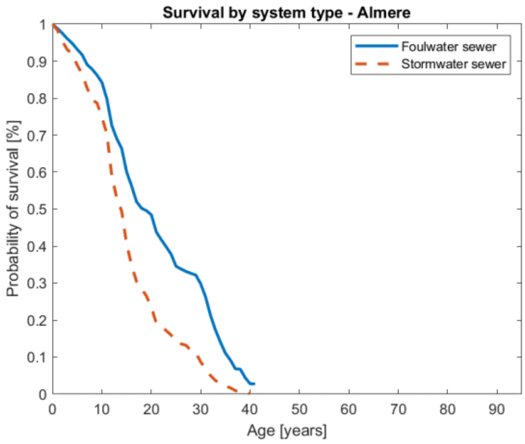
(continue) A.8 Survival by above ground materials per defect - Breda

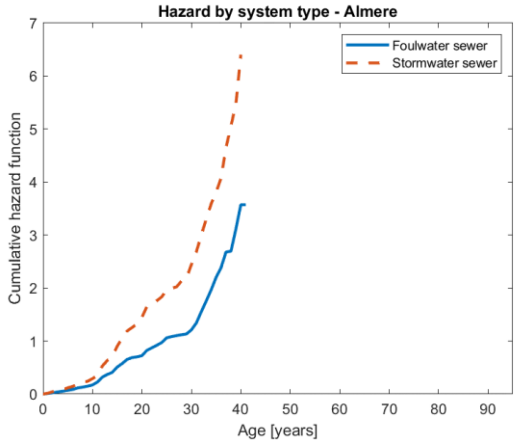
BBF: Infiltration	
	

Appendix B: Non-parametric survival analysis Almere

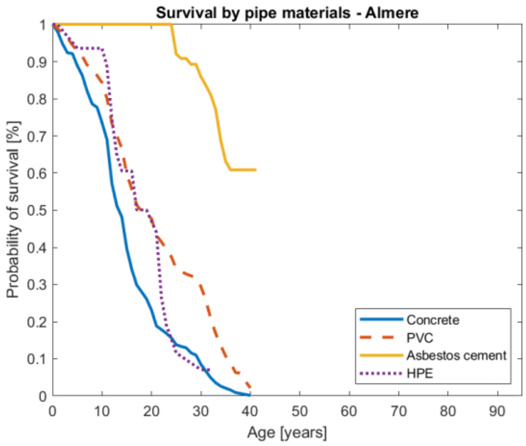
B.1 Aggregate defects. Survival analysis and hazard function

