Gas explosion model for grey cast iron pipes in Amsterdam

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Gas explosion model for grey cast iron pipes in Amsterdam

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The way I passed until I finished this thesis was long and sometimes very winding.

My great adventure with mathematics started as early as at the very beginning of my education. Thus, I would like to thank to my first teachers: Mrs Marta Józwiak – Brudzińska, Mrs Małgorzata Mirkowska, Mrs Jolanta Sus and Mr Marek Przybylski, whose way of teaching and attitude did not daunt me to learn mathematics but inculcate a passion for this field of science.

After I had finished the education in III High School in Zielona Góra (Poland) I started the master studies at the University of Zielona Góra in field of mathematics. On the third year of my study Dr. Dorota Kurowicka appeared at the university with invitation to Delft University of Technology. In this place I would like to thank her as well as Prof. Jolanta Misiewicz and Prof. Roger Cooke for having this great opportunity to study applied mathematics in the “Risk and Environmental Modeling” group at Delft University of Technology.

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This thesis concerns grey cast iron gas pipelines in Amsterdam managed by the regional gas and electricity grid operator Liander. Due to brittle nature and aging process of grey cast iron, probability of explosion in this type of pipelines seems to be increasing.

A model for the gas explosion probability is proposed. Multiple factors are taken into consideration, including pipe's age, length, wall thickens and environmental characteristics (e.g. pH, distance to nearby property).

The model is a tool which provides assessment of the probability of explosion in grey cast iron pipes in Amsterdam. It also counts the contribution of each type of leakage to overall explosion probability. The model works for different pipes subpopulations (e.g. with respect to post code area, type of pressure, age). Numbers presented in this thesis, coming from real databases, have been altered due to confidentiality reasons.
INTRODUCTION

All life depends on the continuous input of energy. \[^{[1]}\]

One of the non-renewable energy sources is natural gas which is colorless, shapeless and odorless in its pure form. The Netherlands is one of the four biggest European natural gas exporters. It supplies 6 European countries (Germany, France, Belgium, Italy, Switzerland and United Kingdom) with gas. \[^{[2]}\] In Groningen, in northern Netherlands, there is the largest gas field in Europe and the tenth largest in the world. \[^{[3]}\] These gas field resources allow production of gas for another 50 years. \[^{[4]}\]

Many companies are involved in the distribution of the natural gas. Firstly gas is extracted from the gas field by one of the following companies: NAM, Shell, Petroland or Clyde. Subsequently it is transported by huge pipes with high pressure networks to large industry and gas receiving stations. In gas receiving stations pressure is reduced to 8 bars and the distribution of gas to houses starts. This part of the gas network is managed by Liander. Liander is a regional grid manager for gas and electricity. It operates mainly in the northern, eastern and western parts of the Netherlands and manages approximately 85.000 km of electricity cables and 35.000 km of gas pipelines. Liander is responsible for gas delivery up to gas-meters. In figure 1 Liander service area is presented.

Figure 1: Liander service area
Approximately 3,000 km of the Liander’s pipelines are made of grey cast iron. A lot of them are located in the city of Amsterdam. The discovery of the gas field in Groningen contributed to rapid development of grey cast iron mains.

Grey cast iron is an alloy of iron and other components (graphite-carbon, manganese and silicon). It is named after its grey fractured surface and graphitic microstructure. In figure 2(a) grey cast iron microstructure is presented. Figure 2(b) shows samples of grey cast iron pipes.

![Grey cast iron microstructure](image)

![Grey cast iron pipes](image)

*Figure 2: Grey cast iron*

Because of this structure gray cast iron pipes tend to be brittle and can break due to bending stress. They are subjected to two types of corrosion: graphitization (an electrochemical process hardly visible with the naked eye) and pitting. Corrosion might be either a direct cause of a leakage or can accelerate the fracturing process. A weakened wall has a larger probability of breaking in stress conditions. These and other failure mechanisms result in gas release which can lead to an explosion. Nowadays, companies like Liander, consecutively replace grey cast iron pipes with cheaper, safer and easier to handle materials, e.g. plastics (PE, PVC).

Gas explosions are a huge danger as they might result in fatalities or heavy injuries as well as in extensive material damages. In the gas combustion process harmful carbon monoxide arises, which can be fatal as well. The main cause of a gas explosion is gas leakage, subsequently its concentration and ignition. Gas explodes when its concentration is between 5% and 15% of all air which is inside the room. In these conditions even small spark will be enough to cause an explosion.

Although there are leak survey programs, some leakages are impossible to detect, thus the replacement of the relative unsafe pipelines is necessary in order to avoid gas explosions. Until now there were 2 gas explosions in The Netherlands caused by leakages in grey cast iron gas mains. The first one took place at Czaar Peterstraat in Amsterdam in August 15th, 2001.[5] As a result of this accident approximately 50 occupants of nearby houses were evacuated and 13 apartments were no longer fit for further occupation. The picture below presents the effect of the gas explosion.
Looking at Figure 3 it is hard to believe that there were no fatal injuries in this accident. Houses number 18 and 20 suffered the largest damage. The roofs of these houses were blown off. The separation wall between houses number 20 and 22 collapsed on the top floor.

Next day after the explosion, the pipe was excavated. It turned out that there was 5mm break. Under the pipeline an old stone wall was found. Parallel to the pipes there were cables for electricity, phone and some plastic conduits.

One of the main causes of the leakage was the brittle fracture of the grey cast iron pipe. The fracture arose due to ground settlement in combination with the stone wall situated below the pipe. Moreover, there was a significant loss of strength due to corrosion. Researchers showed that corrosion which affected the bottom part of the pipe reduced wall thickens by 45%, which accelerated the chance of the fracture. Inspection revealed a permeability of facade. The pipe was too close to the building (0.8-0.9 m) and gas had free way inside the building. No response from occupants led to gas accumulation in the staircase. Ignition was probably caused by an electric circuit on the staircase.

The second explosion took place in an apartment at the corner of the Haarlemmer Houttuinen and Small Houtstraatin in Amsterdam on March 9th, 2008 [6]. The explosion was caused by ignition of natural gas released
from a broken gas main made of grey cast iron with diameter 150 mm. This type of pipe is designed for transportation of gas with pressure up to 100 mbar. The pipe was laid in 1981.

Unexpectedly, gas was smelled on the porch during the cleaning. Measurements of leakage were done immediately and thanks to that the fracture of the grey cast iron pipe was found. It was about 4 meters from the explosion place. Part of the pipe of length about 2 meters (1 meter to the left and right from the fracture) was taken for research and replaced with polyethylene pipe.

The building facade was not tight because of cables and pipes penetrating the wall. Gas entered the closed space and ignited. Due to the explosion a relatively weak single stone wall of the storage was blown off. Moreover, next to the explosion place there was a building site with a groundwater drain installation. This might explain why the sidewalk in the vicinity of the break had subsided about 12 centimeters. Such ground settlements affect underground pipes. There is high probability of fracture due to bending stresses when pipe settles not evenly, especially when there are some obstacles in the ground. These presumptions were confirmed by State Mines Supervision, which claimed that the fracture might have been caused by heavy construction traffic in the nearby. In this accident four people suffered breathing problems, two of them were hospitalized.

Fortunately, in both accidents there were no fatalities. However, accidents in the natural gas chain caused more than 2200 fatalities all over the world in 1969-2000[23], thus danger associated with the gas pipelines cannot be disregarded. Gas companies should take care of risk reduction, and successively replace the dangerous pipes. For that reason, Liander commissioned a project to model explosion probability in grey cast iron pipelines in Amsterdam. The results of this project are presented in this thesis. The idea is to estimate the probability of explosion caused by a leak from each gray cast iron pipe in Amsterdam. This will allow us to calculate the explosion probability of the whole Amsterdam as well as for parts of this city.

The results of this project will be used:
- to estimate the risk of an explosion caused by a leak from a grey cast iron pipe in Amsterdam that Liander faces;
- communication with regulators;
- to revile the hot spots and the most dangerous pipes in Amsterdam;
- for prioritization of replacement of grey cast iron pipes in Amsterdam;

The first step in building the model consisted of extensive literature study which provided us with deep insight in the possible failure mechanism of pipelines. We concluded that the fracture in pipes is the most common cause of leakages and it might occur due to ground load\cite{12} or 3rd party damage\cite{8}. Corrosion is also regarded as one of the main causes of pipeline failures\cite{8,12}. Apart from these mechanisms, Liander experts indicated a connection failure as a source of small leakages.