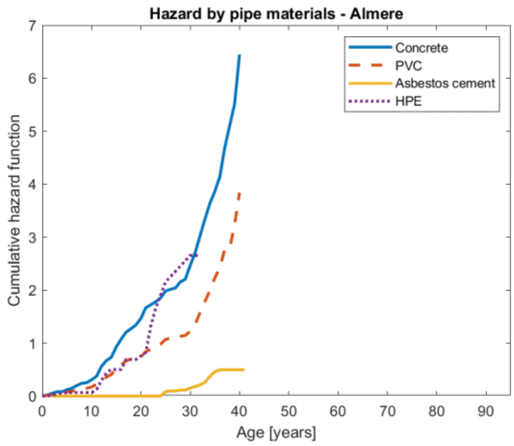
- Sewer system type



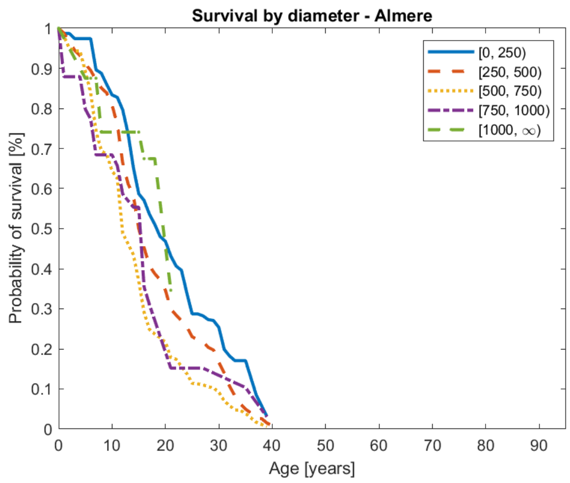


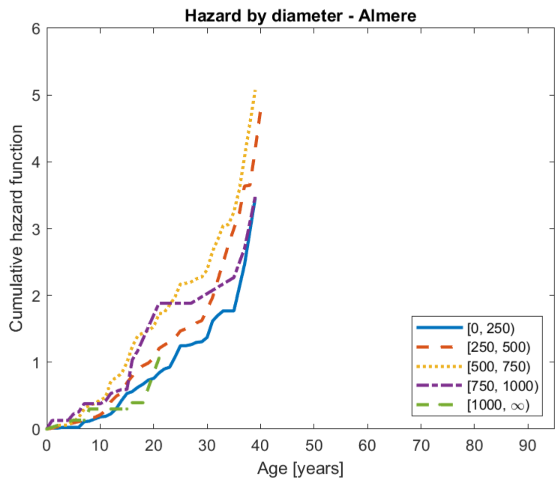
- Materials



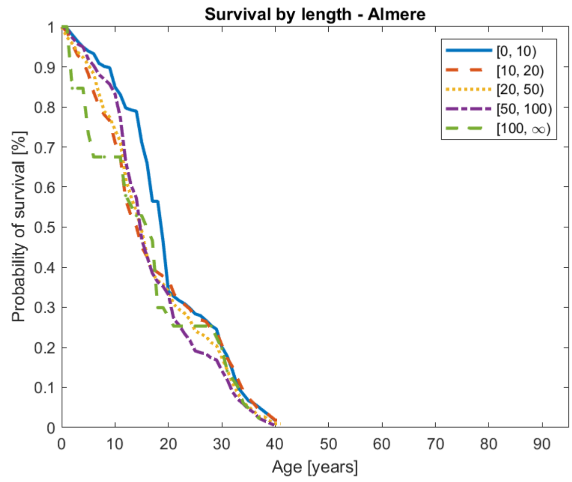


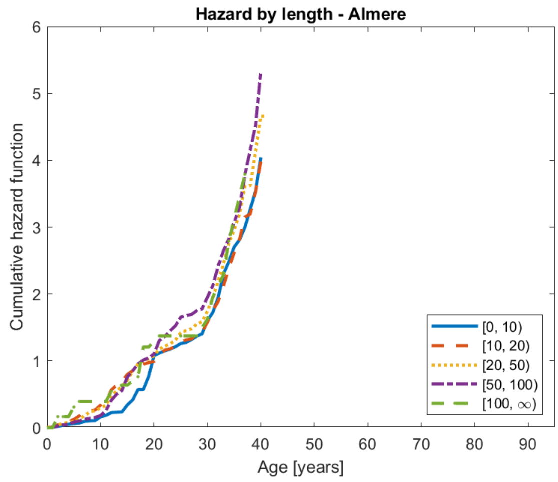
- Diameter



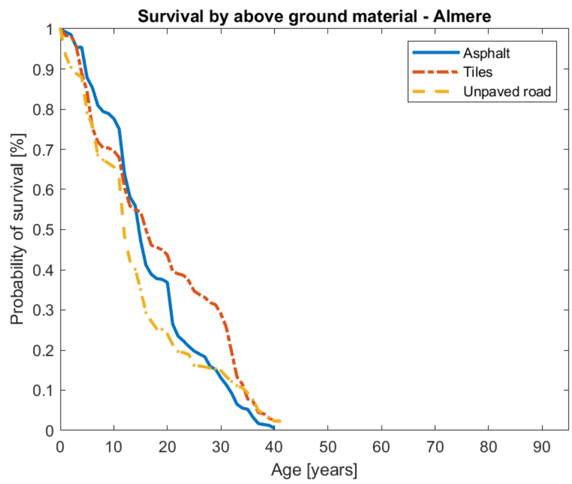


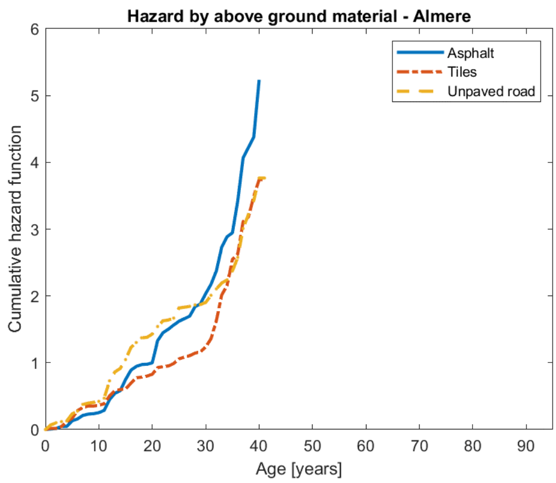
- Length





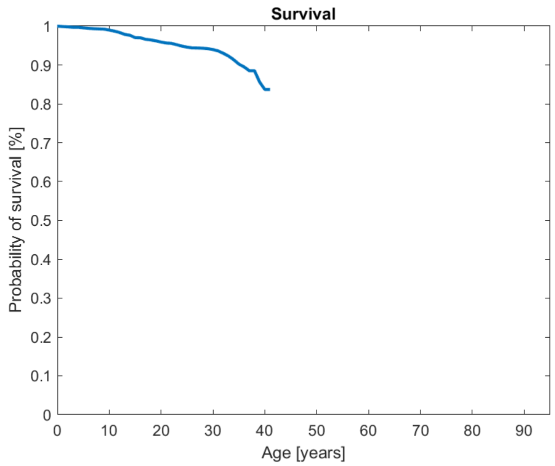
- Above ground material



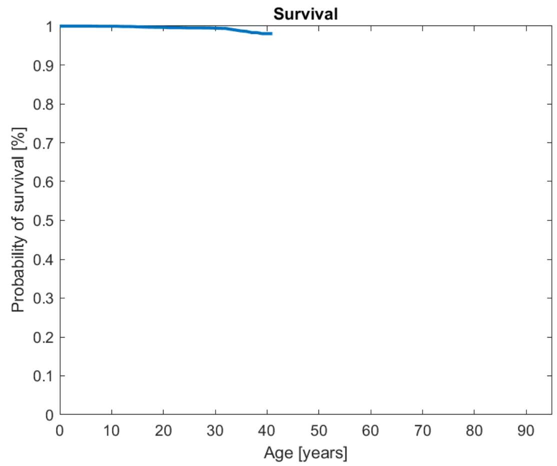


B.2 Survival probability per defect- Almere

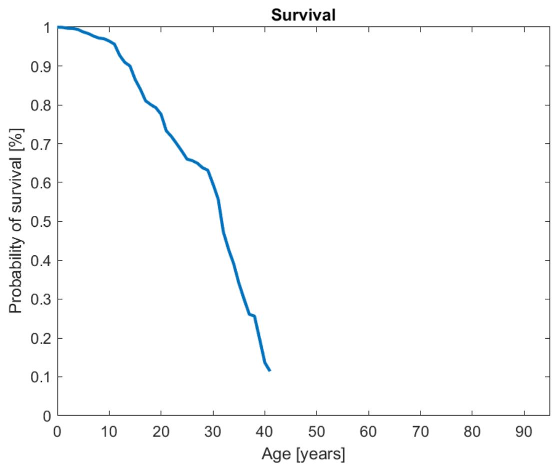
BAB: Crack



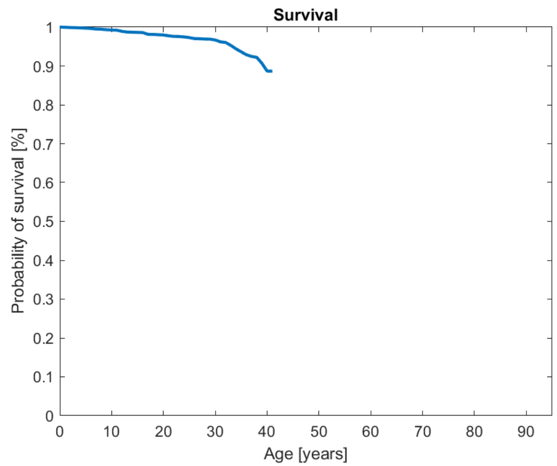
BAC: Break



BAH: Defective connection

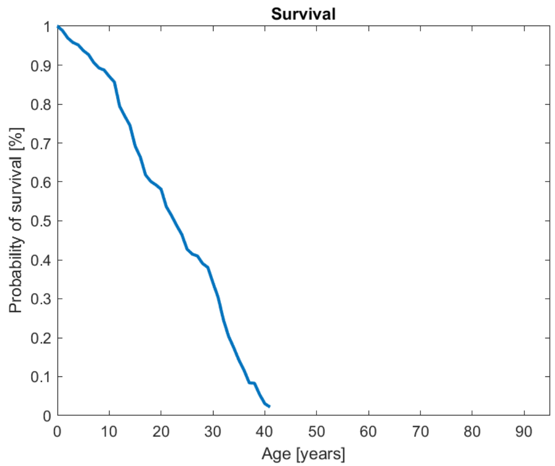


BAI: Intruding sealing material

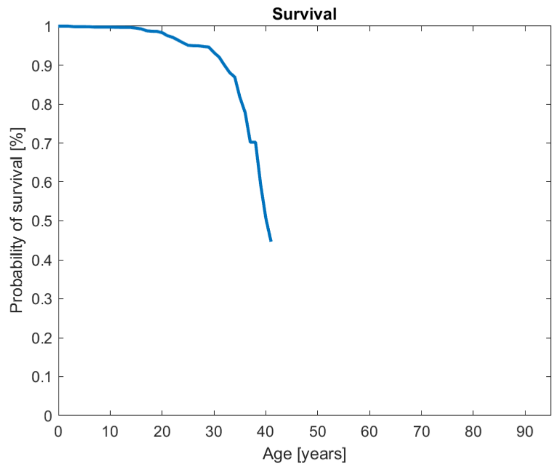


(continue) B.2 Survival probability per defect - Almere

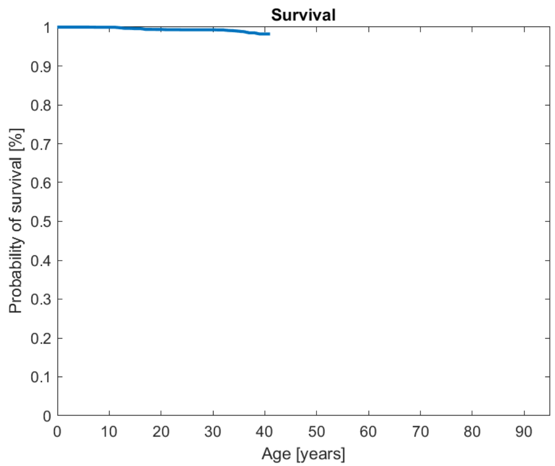
BAJ: Displaced joint



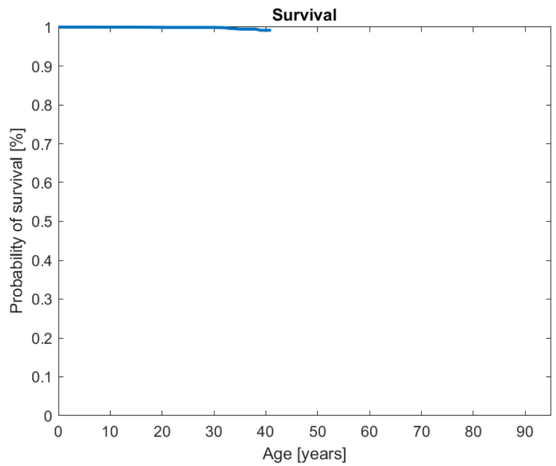
BAN: Porous pipe (Concrete only)



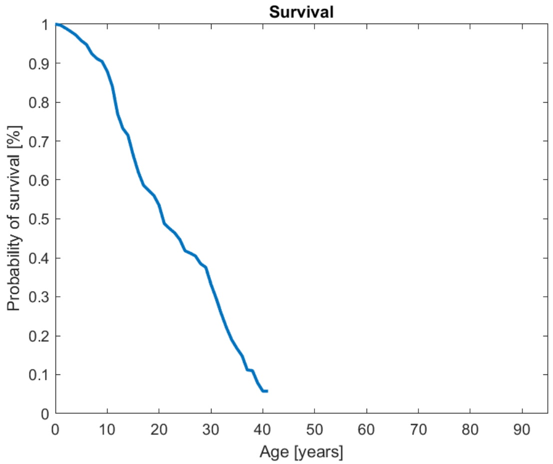
BAO: Soil visible through defect



BAP: Void visible through defect

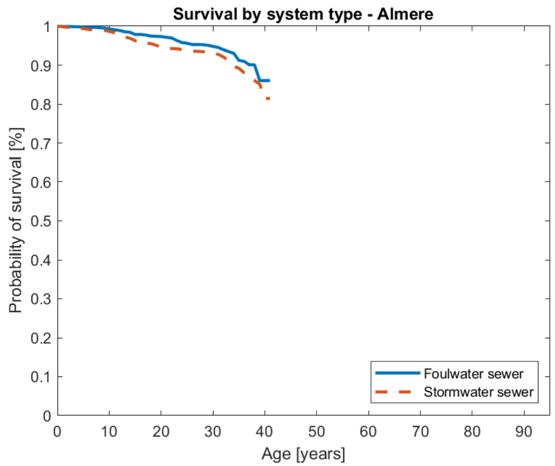


(continue) B.2 Survival probability per defect - Almere

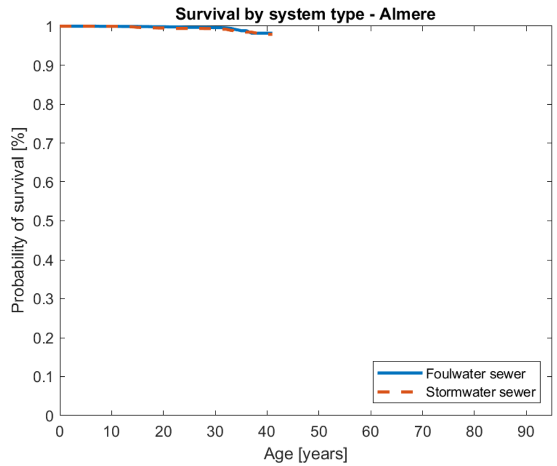
BBF: Infiltration	
	

B. 3 Survival by sewer type per defect - Almere

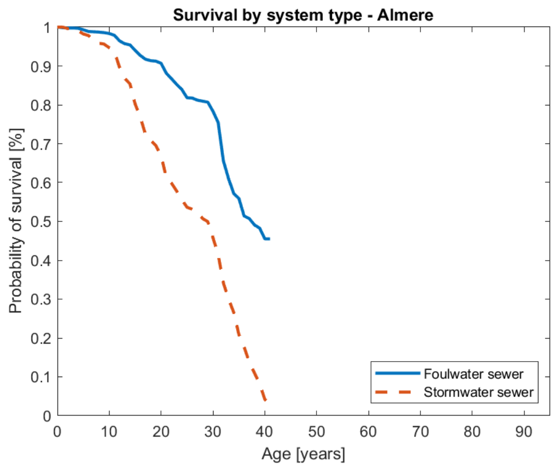
BAB: Crack



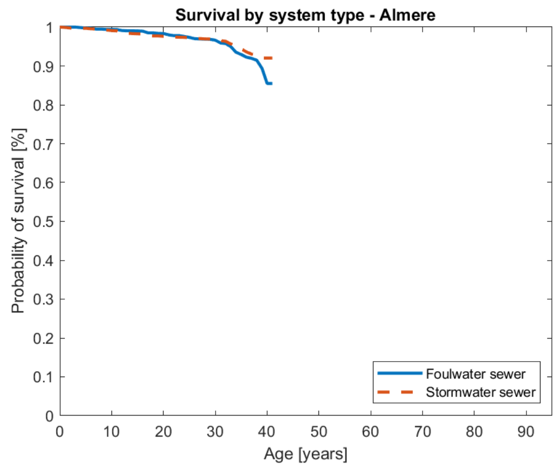
BAC: Break



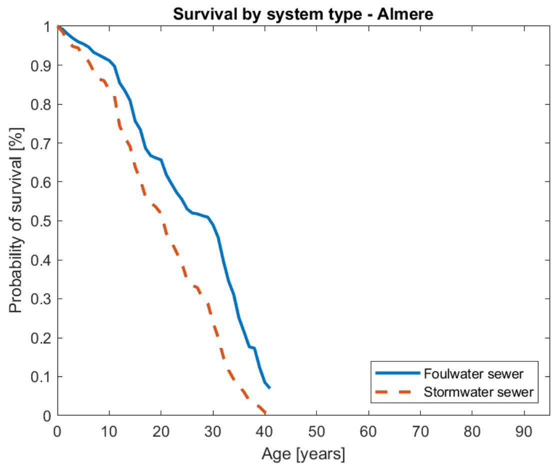
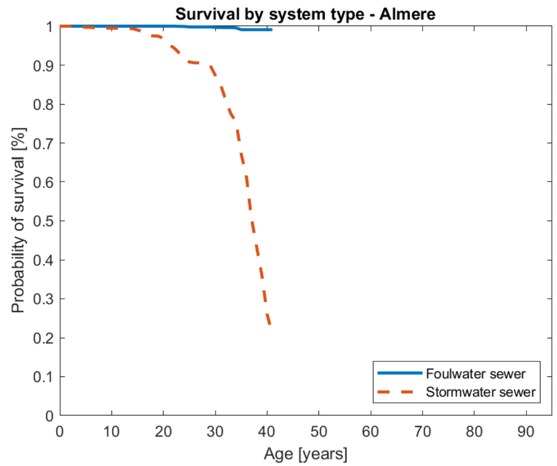
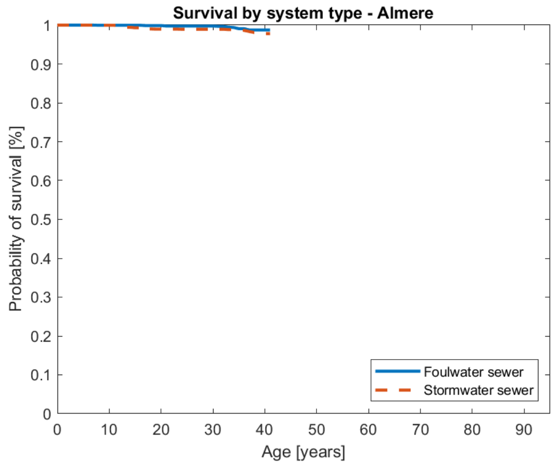
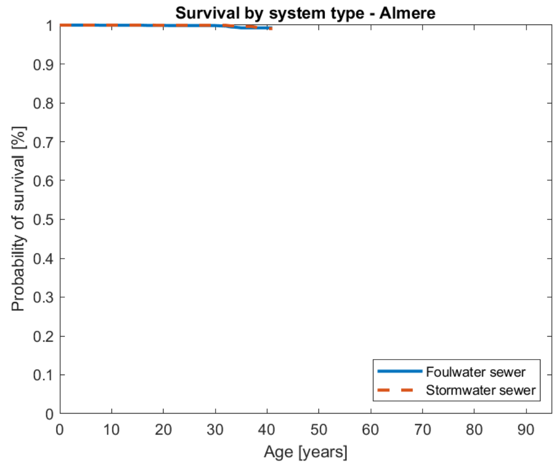
BAH: Defective connection



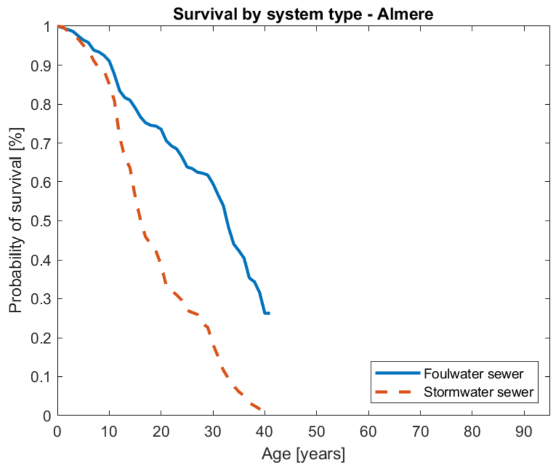
BAI: Intruding sealing material



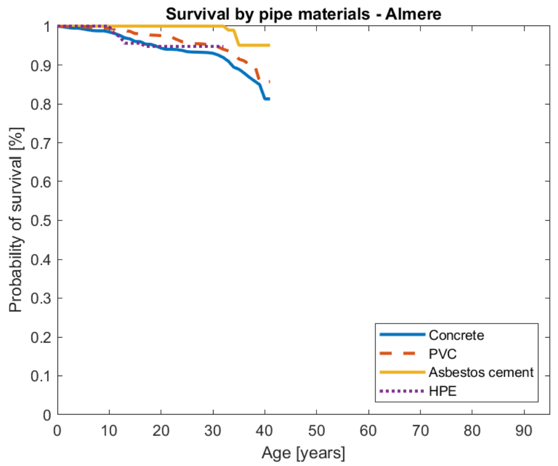
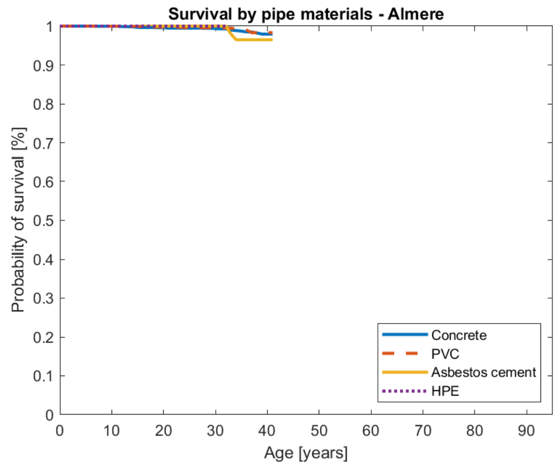
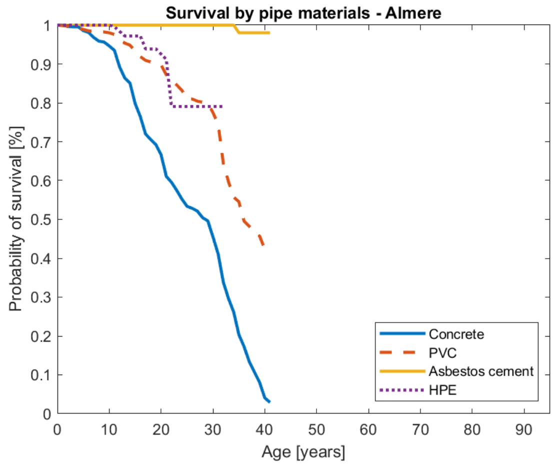
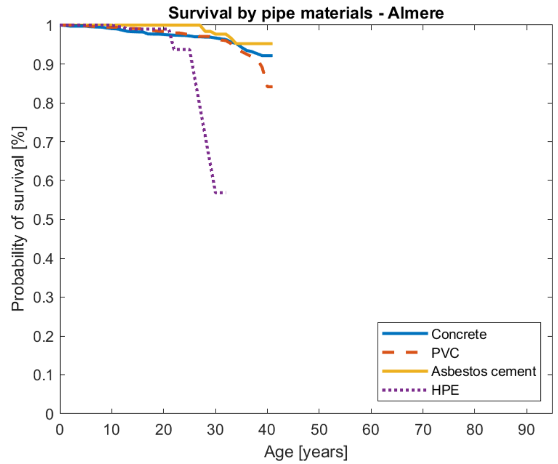
(continue) B.3 Survival by sewer type per defect - Almere

BAJ: Displaced joint	BAN: Porous pipe (Concrete only)
	
BAO: Soil visible through defect	**BAP: Void visible through defect**
	

(continue) B.3 Survival by sewer type per defect - Almere

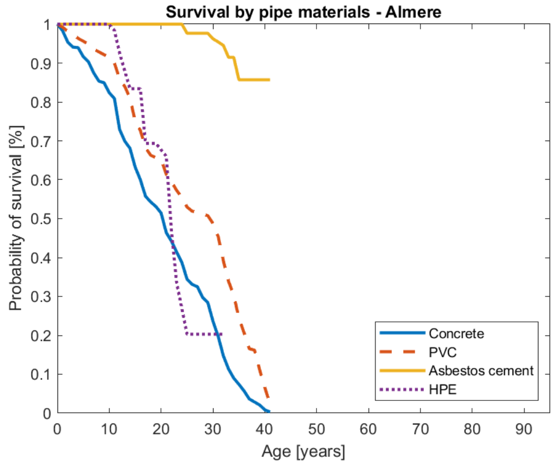
BBF: Infiltration	
	

B. 4 Survival by material per defect - Almere

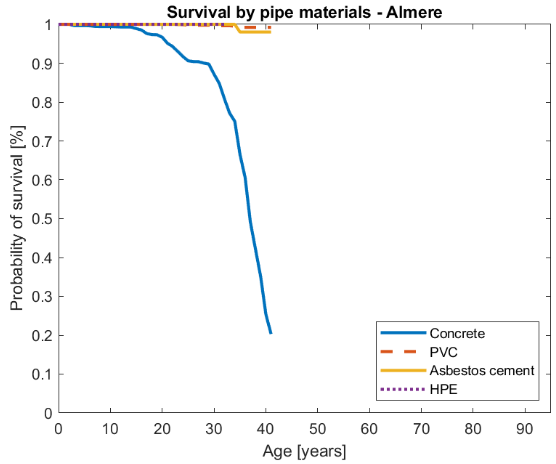
BAB: Crack	BAC: Break
	
BAH: Defective connection	**BAI: Intruding sealing material**
	

(continue) B.4 Survival by material per defect - Almere

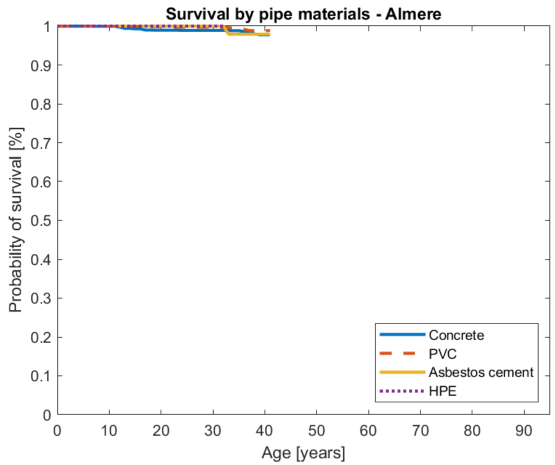
BAJ: Displaced joint



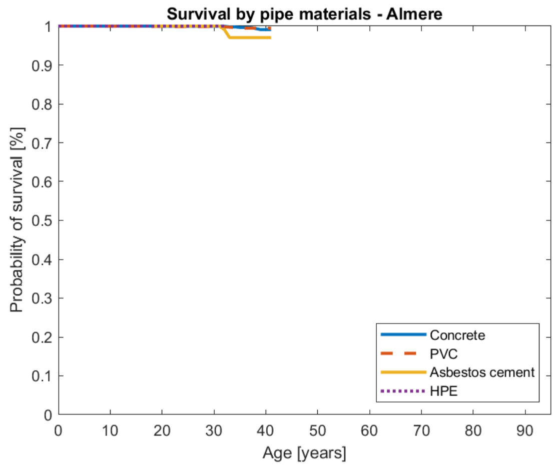
BAN: Porous pipe (Concrete only)