Each failure mechanism depends on several characteristics concerning pipes as well as some environmental characteristics. In\cite{8} the list of the characteristics is proposed. They are e.g. pipe diameter, wall thickness, gas pressure but also soil type and pH, water table etc.

We first studied the databases provided by Liander to learn which parameters are important and should be used in our model\cite{11}. Thus chapter 2 consists of a description of the grey cast iron gas mains in Amsterdam and their characteristics. Moreover, environmental factors as well as study of corrosion database are presented.

In Chapter 3 the model is introduced and all model components and factors involved in the explosion process are described. The probability of explosion will be calculated for each pipe individually and thus will be proportional to the length of the pipe\cite{7}. Overall probability of explosion in Amsterdam will be expressed in km/year, which is the most widely used unit of risk of pipe failure\cite{20}.

Since not all parameters could have been estimated from historical databases, the missing ones had to be found with an expert judgement method. Chapter 3 contains the brief description of the results. The extended report with all details of the expert judgment study is included in the appendix 4.

Results of the model are shown in chapter 4. The thesis report ends with chapter 5 where conclusions and recommendations are drawn. They apply to artificial data used in this thesis as well as to the real data.
CHAPTER 2

Analysis of parameters influencing gas leaks

Study of databases is essential in order to find out how to build the model which should be based as much as possible on available historical data. In this chapter pipes’ and environmental characteristics will be studied. Firstly we will check the important pipes’ parameters. Subsequently we will deliberate which environmental and location parameters should be included in the model.

For the statistical analysis we used “NOR Gasleiding” database. This database consists of information about all pipelines in The Netherlands. We have extracted data about grey cast iron pipelines in Amsterdam. There are about 985 km of such pipes. Main pipes’ characteristics included in this database are: diameter, pressure, age, wall thickness, etc. These parameters might have significant influence on e.g. corrosion or bending process that contribute to the probability of explosion in Amsterdam.

2.1 Pressure

Liander is responsible for gas pipelines from gas receiving station up to gas-meter in household. This part of the chain includes pipes of low and high and low pressure (30 mbar - 8 bar). Since grey cast iron is a material used for low pressure natural gas distribution pipelines [25], our investigation is concerned only with pipes of the following pressures: 30 mbar, 100 mbar and 1 bar. In figure 6 the percentile of each pressure in the whole population is presented. For data summary see Appendix 1.

![Figure 6: Pipelines length with respect to pressure (in %)](image)
We can see that the vast majority of pipes have a pressure of 100 mbar (85%). The remaining 15% represent pipes under pressure of 30 mbar and 1 bar. The 100 mbar pipes are now the standard pressure pipes for gas distribution pipelines while the 30mbar pipes where the standard for gas pipes in the beginning of the 20th century. The 1 bar pipes are only used to provide gas stations with gas to distribute it into the 100 and 30 mbar networks. We can conclude that more attention should be paid to 100 mbar pipes and population of these pipes should be investigated separately.

2.2 Diameter

We found 15 pipe sizes in the database: 80, 100, 125, 150, 200, 225, 250, 300, 400, 450, 500, 600, 750, 800 and 900 mm diameter. Figure 7 presents distribution of these diameters in pipes population. Data summary can be found in Appendix 1.

As we can see, 150mm pipes are the most frequent. They constitute 40.4% of the whole population of grey cast iron gas pipelines in Amsterdam. Diameter is based on the requested capacity of gas which has to be delivered, thus 150 mm diameters seems to be a good size to meet a demand of a largest part of Amsterdam. Less popular are pipes with 100, 200, 250, 300, 400 and 500 mm diameter but their amount is still significant and makes up about 50% of pipes under consideration. Remaining pipes diameters are rare and pipes with those diameters encompass 10% of the population.
2.3 **Age**

The next step was to investigate how old are the pipes in the population. The following distribution of pipes’ ages was obtained from the database:

As shown in the histogram, most of the pipes are of 30 to 60 years old. This is due to discovery of gas field in 1950 in Groningen which led to rapid development of gas mains.

2.4 **Wall thickness**

Wall thickness is involved in modeling the corrosion in pipes. It could also be important for determining the probability of leakage due to bending stress. The NOR database did not contain information about wall thickness of the pipes. Thus we applied the formulas proposed in [26] in order to calculate wall thicknesses from the diameter of the pipe and its pressure. For pipes of 30 and 100 mbar (class A) the wall thickness $e$ can be calculated as:

$$e = \frac{11}{12} (7 + 0.02 \text{ DN})$$

*Equation 1: Formula for wall thickness for pipes under the pressure of 30 and 100 mbar*

For pipes with pressure 1 bar (class B), the wall thickness will be calculated as follows:

$$e = 7 + 0.02 \text{ DN}$$

*Equation 2: Formula for wall thickness for pipes under the pressure of 1 bar*
We can calculate that the minimal wall thickness equal to 7.88 mm have 30 mbar pipes with diameter 80 mm. The thickest walls of 25 mm have 1 bar pipes with 900 mm diameter. The most popular pipes, i.e. those with 150 mm diameter and 100 mbar pressure have 9.17 mm wall thickness.

2.5 LENGTH

In NOR database one can find information about length of each pipe. Length is an important factor because the explosion probability is proportional to the pipe’s length. Lengths of pipes in Amsterdam are not equal and vary from 0.013 m to 687.103 m. The distribution of pipes’ lengths is depicted in figure 9. Majority of the pipes is shorter than mean length which is 21.25 m.

Not only the pipes’ parameters but also environmental characteristics plays important role in assessing pipe’s condition. We analyze now some environmental characteristics that might be of importance for our study.

2.6 pH

Soil pH or soil reaction is an indication of the acidity or alkalinity of soil and is measured in pH units\textsuperscript{[27]}. The pH scale goes from 0 to 14, where 0 is the most acid and 14 is completely alkaline. 7 is the neutral point.
Soil acidity is a very important parameter which affects corrosion process. Dependence between pH value and corrosiveness is presented in table below [15]:

<table>
<thead>
<tr>
<th>pH</th>
<th>Influence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acidic (&lt;6)</td>
<td>High Corrosive</td>
</tr>
<tr>
<td>Close to neutral (6-8)</td>
<td>Non corrosive</td>
</tr>
<tr>
<td>Alkaline (&gt;8)</td>
<td>Low Corrosive</td>
</tr>
</tbody>
</table>

Table 1: Importance of soil acidity

Analysis of dependences between pH and corrosion process are presented in section 2.9 which is dedicated to corrosion analysis.

## 2.7 Soil Type

There are several different soil types: sand, peat, clay and loam. Combinations of those soil types are often observed in nature. Soil type is considered to be an important factor which has influence on corrosion as well as on fractures due to bending stresses of pipes.

Majority of pipes lay in sand, which is composed of small granular. This results with low water resistance and subsequently accelerates settlement process. Grains rapidly go to the most compressed positions. When pipe settles not evenly, it might bend and fracture can occur. Pure sand has neutral pH. Nevertheless, usually sand is not pure and pH value is determined by mixed components.

Unfortunately, NOR database do not include any information about soil type for each pipe. For that reason information about the possible soil types were extracted from KwalUGas database. The database consists of population of 1050 pipes with corrosion measurements. For each pipe the soil type in which it was laid is given. Distribution of all soil types in this population can be found in Appendix 1. Almost 90% of pipes were in sand. Moreover, discussion with Liander employees revealed, that in some cases, original soil is replaced by sand in the surroundings of the pipe because sand provides favorable conditions for pipes (see figure 11).
Relying on database analysis and Liander’s experts’ opinion, we decided to assume that all pipes in our population lay in sand. Nevertheless, we do not assume that pH is always neutral.

2.8 WATER TABLE

Ground water and its quality affect the corrosion process\(^\text{[29]}\). Depending on geochemical conditions, groundwater may have negative influence on pipe material. A pipe might be situated above or below water table. It might also lie in a place where the water table fluctuates and water washes away present corrosion products. This can accelerate the corrosion process.