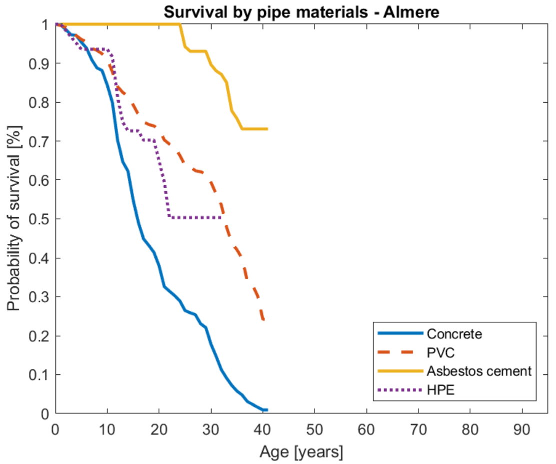
BAO: Soil visible through defect



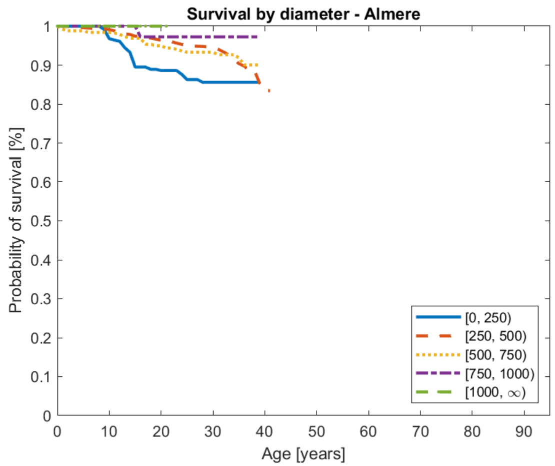
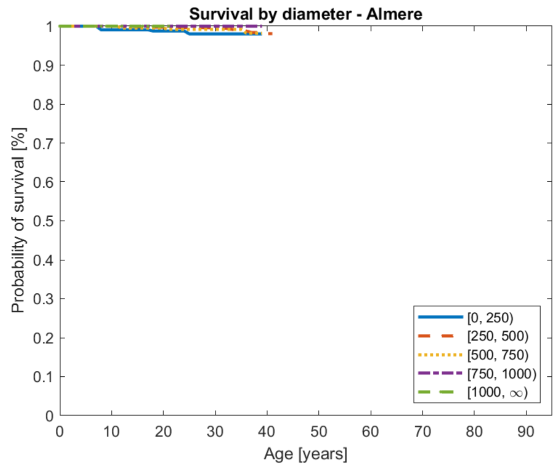
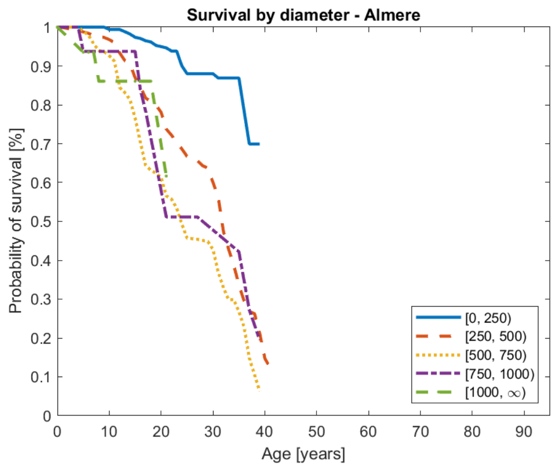
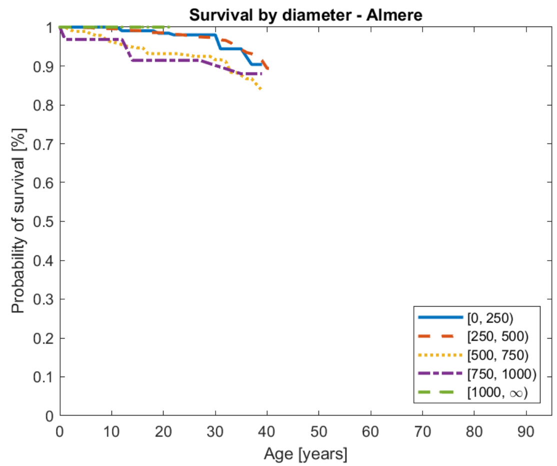
BAP: Void visible through defect



(continue) B.4 Survival by material per defect – Almere

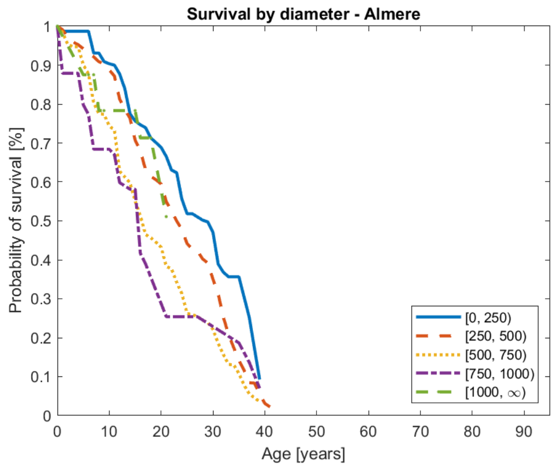
BBF: Infiltration	
	

B.5 Survival by pipe diameter per defect – Almere

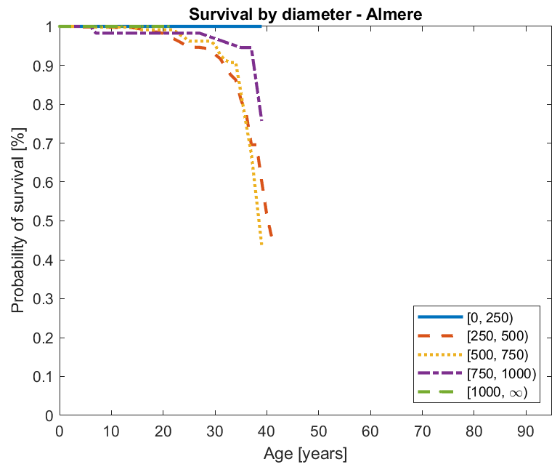
BAB: Crack	BAC: Break
	
BAH: Defective connection	**BAI: Intruding sealing material**
	

(continue) B.5 Survival by pipe diameter per defect - Almere

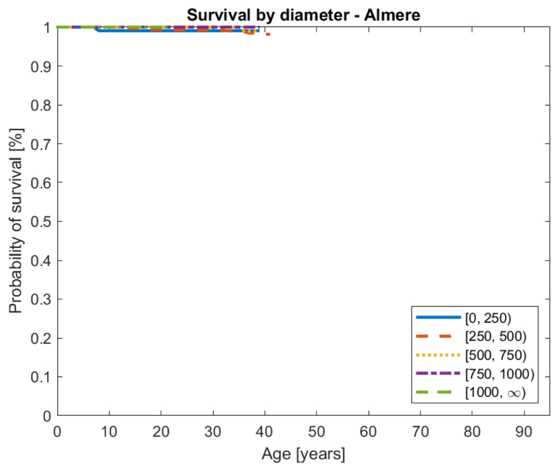
BAJ: Displaced joint



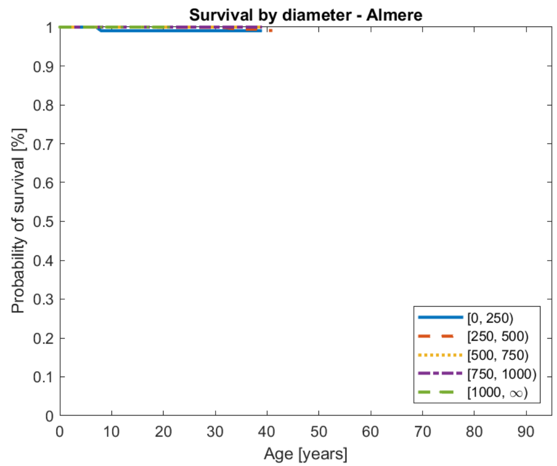
BAN: Porous pipe (Concrete only)