NOR database does not give information about pipelines’ underground location, thus it will be assumed that all pipes have the same conditions with respect to underground water.

2.9 CORROSION ANALYSIS

Many types of corrosion are known. In our case there are two relevant types – pitting and uniform corrosion. Pitting corrosion produces holes in the material, when uniform corrosion attacks the material equally on the whole area.

Grey cast iron is not very susceptible to the corrosion process. Because of its structure, it does not need to have an extra corrosion protection. Thanks to graphite flakes grey cast iron is protected against oxidization and naturally protected against corrosion\(^\text{[30]}\).

The corrosion rate depends on several factors like pipe’s age, soil type, soil resistance, soil pH, underground water level and quality, etc\(^\text{[29]}\).
The KwalUGas database does not contain information about all the above factors influencing corrosion. This database consists of data about corrosion in pipes that were excavated and replaced. They might have been excavated due to many reasons. Some might have had a leak, others could have been replaced as they were digging activities in the neighborhood and they were easily accessible. After excavation these pipes were studied by KwalUGas inspectors who provided information about the corrosion type (pitting, uniform) and the corrosion level for uniform corrosion (non, medium, high), using only ‘eye-measurement’. Figure 13 shows an example of a form that inspectors have to fill in when analyzing an excavated pipe.

In the whole database there were only 70 instances out of 1193 where pitting corrosion was assigned “yes”. There was no information about how deep the corrosion damages in these cases were hence pitting corrosion will not be analyzed separately and only uniform corrosion will be of interest.

Not much information about soil characteristics is included in the KwalUGas database. Hence with this database it is not possible to learn how corrosion level depends of soil characteristics. We decided to model the corrosion level as a function of pipe’s age and pH value of the pipe’s environment. The following section shows KwalUGas database analysis.

2.9.1 DATABASE ANALYSIS

In this section we will investigate relationships between:

- corrosion level and pipe’s age;
- corrosion level and pH value of the soil in pipe’s surroundings

We start to examine pipes’ ages in this population. The following figure shows the histogram of age for pipes in the KwalUGas database.
We see that the majority of pipes are between 30-60 years. In the top right corner the histogram of age of pipes in Amsterdam is shown. We see that also in Amsterdam the majority of pipes are between 30-60 years old. Thus it can be assumed that the KwalUGas database is representative for pipelines in Amsterdam.

Subsequently the distribution of pipes’ pH values was investigated. In the KwalUGas database we can distinguish the following pH intervals:

- <5.6
- 5.6 – 6.0
- 6.1 – 6.5
- 6.6 – 7.0
- 7.1 – 7.5
- 7.6 – 8.0
- 8.1 – 8.5
- >9.5

The Table in Appendix 1 shows distribution of pH in this population. It turned out that as much as 91.25% of all pipes were laid in pH close to neutral. This will make the analysis of dependence between pH and corrosion level difficult. Table 2 presents distribution of the soil pH close to neutral in KwalUGas database.

<table>
<thead>
<tr>
<th>Soil pH</th>
<th>6.1-6.5</th>
<th>6.6-7.0</th>
<th>7.1-7.5</th>
<th>7.6-8.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>of samples</td>
<td>11</td>
<td>157</td>
<td>299</td>
<td>54</td>
</tr>
<tr>
<td>in %</td>
<td>1.93%</td>
<td>27.50%</td>
<td>52.36%</td>
<td>9.46%</td>
</tr>
</tbody>
</table>

*Table 2: Distribution of the soil pH close to neutral in KwalUGas database*

The last parameter is corrosion level. Table 3 shows the distribution of corrosion level.

<table>
<thead>
<tr>
<th>Corrosion level</th>
<th>No corrosion</th>
<th>Average</th>
<th>Big</th>
<th>Leakage</th>
</tr>
</thead>
<tbody>
<tr>
<td># of samples</td>
<td>568</td>
<td>501</td>
<td>92</td>
<td>20</td>
</tr>
<tr>
<td>in %</td>
<td>48.09%</td>
<td>42.42%</td>
<td>7.79%</td>
<td>1.69%</td>
</tr>
</tbody>
</table>

*Table 3: Distribution of the pipes’ corrosion level in KwalUGas database*

About 48% of all samples had no corrosion. Moreover, corrosion is not given in quantitative way - in % of wall thickness degradation or simply in millimeters. We only know that four possible corrosion levels specified by experts: 0, low, medium and high. No corrosion means exactly 0% of wall loss. Average corrosion is up to 20%
wall loss and high – above 20%. Another difficulty in interpreting data from this database was that some of those pipes already had a leakage, but were not assigned as pipes with leakage but with high corrosion. In order to recognize these pipes, two databases have been merged. In our model the critical value of wall thickness loss due to corrosion is fixed to 0.9mm of remained wall thickness called critical level. This value corresponds to 90% of the initial wall thickness of the most popular grey cast iron pipe in Amsterdam (150 mm diameter and 100 mbar pressure). When a pipe achieves this level we assume that there is a leakage. Therefore pipes with leakages were attributed with the critical corrosion level equal to \( wt - 0.9mm \), where \( wt \) denotes initial wall thickness.

**Analyze 1 – Corrosion vs. pipe’s age.**

In figure 15 pipes’ ages were plotted against corrosion levels. No corrosion is attributed with value 0, average with 1, high with 2 and leakage with 3.

![Figure 15: Pipe’s age vs. corrosion level in mm](image)

Most pipes in the KwalUGas database are 20-60 years old. Majority of these pipes have average or no corrosion. However, we can observe also high corrosion as well as leakages in this age group. Surprisingly we see pipes that are older than 80 years with 0 corrosion level.

**Analyze 2 - Corrosion vs. soil pH**

In the KwalUGas database there are 10 pH intervals. The intervals were enlisted above.

About 91% of all pipes come from soil with pH close to neutral (6pH-8pH). This pH has small tendency to be corrosive. It is confirmed by the fact that around 54% of pipes in this pH have no corrosion. Moreover, due to lack of data we cannot conclude that for acidic or alkaline pH values, corrosion is higher or lower than for neutral ph. The database does not provide enough information about the relation between corrosion level and pH value. However, pH is an important parameter which has significant influence on the corrosion rate \(^{[15]}\), thus it will be included in the model.
Since vast majority of samples was from environment with pH close to neutral (6pH-8pH), we decided to first build a model of corrosion using data with neutral pH. Corrosion for acidic and alkaline pH – will be obtained with expert judgement method.

According to experts’ opinions as well as information found in the literature [30], corrosion is not considered to be the biggest problem of grey cast iron pipes. Leakages due to corrosion are rare because this material is not susceptible to a corrosion process. Moreover, the database was insufficient to conduct robust analysis of causes of the corrosion, thus it was decided to build a simple linear corrosion model. The model is described in the following chapter.

The model will be based on KwalUGas corrosion data. Since in the database corrosion is not given in quantitative way as a % of wall thickness loss or simply in millimeters and only corrosion levels are provided we had to preprocess the data first. Qualitative corrosion values (no, average, high and leakage) were transformed into quantitative values (mm of wall thickness loss).

No corrosion is simply 0 mm of wall thickness loss and leakage means that there is \( wt = 0.9mm \) corrosion. Average and high corrosion levels were sampled from the normal distribution on interval \((0,20)\) and \((20, \frac{wt^{-0.9} \times 100}{wt})\) respectively with parameters indicated by Liander employees yielding wall thickness loss given in percentiles. Last step was to convert it to wall thickness loss given in millimeters. With this procedure we obtained the corrosion data (figure 16) that will be used for further analysis. Details of the transformation procedure can be found in Appendix 1.

This chapter showed which data is available in our case and gave the first idea on which parameters the model should depends on. In the next chapter we will present the model and its quantification.
CHAPTER 3

The model and its quantification

“Mathematical modeling is about rules - the rules of reality.”

~ John Casti

The problem of a gas explosion due to leak from grey cast iron pipes is one of the real dangers which one can face in present days. In order to build the model which predicts the probability of such an explosion, the analyst has to investigate the rules governing failure mechanisms of grey cast iron pipes. Moreover the chain of events which lead to an explosion has to be identified.