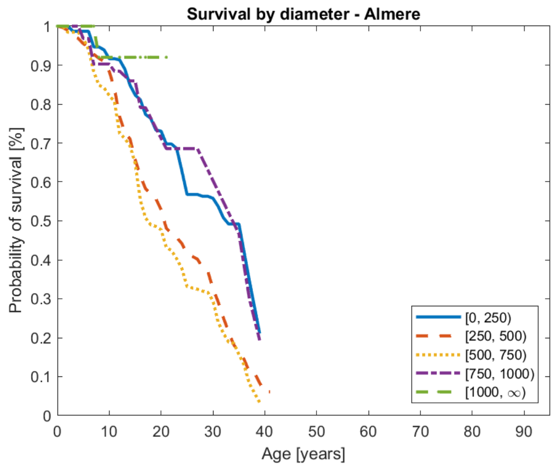
BAO: Soil visible through defect



BAP: Void visible through defect

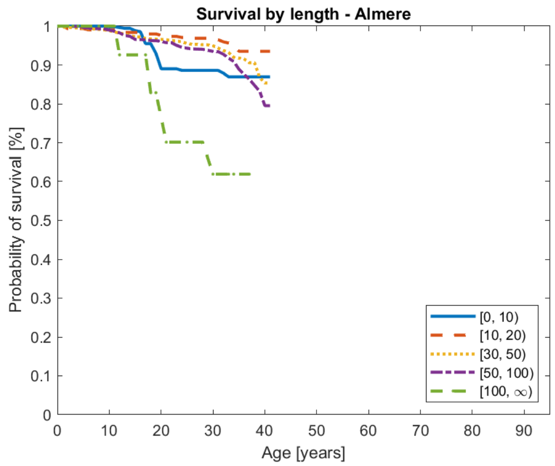


(continue) B.5 Survival by pipe diameter per defect - Almere

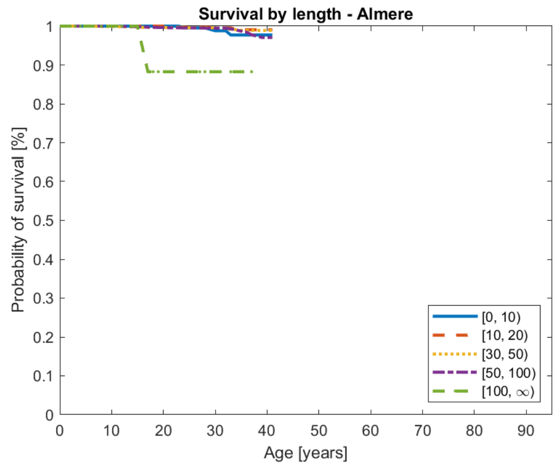
BBF: Infiltration	
	

B.6 Survival by pipe length per defect – Almere

BAB: Crack

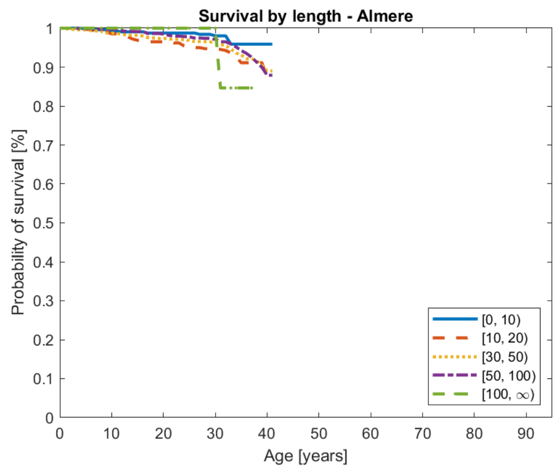


BAC: Break

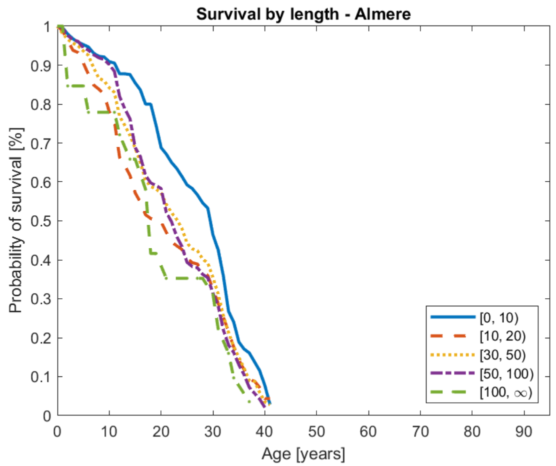
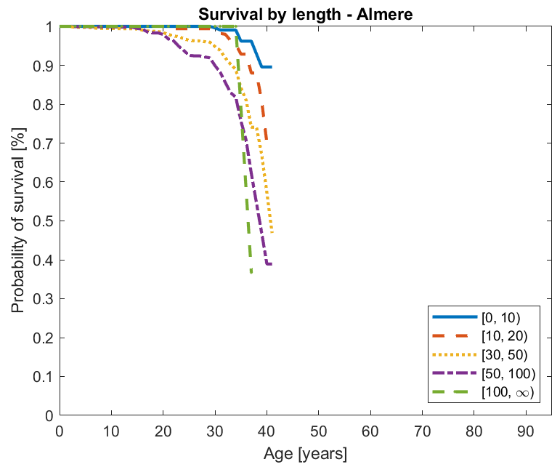
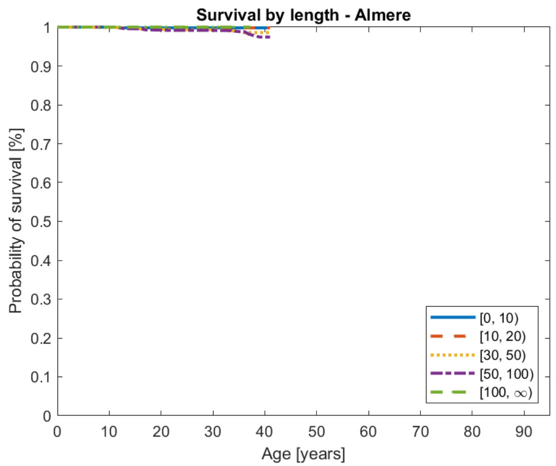
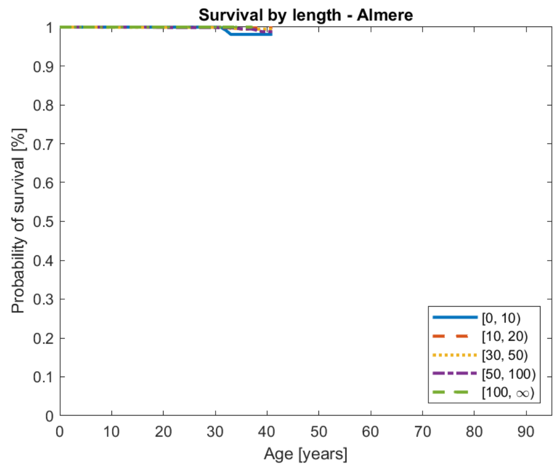


BAH: Defective connection

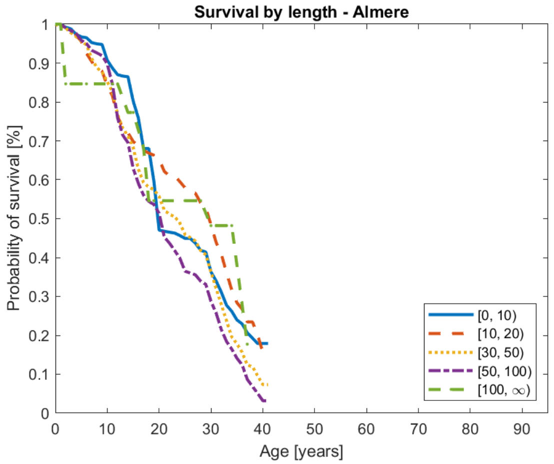
BAI: Intruding sealing material



(continue) B.6 Survival by pipe length per defect - Almere

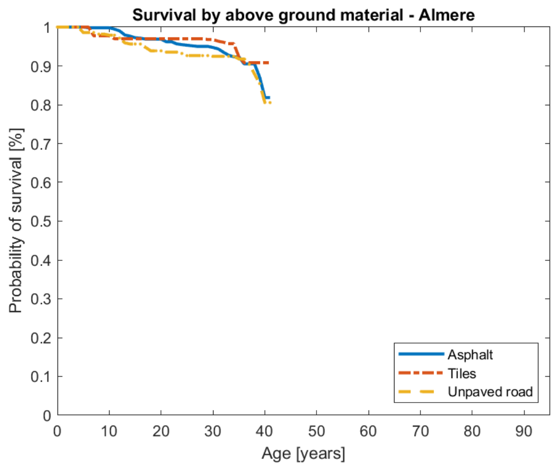
BAJ: Displaced joint	BAN: Porous pipe (Concrete only)
	
BAO: Soil visible through defect	**BAP: Void visible through defect**
	

(continue) B.6 Survival by pipe length per defect - Almere

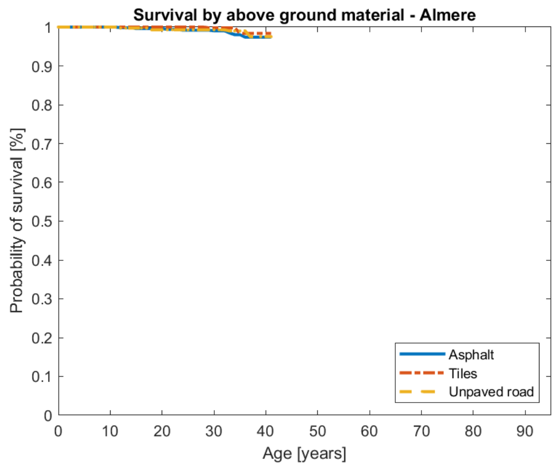
BBF: Infiltration	
	

B.7 Survival by above ground materials per defect – Almere

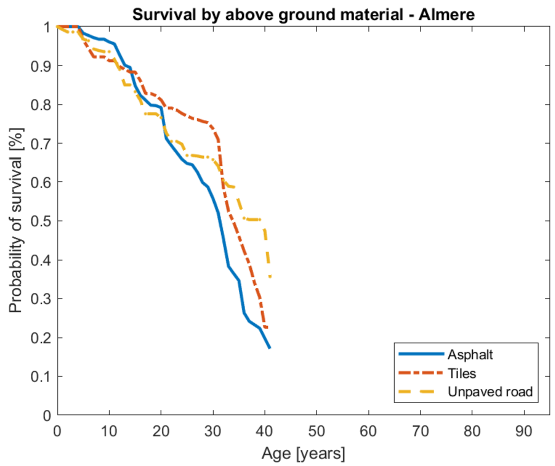
BAB: Crack



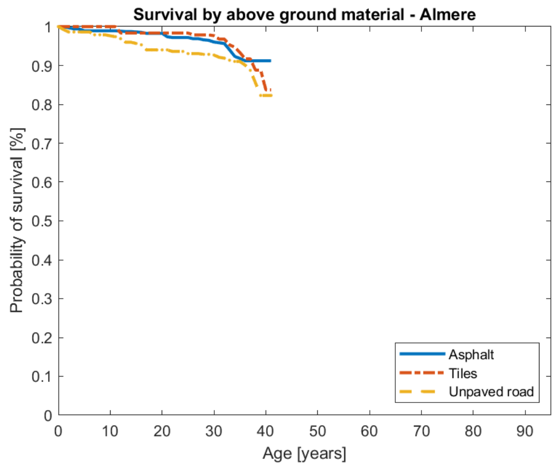
BAC: Break



BAH: Defective connection

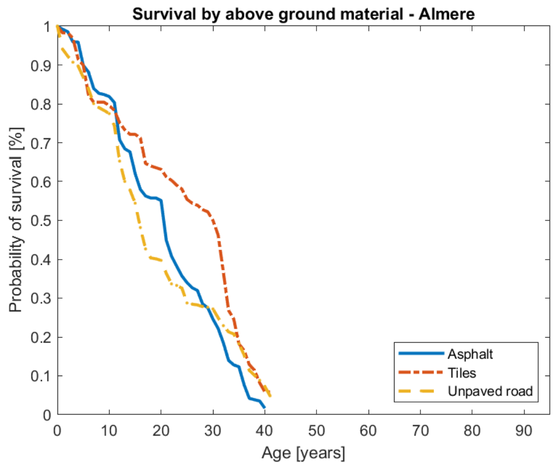


BAI: Intruding sealing material

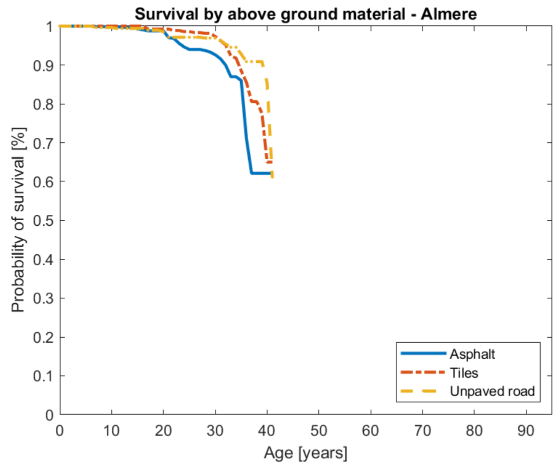


(continue) B.7 Survival by above ground materials per defect - Almere

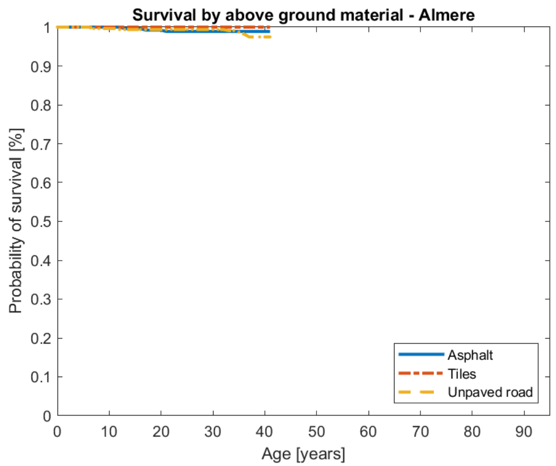
BAJ: Displaced joint



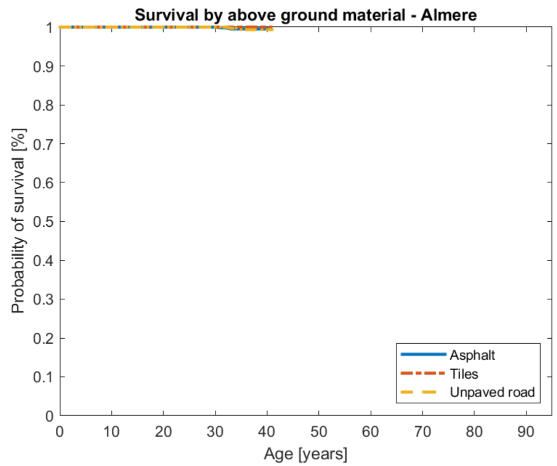
BAN: Porous pipe (Concrete only)



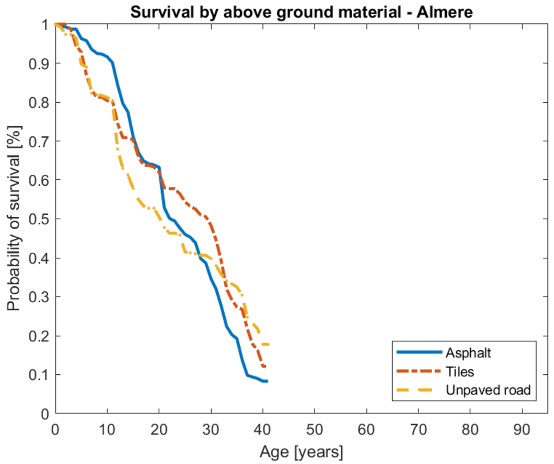
BAO: Soil visible through defect



BAP: Void visible through defect



(continue) B.7 Survival by above ground materials per defect - Almere

BBF: Infiltration	
	

Appendix C: Validation Cox proportional hazard model

C.1 Graphical validation (-ln (-ln ESE))

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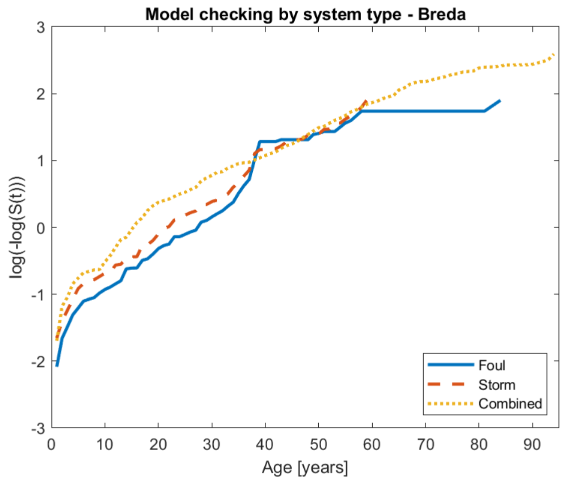
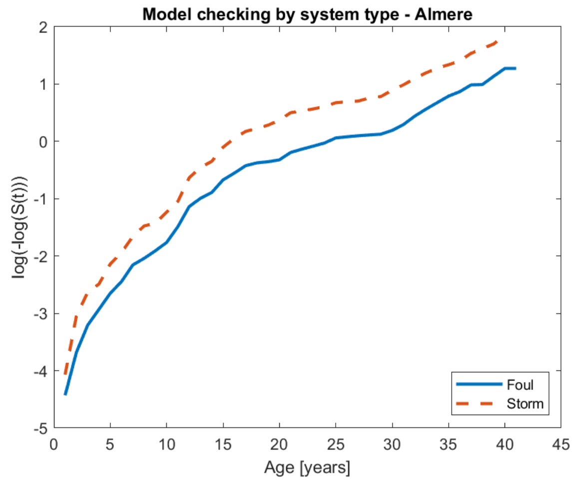
<tr><td>Sewer System</td><td>
</td><td>
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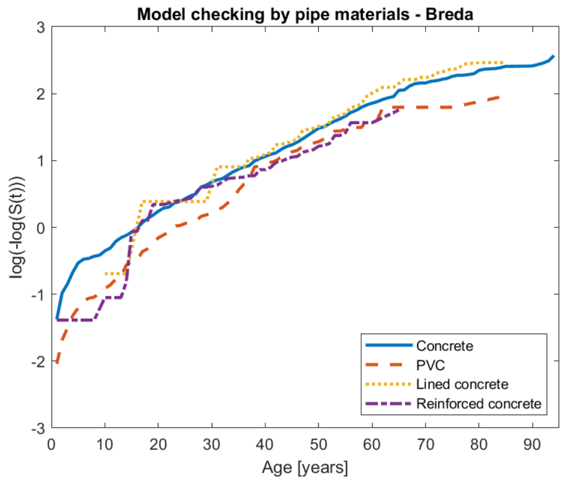
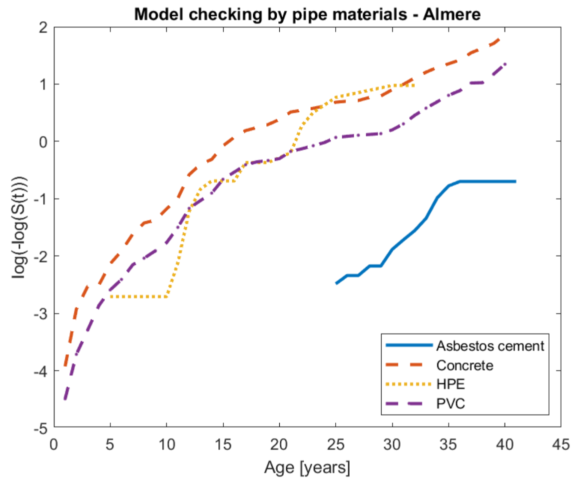
<tr><td>Materials</td><td>
</td><td>
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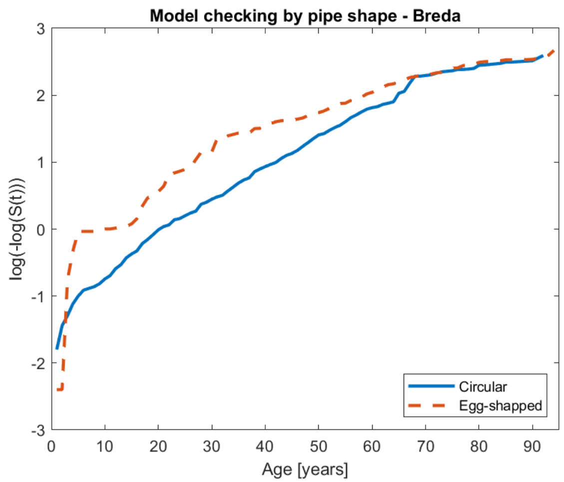
<tr><td>Shape</td><td>
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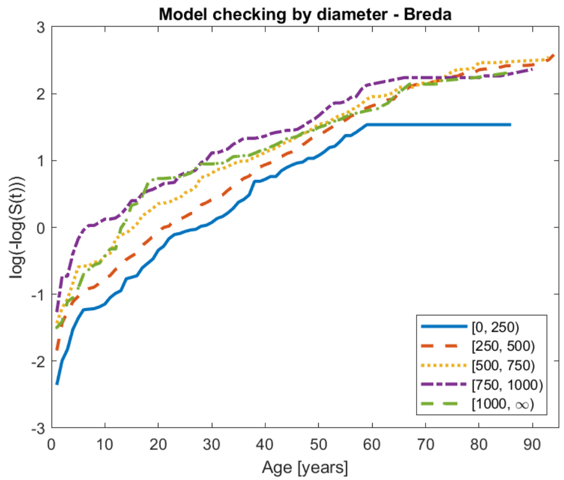
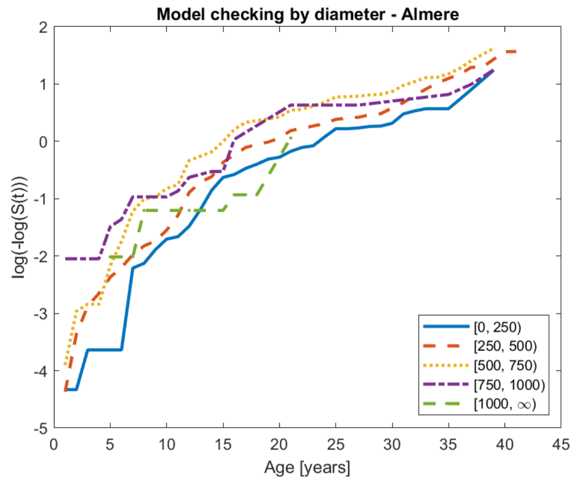
<tr><td>Diameter</td><td>
</td><td>
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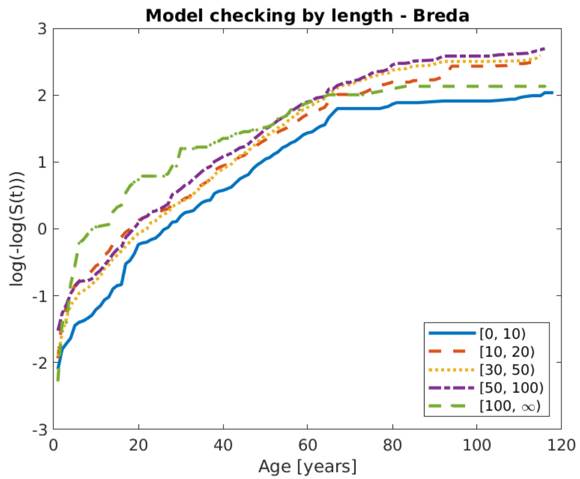
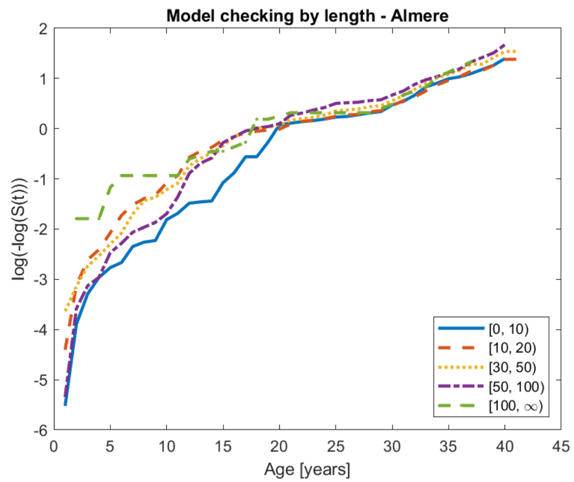
<tr><td>Length</td><td>
</td><td>
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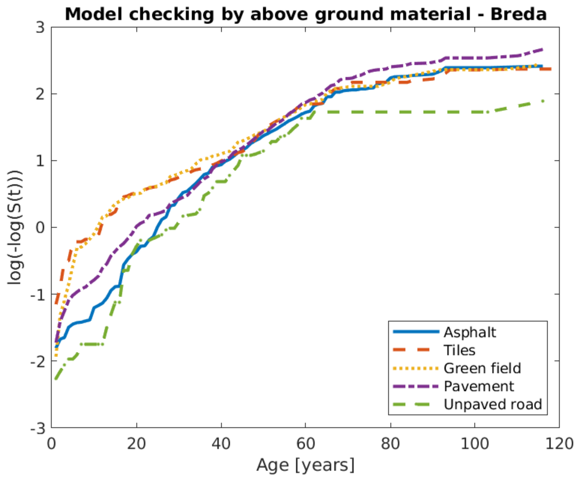
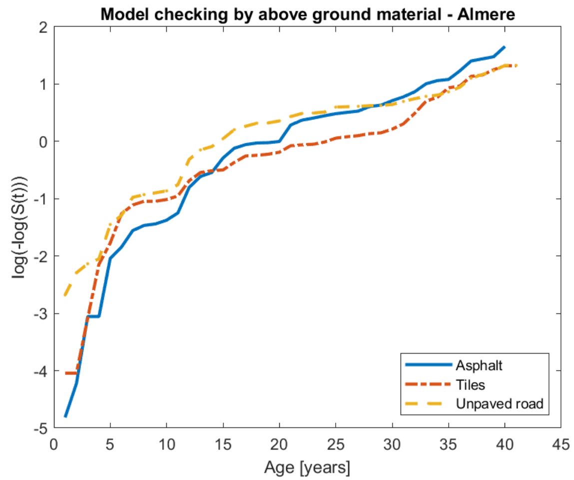
<tr><td>Above ground material</td><td>
</td><td>
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C.2 Graphical validation (Observed vs Expected)