As explained in Chapter 2, a study of databases is essential in order to learn which characteristics influencing the chance of an explosion should be included in the model. From the analysis in Chapter 2 the model will dependent on the following parameters: pipe’s age, wall thickness (dependent on diameter and pressure), length, soil ph (alkaline, acidic and neutral). Other parameters will be also included.

The model was developed and is depicted in figure 17. It is a fault tree type model. It distinguishes four main types of gas leakages: from connection failure, due to corrosion, due to bending stresses caused by ground movement and due to 3rd party damage. These types of leakages were divided into two groups: small and big ones. Leakages due to corrosion and connection failure were rated among small leakages. Leakages due to 3rd party damages and bending stresses caused by ground movement are considered to be the big leakages. It is assumed that explosion can happen only when there is a leakage and when gas can store and ignite. Thus, the model assumes that only leakages from pipes which are closer than 1 meter to the nearby property can lead to gas accumulation and subsequently ignition. In figure 17 the contribution of different types of leakages to the probability of explosion is depicted. The sum of these contributions constitutes the explosion probability. The contribution of leakage due to corrosion is a product of the probability of leakage due to corrosion for pipes located in the neighborhood of a building and the chance that gas will accumulate and ignite (factor 1). Similarly the remaining ones are calculated. We can see them located in four squares in figure 17.
This model is partially quantified with data collected from several databases. Missing parameters were obtained with expert judgement method.

Each component of the model calculates the probability of leakage per one kilometer of pipe per year. In the next sections we show in details all components of this model and how they are quantified.

### 3.1 Probability of Leakage Due to Connection Failure

Leakages which are caused by connection failure are usually small, which not always means good. On the one hand small amount of released gas is not as dangerous as big one. On the other hand small leakage is harder to detect. It might be discovered when significant gas concentration will be achieved. This, in extreme cases might lead to explosion.

There is no good data about connections’ failures. Only Nestor database provide some knowledge about leakages due to connection failures. Nestor is a Dutch database with historical data about failures of the distribution grids. In this database we find that there were 705 leakages in main pipelines in 2009 in Amsterdam, out of which 488 come from connections. It is as much as 69% of all leakages.

---

**Figure 17: The model**

**Figure 18: Sources of leakages in 2009, NESTOR**
The probability of leakage due to connection failure is assumed not to depend on connection age or any characteristics of the environment. This is due to lack of data and Liander’s believe that connections don’t contribute significantly to the probability of explosion as they usually cause small leakages. Leakage due to connection failure can be estimated from data as a percentage of failed connections in Amsterdam which was equal to $p = 0.00198$.

The confidence interval $(p_L, p_U)$ for $p$ calculated with normal approximation interval, also known as a Wald formula is:

$$p \pm z \frac{p(1-p)}{n}$$

*Equation 3: Normal approximation interval*

where $p = 0.00198$, $z = 0.1$, $z_{1-\alpha} = 1.65$ and $n$ is a number of connections in Amsterdam. On average, there is one pipe connection for each 4 meters of the pipes. Thus there are about 246400 connections in Amsterdam.

The Wald formula yields the following confidence bound of $p$: $p \in (0.001833, 0.00213)$.

The probability of at least one connection failure per kilometer pipe in Amsterdam will be calculated with binomial probability as $1 - P(X = 0)$ where $P(X = k)$ is given in Equation 4.

$$P(X = k) = \binom{n}{k} p^k (1-p)^{n-k}$$

*Equation 4: Binomial distribution – probability mass function*

In one kilometer of pipe there are about 250 connections. Hence, the probability of at least one connection failure per one kilometer of the pipe, assuming $p = 0.00198$, is as follows: $P(X \geq 1) = 0.3907$.

### 3.2 Leakage due to corrosion

We will model the wall thickness loss (in mm) as a linear model of pipe’s age. This type of models is widely used to predict the corrosion, not only in grey cast iron pipes, but also in other materials, like e.g. steel\cite{31,33}.

#### 3.2.1 Corrosion model

In a linear model it is assumed that wall thickness loss, $y$, is proportional to pipe’s age, $x$. Proportionality constant $A$ is called the corrosion rate. The simplest model assumes that corrosion starts when pipe is buried. It can be expressed by the following equation:

$$y = A \times x$$

*Equation 5: Linear corrosion model, B=0*

The model for corrosion will be built for pH close to neutral on the basis of KwalUGas corrosion database. From data we estimated that the corrosion is present in a pipe with probability 0.52 (because 48% pipes had no corrosion according to the KwalUGas database) and if the corrosion is present its growth is modeled with equation 5. To find the corrosion rate data presented in Chapter 2 in figure 16 is going to be used.
Most common approach of modeling this problem is to use linear regression. On the basis of corrosion measurements, a straight line is fitted to data points and its slope is a corrosion rate. The data set consists of 233 pipes with corrosion. For $i^{th}$ pipe its age $x_i$ and corrosion level $y_i$ is given. It is imposed that linear fit has to start in 0. We are looking for such $A$ that minimize $\sum (y_i - Ax_i)^2$.

The parameter $A = 0.0376$ was found using Matlab function `fminsearch`. Linear fit of the function $y = 0.0376 \times x$ is presented in figure 19.

![Figure 19: Linear regression with imposed start in 0](image)

The result which we obtained is not very intuitive as if one wanted to use the model, it would mean that one should wait on average 219 years for a leakage from a pipe with initial wall thickness 9.17 mm. Hence, other method has to be found in order to obtain more probable result.

In the second approach (which is actually comparable with the first one) we calculate $A$ as an average of slopes of lines joining point (0,0) with each data point (Figure 20). For each $(x_i, y_i)$ we have $a_i = \frac{y_i}{x_i}$.

In this way we obtained 233 instances of $a_i, i = 1, \ldots, 233$. Their histogram is presented in figure 21.
The expected value of corrosion rates is equal to 0.04 which is comparable with the first approach and similar conclusions can be drawn in this case.

In the third approach it is assumed that corrosion must start somewhere between 0 and pipes' age. Hence we consider the following model:

$$Y = A \times (x - B)$$

*Equation 6: Linear corrosion model*

$A$ denotes the corrosion rate and $B$ the start of the corrosion process. We will consider $A, B$ as uncertain and their uncertainty will be expressed in form of exponential distribution with parameter $\lambda$ for $A$ and Beta...
distribution on interval $[0, x]$ with parameters $\alpha$ and $\beta$. Beta distribution has a variety of shapes, and contains the uniform distribution when $\alpha = 1$ and $\beta = 1$ (figure 22). It is reasonable to assume that the corrosion rate $A$ and the point when the corrosion starts $B$ are independent.

![Beta distribution, pdf](image)

To find parameters $\lambda$, $\alpha$ and $\beta$ from data, the maximum likelihood estimation procedure was used. Since for $i$th sample the realization of $B$ would come from a distribution on the interval $[0, x_i]$ we rewrite our model to simplify development of the likelihood function. We know that if $B$ has beta distribution on the interval $[0,1]$ with parameters $\beta$ and $\alpha$, then $x - x \cdot B$ has the beta distribution on $[0, x]$ with parameters $\alpha$ and $\beta$. Then our model can be rewritten as:

$$Y = A \cdot (x - (x - x \cdot B)) = x \cdot A \cdot B$$

where

$$B \sim Beta_{(0,1)}(\alpha, \beta) \text{ and } A \sim \text{exp}[\lambda]$$

On the basis of the new version of the formula for $Y$, the probability density function of $Y$ was calculated (equation 7).

$$f_Y(y, x) = \int_{a = y \cdot \frac{1}{x}}^{a = \infty} \text{exppdf}(a, \frac{1}{\lambda}) \cdot \text{betapdf}(\frac{y}{x \cdot a}, \beta, \alpha) \cdot \frac{1}{a} \, da$$

*Equation 7: Y probability density function*

where exppdf denotes the probability density function (pdf) of the exponential distribution with mean parameter $\mu = \frac{1}{\lambda}$ evaluated in $a$. Similarly, betapdf is the beta pdf with parameters $\beta$ and $\alpha$ (in the Appendix 2 detailed calculations of equation 7 are shown).

The log likelihood function for this model is:

$$\ln \mathcal{L}(\lambda, \beta, \alpha | y_1, ..., y_n, x_1, ..., x_n) = \sum_{i=1}^{n} \ln f_Y(y_i, x_i | \lambda, \beta, \alpha)$$

*Equation 8: The log likelihood function of the Y*
The optimization procedure in Matlab using function `fmincon` led to the following results:

\[ \lambda = 6.4514, \quad \alpha = 1.3163, \quad \beta = 0.9601 \]

For this model the expectation of \( A \) is 0.16. In this case, 9.17 mm pipe would have a leak on average after 52 years which is intuitively more accurate than results in previous approaches. Thus, as a corrosion rate for the neutral ph we decided to use the mean of the exponential distribution. Corrosion rates for acidic and alkaline environment were obtained via expert judgment method. The starting points of corrosion will by randomly chosen from the beta distribution independently of soil pH.

To check the model performance, a set of new corrosion levels for pipes in the database were generated according to the model. The detailed procedure for generating corrosion levels is presented in Appendix 2. Result of the model performance is depicted in figure 23.

![Figure 23: Corrosion data and simulated corrosion data](image-url)

Taking into account database quality, the accuracy of the model can be assumed as sufficient. The model will be used for generating corrosion in the population of pipes in Amsterdam, and on the basis of the results the probability of leakage due to corrosion will be calculated in the way shown in the following section.

### 3.2.2 Probability of Leakage Due to Corrosion

On the basis of the model presented in previous section, wall thickness loss for each pipe can be calculated. From the model above we get the wall thickness loss. If the remaining wall thickness is smaller than 0.9mm (called critical corrosion level) then this pipe has a leakage. This level was set by Liander experts and it corresponds to 10% of initial wall thickness of the most popular pipes in the population (diameter 150 mm and pressure 100 mbar). It is assumed that whole pipe is affected by the corrosion.

In order to calculate probability of leakage due to corrosion in Amsterdam, one has to use the following formula:
\[ P(\text{leakage due to corrosion}) = \frac{\text{# km pipes with leakage}}{\text{total # of km pipes in Amsterdam}} \]

Equation 9: Probability of leakage due to corrosion

Hence, probability of leakage due to corrosion is a ratio of the length of the corroded pipes to the total length of pipes in Amsterdam.

### 3.3 Leakage due to Bending Stresses caused by Ground Movement

The third component of the model is responsible for the calculation of the probability of leakage due to bending stresses caused by ground movement. It is difficult to predict soil movement and how it can contribute to the probability of pipes’ failure. After discussions with Liander’s experts and on basis of investigation that were carried out after the two explosions in Amsterdam [5], [6], [15], [16], we decided to distinguish three main causes of ground movement: natural settlement, traffic load and nearby digging activities.

Natural settlement in Amsterdam is assessed at 1-3 mm per year. However, not only the natural forces cause underground movements. Big traffic and heavy cars create stresses which affect ground settlement. Thus traffic load is expected to have influence on ground movement. Also digging activities have significant affect on surrounding area. Especially places with deep diggings might cause great subsidence in the proximity, as it was in case of the second explosion. At the moment it is impossible to assess the impact of nearby diggings on pipes settlement in the surroundings of the digging area. There is lack of knowledge about exact places of the diggings, their areas and depths. Also the data about how deep under the ground the pipes are is missing. Thus the nearby digging activity factor in the ground movement model has to be omitted. Since corrosion plays a big role in the bending process, it will be also included in the model as a factor which accelerates occurrence of the fracture.

When ground settles not equally, bending stresses may occur very easily. However, also in the case of equal settlement, fracture due to the bending stresses can occur. This might be caused by underground obstacles as well as soil type changes. The process is accelerated by the corrosion. When a pipe is weakened by corrosion, probability of fracture increases.

In [8] Cooke proposed the modeling approach which main idea is to calculate frequencies on basis of the observed average frequencies and assess changes from this average state. It uses linear Taylor expansion around the average value observed from data. From data we were able to compute the probability of leakage due to ground movement for average situation, and the result is \( P_{GM0} = 0.0365 \). We assume that this probability is valid for traffic with 5000 cars per day and average corrosion level in Amsterdam (15.36% of wall thickness loss).

The function which calculates the probability of leakage due to bending stresses caused by ground movement \( P_{GM} \) will depend on the corrosion level predicted by the corrosion model \( cr \) and traffic type \( tr \).

\[ P_{GM} = P_{GM0} + p_1(tr - tr_0) + p_2(cr - cr_0) \]
where $p_1(t - t_0)$ is an increase (decrease) of the $P_{GM}$ while traffic changes to high (low), and $p_2(c - c^0)$ is responsible for changes of $P_{GM}$ when corrosion changes.

Experts were asked three questions about the changes of the probability of leakage due to ground movement in different than average situations. Their answers are presented in table below.

<table>
<thead>
<tr>
<th></th>
<th>5%</th>
<th>50%</th>
<th>95%</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.00130</td>
<td>0.01623</td>
<td>0.03090</td>
<td>probability of leakage due to bending stress for a pipe which is in the neighborhood of a street with low traffic and with average corrosion level</td>
</tr>
<tr>
<td></td>
<td>0.02939</td>
<td>0.05245</td>
<td>0.25405</td>
<td>probability of leakage due to bending stress for a pipe which is in the neighborhood of a street with high traffic and with average corrosion level</td>
</tr>
<tr>
<td></td>
<td>0.03845</td>
<td>0.07020</td>
<td>0.17978</td>
<td>probability of leakage due to bending stress for a pipe which is in the neighborhood of a street with average traffic and with corrosion level equal to 30% of wall thickness loss</td>
</tr>
</tbody>
</table>

Table 4: Expert judgement – results for uncertain parameters for ground movement model

Values of $p_1$ and $p_2$ were acquired taking 50% values provided by experts as follows:

Firstly experts were asked about the value of $P_{GM}$ when traffic is low, and corrosion remains average. Hence $p_1$ for the low traffic was calculated from the equation

$$P_{GM,low} = P_{GM0} + p_{1L}(t - t_0)$$

$$p_{1L} = P_{GM,low} - P_{GM0} = 0.01623 - 0.03090 = -0.02027$$

The same question was asked for the high traffic yielding $p_1$ for high traffic.

$$P_{GM,high} = P_{GM0} + p_{1H}(t - t_0)$$

$$p_{1H} = P_{GM,high} - P_{GM0} = 0.05245 - 0.03090 = 0.01595$$

Last question was about $P_{GM}$ when traffic is average, but corrosion changes from average to 30% of wall thickness loss. Hence $p_2$ was established from the following equation:

$$P_{GM,corrosion,30\%} = P_{GM0} + p_2(c - c^0)$$

$$p_2 = \frac{P_{GM,corrosion,30\%} - P_{GM0}}{(c - c^0)} = \frac{0.07020 - 0.03090}{0.3 - 0.1536} = \frac{0.0393}{0.1464} = 0.23019$$

Linear model for certain values of $c^0$ might lead to results that are outside the interval [0,1].

The logistic model for $P_{GM}$ can be used to prevent results outside the unit interval.

$$P_{GM} = \frac{P_{GM0} * e^{(c - c^0) + p_1L} + P_{GM0} * e^{(t - t_0) + p_1H}}{1 + P_{GM0} * e^{(c - c^0) + p_2} + P_{GM0} * e^{(t - t_0) + p_1L}}$$

Equation 10: The logistic model for the probability of leakage due to ground movement

For the logistic model we need to find values of $p_1$ and $p_2$ that should be related to $P_{GM}$ provided by experts. We have that for average corrosion level $P_{GM}$ is:

$$P_{GM} = P_{GM0} + p_1(t - t_0)$$

25
We want to express $P_{GM}$ with logistic model hence

$$P_{GM} = \frac{P_{GM_0} \cdot e^{(tr-tr_0)\cdot \bar{p}_1}}{1 + P_{GM_0} \cdot e^{(tr-tr_0)\cdot \bar{p}_1}}$$

The relationship between $p_1$ and $\bar{p}_1$ is found as follows. Since

$$P_{GM_0} \cdot e^{(tr-tr_0)\cdot \bar{p}_1} \approx P_{GM_0} \cdot e^{(tr-tr_0)\cdot \bar{p}_1}$$

we have

$$P_{GM_0} + p_1(tr-tr_0) = P_{GM_0} \cdot e^{(tr-tr_0)\cdot \bar{p}_1}$$

and

$$\bar{p}_1 = \frac{p_1}{P_{GM_0}}$$

The same procedure can be applied for $p_2$ yielding

$$\bar{p}_2 = \frac{p_2}{P_{GM_0}}$$

The probability $P_{GM}$ for leakage due to ground movement is shown in figure 24:

![Figure 24: Probability of leakage due to bending stresses caused by ground movement.](image)

### 3.4 Leakage due to 3rd Party Damage

As damage caused by 3rd party activities we regard damage caused by mechanical diggings. Since July 2008 all mechanical diggings have to be reported to KLIC database (Dutch organization for the prevention of the third
party damage of cables and pipelines). However, there are still a lot of unreported digs. In 2006 relation of reported and unreported diggings was estimated at about 1:1 \[34\]. Liander’s experts suspect that nowadays only 5%-8% of all diggings have no KLIC announcement.