C.2.1 Almere

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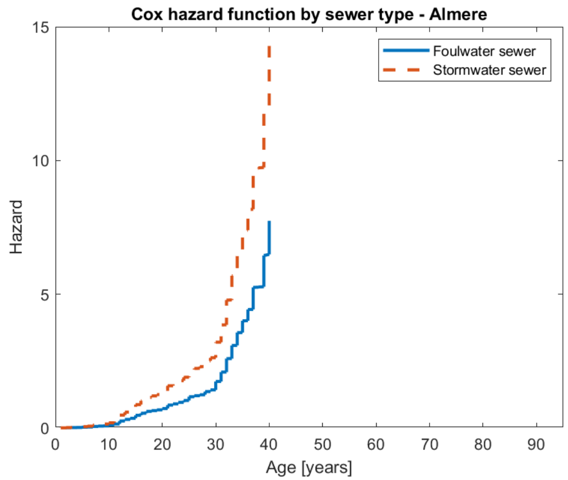
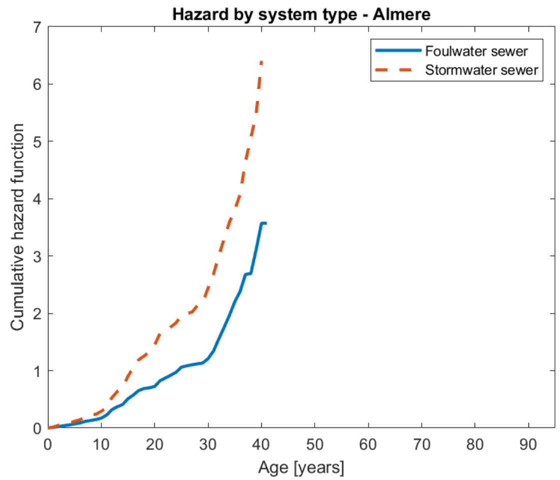
<tr><td>Sewer System</td><td>
</td><td>
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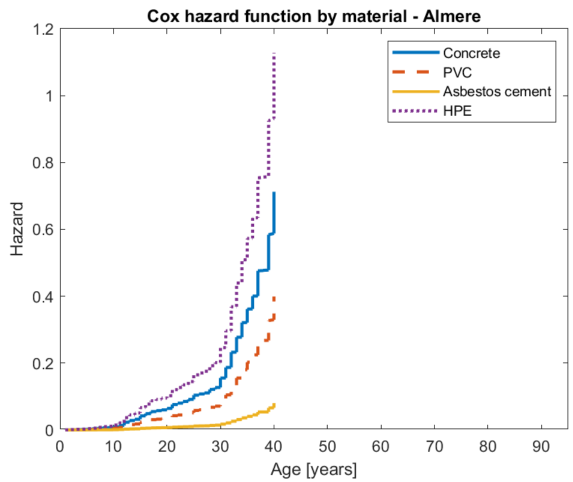
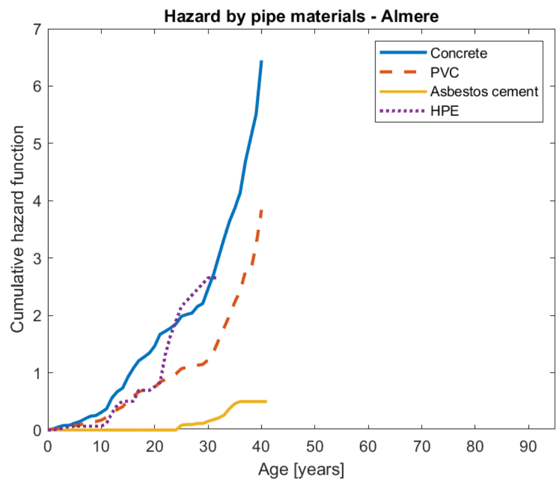
<tr><td>Materials</td><td>
</td><td>
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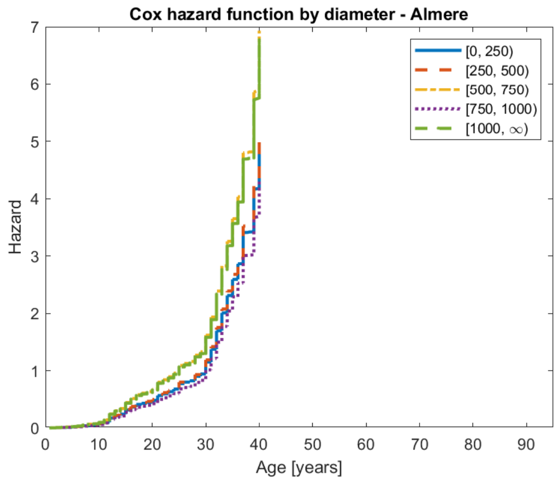
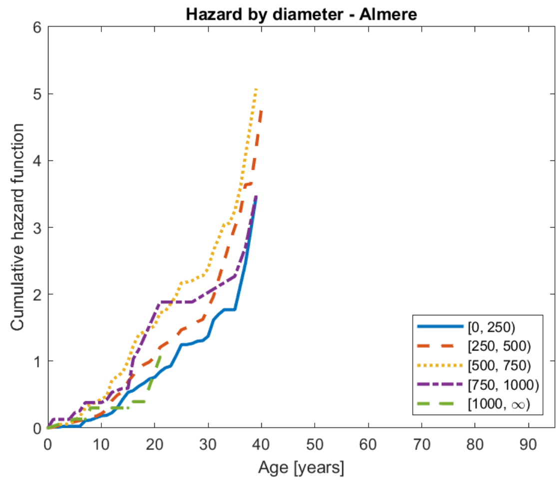
<tr><td>Diameter</td><td>
</td><td>
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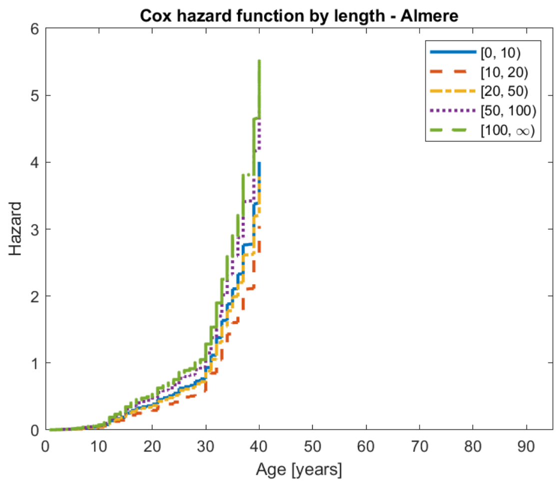
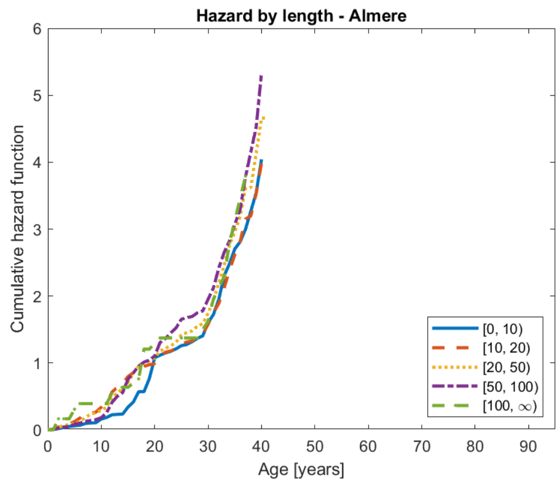
<tr><td>Length</td><td>
</td><td>
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C.2.2 Breda