During digging activities a pipe can be damaged by heavy mechanical equipment which can lead to a leakage. It is believed that damages can be minimized when diggings are reported. Then necessary documents and maps with information about pipelines and cable lines in the neighborhood of the dig are sent to the company responsible for the dig. In some cases Liander sends its supervisor in order to control digging process. This procedure might have an influence on reducing probability of damage and possible consequences.

When digging is unreported, the probability of pipe’s damage might increase and possible leakages may be undetected.

Approach to modeling the probability of the leakage due to 3\(^{rd}\) party damage is based on the available data. We assume that the necessary condition for the leakage is that the pipe is exposed to the 3\(^{rd}\) party activity. If it is exposed, some mechanical damage might occur and then one can expect a leakage. Not all damages lead to leakages. Hence, the probability of a leakage can be written as:

\[
P(\text{leakage due to damage caused by 3rd party activity}) = P(\text{3rd party activity}) \times P(\text{damage | 3rd party activity}) \times P(\text{leakage | damage})
\]

and shortened to:

\[
P_{3rd} = P_{\text{digg}} \times P_{\text{damage}} \times P_{\text{leakage}}
\]

*Equation 11: Probability of the leakage due to 3\(^{rd}\) party damage*

The probability of leakage due to damage caused by 3\(^{rd}\) party in Amsterdam in 2009 is estimated from Nestor database and is equal to 0.00507. In principle we could use only this probability without subdividing it further. The idea behind this subdivision was to allow differentiation of parts of Amsterdam with respect to the number of kilometers of pipes exposed to digging activities. If these numbers were known for e.g. post codes in Amsterdam, we could include them in the following way: \(P_{\text{3rd}}\) and \(P_{\text{damage}}\) are known from data; \(P_{\text{leakage}}\) was established via expert judgment method. \(P_{\text{digg}}\) can be calculated as follows:

\[
P_{\text{digg}} = P(\text{3rd party activity}) = \frac{\# \text{ km pipes exposed to digging activities in Amsterdam}}{\# \text{ km pipes in Amsterdam}}
\]

Using 50% quantile of \(P_{\text{leakage}}\) and all estimates of other probabilities in equation 11 we could calculate that the number of kilometers of pipes exposed to digging activities in Amsterdam is 3668 km. For detailed calculations see Appendix 2.

### 3.5 SMALL AND BIG LEAKAGE FACTOR

When pipe has a leakage (big or small) and is in the proximity of the property, explosion of the released gas becomes probable. Experts were asked to assess probability of explosion in case of such leakage. They answers are included in the model as a factor 1 and 2. Factor 1 corresponds to small leakage and factor 2 to the big one.
They represent favorable conditions for gas explosion occurrence. These factors are probabilities of an explosion given that a leakage occurs in the proximity of a property (distance smaller than 1 m).

\[ Factor\ 1 = P(\text{explosion} | \text{small leakage \& distance to nearby property} < 1m) \]

\[ Factor\ 2 = P(\text{explosion} | \text{big leakage \& distance to nearby property} < 1m) \]

These factors were obtained with expert judgement method and are presented in table below:

<table>
<thead>
<tr>
<th>5%</th>
<th>50%</th>
<th>95%</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0,00010</td>
<td>0,00435</td>
<td>0,09840</td>
<td>probability of explosion given small leakage and distance to nearby property smaller than 1 m</td>
</tr>
<tr>
<td>0,00101</td>
<td>0,01120</td>
<td>0,15630</td>
<td>probability of explosion given big leakage and distance to nearby property smaller than 1 m</td>
</tr>
</tbody>
</table>

*Table 5: Results of expert judgement study for small and big leakage factor*

### 3.6 Expert Judgement

This section presents brief summary of expert judgement study which was conducted in order to obtain missing parameters of the model. For detailed report we refer to Appendix 4.

The missing parameters are presented in table 6.

11 experts took part in elicitation session. They were employees of Liander (7), Enexis (2) and Kiwa Gastec (2). They were asked to provide their assessments for questions included in a questionnaire. The questionnaire consisted of 18 questions: 10 seed questions and 8 questions about uncertain parameters. Below there are presented two examples of questions:

**Example of seed question:**

*There were 59,432 reported digging activities in the Liander gas network in 2004 (KLIC database). How many digging activities were reported in 2009?*

**Example of question of interest:**

*Consider a gray cast iron pipe with small leakage located in the distance smaller than 1 meter from a nearby property. What is the probability of explosion caused by this leak?*

Experts gave answers in form of three quantiles: 5% quantile, 50% quantile and 95% quantile.

<table>
<thead>
<tr>
<th>Notation</th>
<th>Parameter description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_{small,1} )</td>
<td>probability of explosion given small leakage and distance to nearby property smaller than 1 m</td>
</tr>
<tr>
<td>( P_{big,1} )</td>
<td>probability of explosion given big leakage and distance to nearby property smaller than 1 m</td>
</tr>
</tbody>
</table>
\( \alpha_{\text{acidic}} \) corrosion rate per year in acidic environment

\( \alpha_{\text{alkaline}} \) corrosion rate per year in alkaline environment

\( P_{\text{low}} \) probability of leakage due to bending stress for a pipe which is in the neighborhood of a street with low traffic and with average corrosion level

\( P_{\text{high}} \) probability of leakage due to bending stress for a pipe which is in the neighborhood of a street with high traffic and with average corrosion level

\( P_{\text{corrosion,30}} \) probability of leakage due to bending stress for a pipe which is in the neighborhood of a street with average traffic and with corrosion level equal to 30% of wall thickness loss

\( P_{\text{damage}} \) probability of unreported, undetected and not immediately repaired leakage from damaged during the 3\(^{rd}\) party activity pipe

Table 6: Expert Judgement – missing parameters

All computations can be performed in Excalibur software. Expert number 4, 7 and 10 were weighted and they contribute to Decision Maker. After extensive analysis of gathered data, we obtained results presented in table 7:

<table>
<thead>
<tr>
<th>Description</th>
<th>5%</th>
<th>50%</th>
<th>95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>probability of explosion given small leakage and distance to nearby property smaller than 1 m</td>
<td>0.00010</td>
<td>0.00435</td>
<td>0.09840</td>
</tr>
<tr>
<td>probability of explosion given big leakage and distance to nearby property smaller than 1 m</td>
<td>0.00101</td>
<td>0.01120</td>
<td>0.15630</td>
</tr>
<tr>
<td>corrosion rate per year in alkaline environment</td>
<td>35,3864</td>
<td>58,16013</td>
<td>132,0553</td>
</tr>
<tr>
<td>corrosion rate per year in acidic environment</td>
<td>16,29407</td>
<td>39,71744</td>
<td>49,79674</td>
</tr>
<tr>
<td>probability of leakage due to bending stress for a pipe which is in the neighborhood of a street with low traffic and with average corrosion level</td>
<td>0.00130</td>
<td>0.01623</td>
<td>0.03090</td>
</tr>
<tr>
<td>probability of leakage due to bending stress for a pipe which is in the neighborhood of a street with high traffic and with average corrosion level</td>
<td>0.02999</td>
<td>0.05245</td>
<td>0.25405</td>
</tr>
<tr>
<td>probability of leakage due to bending stress for a pipe which is in the neighborhood of a street with average traffic and with corrosion level equal to 30% of wall thickness loss</td>
<td>0.03845</td>
<td>0.07020</td>
<td>0.17978</td>
</tr>
<tr>
<td>probability of unreported, undetected and not immediately repaired leakage from damaged during the 3(^{rd}) party activity pipe</td>
<td>0.07701</td>
<td>0.47058</td>
<td>0.69657</td>
</tr>
</tbody>
</table>