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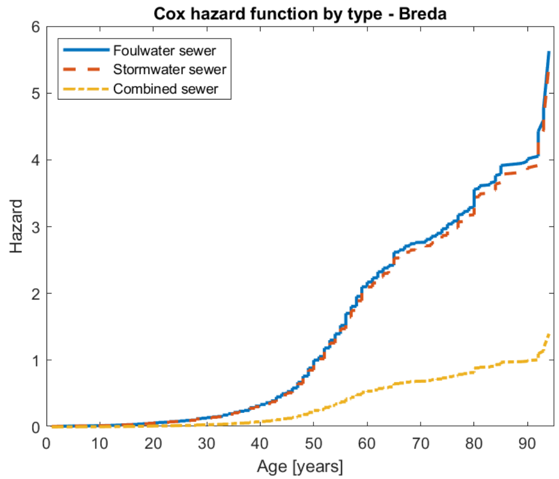
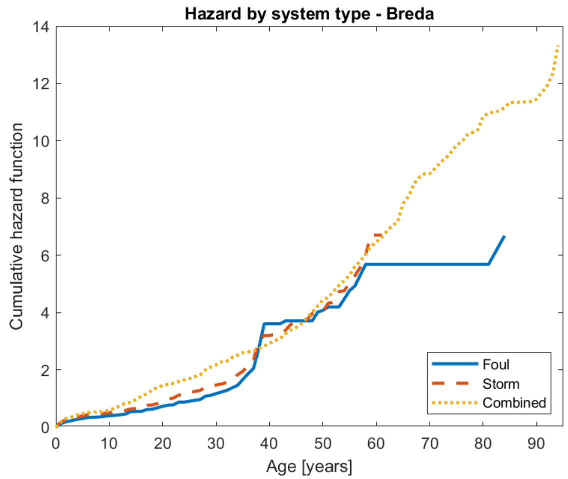
<tr><td>Sewer System</td><td>
</td><td>
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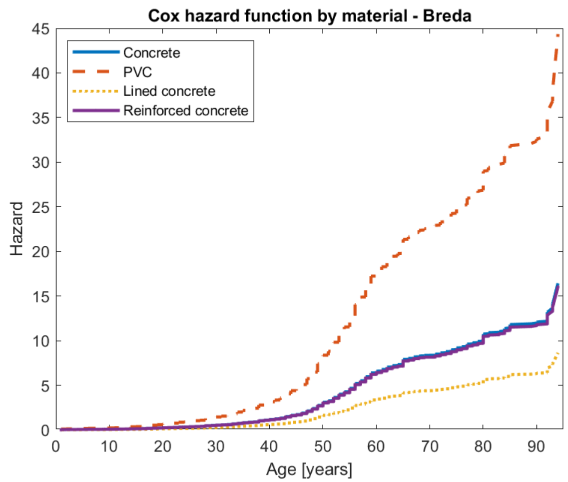
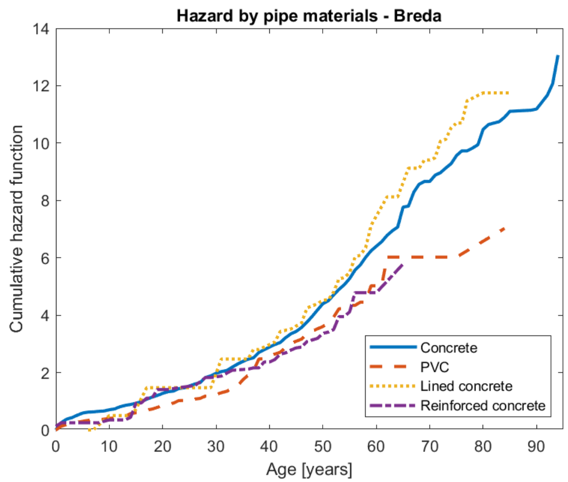
<tr><td>Materials</td><td>
</td><td>
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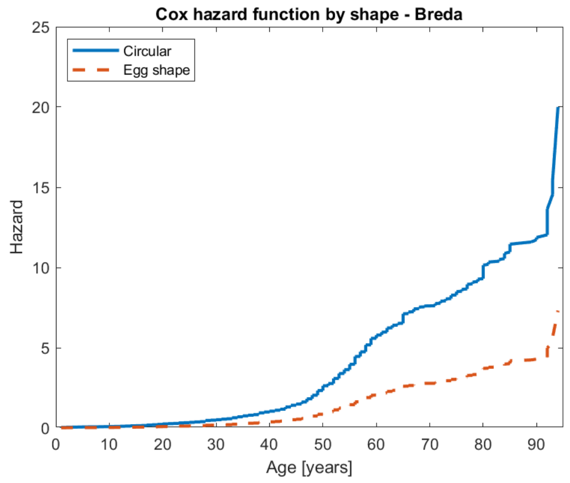
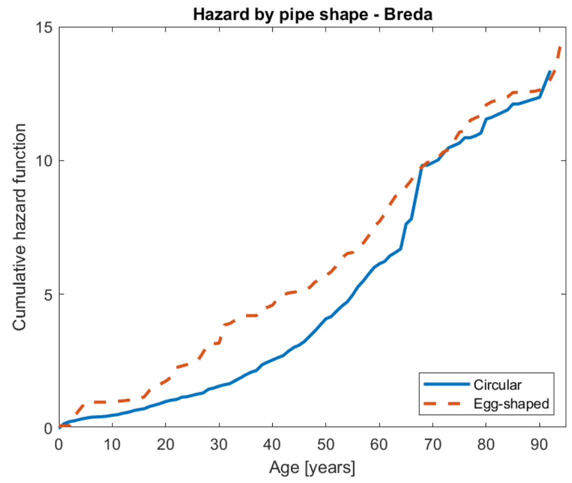
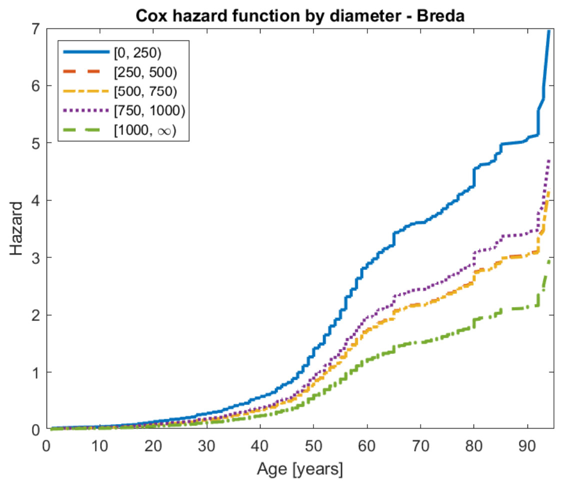
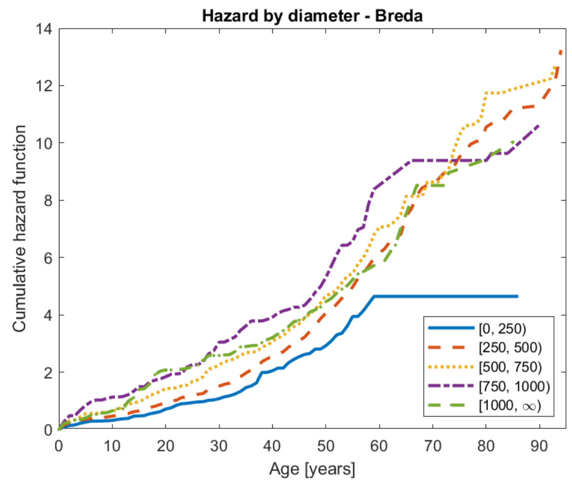
	Cox	ENE
Shape		
Diameter		

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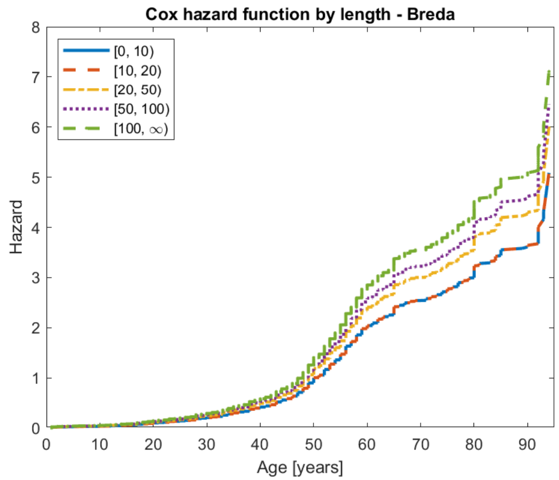
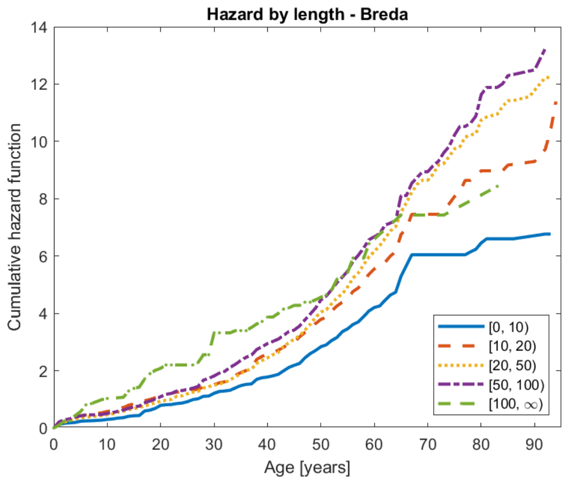
<tr><td>Length</td><td>
</td><td>
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