Table 7: Expert Judgement – results

3.7 Uncertainty Propagation and Modeling Approach

Our model is a Monte Carlo simulation type model. In each iteration a set of random inputs from their probability distributions is sampled and the model output is calculated for this set of inputs.
The gas explosion model has some uncertain parameters. For each pipe the following characteristics were given in NOR database: post code, age, wall thickness, diameter, pressure, and length. Wall thicknesses were calculated using formulas given in section 2.4 by equation 1 and 2. Traffic type was indicated by Liander experts and assigned to each post code. Parameters which are uncertain for each pipe are: ph, corrosion starting point, corrosion level, and probability of connection failure. They change in each Monte Carlo simulation and for each pipe. The following parameters change only in each Monte Carlo simulation: factor 1, factor 2 and probability of leakage due to damage. We used 10,000 evaluation of the model which yields distribution of the model output.

The model provides us with the following probabilities:

- probability of explosion due to leakage;
- probability of explosion due to one out of four leakage types;
- probability of each leakage type;

In the model one can easily select pipes’ sub populations (e.g. pipes with pressure 100 mbar) and obtain results only for these pipes.

In this chapter we explained the gas explosion model and how it was quantified. In the next chapter results of the model will be presented.
CHAPTER 4

Results of the model

The goal of this project was to establish a simulation model to assess the probability of explosion in grey cast iron pipelines in Amsterdam.

With the model we can obtain the following results:

- Distribution of the explosion probability due to leakage in Amsterdam;
- Explosion probability due to each kind of leakage (its mean, variance, standard deviation, minimal and maximal value);
- Probability of each type of leakage in Amsterdam;
- The explosion probability for each pipe and subsequently indicate the most dangerous pipes;

Similar results are calculated for pipes for certain sub populations. Pipes will be divided with respect to post code, age, diameter and pressure. The map of risk explosion in Amsterdam will be presented.

The model was implemented in Matlab. Time which is needed to obtain results for whole Amsterdam is about 135 min (on computer with 4 GB RAM and processor Inter Core 2 Duo 2.13 GHz). Fortunately, one use of the program gives all results indicated above. For smaller sub populations, e.g. one post code, the time which is necessary for calculations is significantly shorter. Results from the model can be easily stored in Matlab or exported to Excel.

4.1 AMSTERDAM

The first case study concerns the whole area of Amsterdam. The model firstly reads data about all grey cast iron pipes. Subsequently, it calculates overall explosion probability in grey cast iron pipelines in Amsterdam, as well as contribution of each leakage type. The results are presented below.
**Probability of explosion in Amsterdam in km/year**

The result of 10,000 Monte Carlo simulations is presented in the histogram below. Figure 25 (b) presents cumulative distribution function of explosion probability. From this figure one can read that there is 50% chance that explosion probability is smaller than 0.0002 per km/year in Amsterdam.

![Histogram and Cumulative Distribution Function](image)

*Figure 25: Probability of explosion due to leakage in km/year in Amsterdam*

The average, standard deviation, minimum and maximum for the distribution of explosion probability obtained from simulations are shown in Table 8.

<table>
<thead>
<tr>
<th>Mean</th>
<th>Variance</th>
<th>Standard deviation</th>
<th>Min. probability of explosion</th>
<th>Max. probability of explosion</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.08E-04</td>
<td>1.17E-08</td>
<td>1.08E-04</td>
<td>2.36E-06</td>
<td>6.59E-04</td>
</tr>
</tbody>
</table>

*Table 8: Results: Probability of explosion due to leakage in km/year in Amsterdam*

Since there is about 985 kilometers of grey cast iron pipes in Amsterdam, overall probability of explosion is as follows:

<table>
<thead>
<tr>
<th>Mean</th>
<th>Variance</th>
<th>Standard deviation</th>
<th>Min. Probability of explosion</th>
<th>Max. Probability of explosion</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.20</td>
<td>0.0113</td>
<td>0.11</td>
<td>0.0023</td>
<td>0.65</td>
</tr>
</tbody>
</table>

*Table 9: Results: Probability of explosion due to leakage per year in Amsterdam*

The chance of 0.2 of explosion in Amsterdam in the next year might be perceived as very high as this means that we can expect 2 explosions in the following 10 years. Historical data confirms that in the past 10 years exactly two explosions took place. Nevertheless, these two explosions were also for the whole period when grey cast iron pipes are used, but since the model is based on data from 2009, it would not be relevant to consider longer period to estimate explosion probability. Pipes were then much younger and some environmental as well as location factors were different than currently. Besides, in April 2003 construction
works on Noord-Zuid metro line have started (figure 26). The magnitude of these works is large. Consequently, many pipes may get damaged due to this 3rd party activity. Moreover, the analysis is based on fictive data, which has to be improved, as recommended in Chapter 5.

![Figure 26: Construction site of the Noord/Zuidlijn of the Amsterdam metro, at the Damrak (post code 1012).](image)

It might be of interest to see the contribution of different types of leakages on the probability of explosion. These results are shown in Table 9.

<table>
<thead>
<tr>
<th>Leakage type</th>
<th>Mean explosion probability</th>
<th>Variance</th>
<th>Standard deviation</th>
<th>Min. explosion probability</th>
<th>Max. explosion probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Connection failure</td>
<td>1.59E-04</td>
<td>9.24E-09</td>
<td>9.61E-05</td>
<td>2.43E-07</td>
<td>5.01E-04</td>
</tr>
<tr>
<td>Corrosion</td>
<td>9.50E-06</td>
<td>6.36E-11</td>
<td>7.98E-06</td>
<td>0.00E+00</td>
<td>6.18E-05</td>
</tr>
<tr>
<td>3rd party damage</td>
<td>2.24E-06</td>
<td>3.02E-11</td>
<td>5.50E-06</td>
<td>0.00E+00</td>
<td>9.51E-05</td>
</tr>
<tr>
<td>Ground movement</td>
<td>3.73E-05</td>
<td>8.77E-10</td>
<td>2.96E-05</td>
<td>0.00E+00</td>
<td>2.66E-04</td>
</tr>
</tbody>
</table>

Table 10: Results: Probability of explosion due to given leakage in km/year in Amsterdam

One can notice that the biggest contribution to overall explosion probability have leakages due to connection failure. This suggests that these leakages should not be belittled. Historical data showed that the biggest amount of leakages was in fact due to connection failure. On the other hand, this high value might be a consequence of overestimation of the small leakage factor by experts. To remind, 50% of this factor is equal to 0.00435, i.e. probability of explosion in pipe with small leakage which is closer than 1 meter to nearby property is 0.4%.
In Table 11 we see how probable different types of leakages are.

<table>
<thead>
<tr>
<th>Leakage type</th>
<th>Mean</th>
<th>Variance</th>
<th>Standard deviation</th>
<th>Min. explosion probability</th>
<th>Max. explosion probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Connection failure</td>
<td>3.21E-02</td>
<td>5.60E-06</td>
<td>2.37E-03</td>
<td>2.39E-02</td>
<td>4.06E-02</td>
</tr>
<tr>
<td>Corrosion</td>
<td>3.17E-03</td>
<td>2.04E-07</td>
<td>4.52E-04</td>
<td>1.61E-03</td>
<td>5.05E-03</td>
</tr>
<tr>
<td>3rd party damage</td>
<td>2.88E-04</td>
<td>5.50E-08</td>
<td>2.34E-04</td>
<td>0.00E+00</td>
<td>1.64E-03</td>
</tr>
<tr>
<td>Ground movement</td>
<td>4.74E-03</td>
<td>5.86E-07</td>
<td>7.65E-04</td>
<td>2.30E-03</td>
<td>8.15E-03</td>
</tr>
</tbody>
</table>

Table 11: Results: Probability of each leakage in km/year in Amsterdam

We see that connection failure has the highest probability of occurrence.

In our model the leakage probability is counted as a ratio of number of kilometers pipes with leakages to the total number of kilometers in considered population. If we just count average number of leakages (leaking pipes) due to each cause, we can compare the model performance with NESTOR database for 2009. The results of the investigation are depicted in table 12.

<table>
<thead>
<tr>
<th>Leakage type</th>
<th>NESTOR database</th>
<th>The model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Connection failure</td>
<td>488</td>
<td>440</td>
</tr>
<tr>
<td>Corrosion</td>
<td>16</td>
<td>140</td>
</tr>
<tr>
<td>3rd party damage</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Ground movement</td>
<td>36</td>
<td>70</td>
</tr>
</tbody>
</table>

Table 12: Comparison of performance of the model with NESTOR database (2009)

From the table above, one can conclude that connection failure as well as 3rd party damage model performs very well. However, corrosion model overestimates the number of pipe with leakages. This might be caused by not accurate choice of corrosion critical value or overrated corrosion rates. However this conclusion cannot be made without careful study concerned with the probability of corrosion’s detection. If we however could agree that the number of leakages due to corrosion is overestimated then since corrosion has influence on leakage due to ground movement we could explain also higher number of leaks due to ground movement in our model.

4.2 POST CODES

In this section we will show results for two different postcodes of Amsterdam. First is the postcode number 1012. It is located next to the Amsterdam Central Station (figure 27).
In this post code there are about 21.12 kilometers of grey cast iron pipes, while average number of kilometers per post code is 12.6 km. Traffic in this postcode is considered to be high. We do not have data about number of diggings in this area thus we will conduct two analyses. In the first one, we will use average Amsterdam’s probability of leakage due to 3rd party damage. In the second one, we will assume that in this region, the probability is twice as high as the average, due to extensive diggings caused by development of the metro.

In Table 13 mean and variance for the probability of explosion in post code 1012 are depicted:

<table>
<thead>
<tr>
<th>Mean</th>
<th>Variance</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.45E-04</td>
<td>6.88E-08</td>
<td>2.62E-04</td>
</tr>
</tbody>
</table>

**Table 13: Results: Probability of explosion due to leakage in km/year in post code 1012**

As we can see, the average probability of the explosion per one kilometer is higher in this postcode than in whole Amsterdam. Taking into account number of kilometers in this post code, we obtained annual explosion probability of 0.00517 in this area.

<table>
<thead>
<tr>
<th>Mean</th>
<th>Variance</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.17E-03</td>
<td>3.07E-05</td>
<td>5.54E-03</td>
</tr>
</tbody>
</table>

**Table 14: Results: Probability of explosion due to leakage per year in post code 1012**

If run the model for this postcode with twice higher probability leakage due to 3rd party damage we get the following results:

<table>
<thead>
<tr>
<th>Mean</th>
<th>Variance</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.99E-04</td>
<td>9.53E-08</td>
<td>3.09E-04</td>
</tr>
</tbody>
</table>

**Table 15: Results: Probability of explosion due to leakage in km/year in post code 1012, \( P_{gm}\)**

On can observe, that probability increased from 0.000245 to 0.0003. Thus overall probability of explosion in this postcode is now equal to 0.006.

<table>
<thead>
<tr>
<th>Mean</th>
<th>Variance</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.006</td>
<td>4.25E-05</td>
<td>6.52E-03</td>
</tr>
</tbody>
</table>

**Table 16: Results: Probability of explosion due to leakage per year in post code 1012, \( P_{gm} \)**

The second post code which will be studied is 1108. It located on the suburbs of Amsterdam, in Amsterdam Zuidoost. It is a district dominated by free standing houses and green areas. There are only 4.9 km of grey cast iron pipes and traffic in this area is low. Again, two studies will be conducted, but this time in the second approach probability of leakage due to 3rd party damage is reduced by half as compared to the average in Amsterdam. Results are enlisted in table 17.

<table>
<thead>
<tr>
<th>Mean</th>
<th>Variance</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.33E-06</td>
<td>3.57E-10</td>
<td>1.89E-05</td>
</tr>
<tr>
<td>Overall</td>
<td>6.56E-06</td>
<td>8.62E-09</td>
</tr>
<tr>
<td>In km/year, ( P_{gm} )**</td>
<td>1.24E-06</td>
<td>2.85E-10</td>
</tr>
</tbody>
</table>
We can see that in this post code overall probability of explosion is equal to 6.56E-06 which is significantly smaller than in case of post code 1012 where this probability was equal to 5.17E-03.

The model is sensitive only for changes in overall length of the pipes and traffic in given area. If better data was available, the probability of explosion in different subareas of Amsterdam might differ also due to changes in soil ph or number of km pipes exposed to digging activities.

Study on explosion probability was conducted for each post code. Detailed results can be found in appendix 3. For 78 post codes the mean explosion probability was calculated. To construct the risk map for Amsterdam 5 groups of the severity have been chosen. Each group is assigned with the color in the following way:

The risk map of explosion with respect to post code is presented below.

It turned out that post code 1056 and 1097 have the highest risk of explosion equal to 9.68E-03 and 1.01E-02 respectively. In postcode 1097 the biggest number of grey cast iron pipelines is located, about 30 km, and there
is average traffic. In 1056 there is 20km of pipes, which is still a significant amount, above average (12 km). However, traffic in this area is high. In both cases significant number of kilometers of pipes was in the proximity of the buildings (about 12%). In post code 1097 the average age is 47 years and in 1056 39. In both post codes very old pipes (about 88 years old) are to found. Detailed results of the analysis of post codes can be found in Appendix 3.

4.3 PIPES SUBPOPULATIONS

In this section we will investigate the probability of explosion in pipes subpopulations with respect to age, pressure and diameter.

We will start with study based on pipes’ ages. Most of the pipes in Amsterdam are 30-60 years. Thus, the following age intervals: <30, [30, 40), [40, 50), [50, 60] and ≥60 were checked. Results are presented in table below.

<table>
<thead>
<tr>
<th>Age</th>
<th>Mean explosion probability in km/year</th>
<th># km of pipes</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 30 years</td>
<td>1,76E-04</td>
<td>123.84</td>
</tr>
<tr>
<td>[30, 40) years</td>
<td>2,80E-04</td>
<td>357.8</td>
</tr>
<tr>
<td>[40, 50) years</td>
<td>1,65E-04</td>
<td>270.32</td>
</tr>
<tr>
<td>[50, 60) years</td>
<td>1,50E-04</td>
<td>177.76</td>
</tr>
<tr>
<td>≥60 years</td>
<td>1,58E-04</td>
<td>55.84</td>
</tr>
</tbody>
</table>

Table 19: Results: Probability of explosion due to leakage per km/year in pipes subpopulation w. r. t. age

The second study is based on pipes pressure. There are 3 pipes’ pressures: 30 mbar, 100 mbar and 1 bar. Mean explosion probability for these subpopulations is depicted in table 20.

<table>
<thead>
<tr>
<th>Pressure</th>
<th>Mean explosion probability</th>
<th># km of pipes</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 mbar</td>
<td>2,5E-04</td>
<td>100.67</td>
</tr>
<tr>
<td>100 mbar</td>
<td>2,12E-04</td>
<td>832.1</td>
</tr>
<tr>
<td>1 bar</td>
<td>4,03E-04</td>
<td>52.8</td>
</tr>
</tbody>
</table>

Table 20: Results: Probability of explosion due to leakage per km/year in pipes subpopulation w. r. t. pressure

Last study concerns pipe’s diameters. For examination there were taken only diameters which amount was significant, i.e. bigger than 10% of the total population. Obtained values are gathered in table below:

<table>
<thead>
<tr>
<th>Diameter</th>
<th>Mean explosion probability</th>
<th># km of pipes</th>
</tr>
</thead>
<tbody>
<tr>
<td>150 mm</td>
<td>2,6E-04</td>
<td>398.38</td>
</tr>
<tr>
<td>100 mm</td>
<td>2,68E-04</td>
<td>161.28</td>
</tr>
<tr>
<td>300 mm</td>
<td>1,52E-04</td>
<td>126.16</td>
</tr>
<tr>
<td>200 mm</td>
<td>1,68E-04</td>
<td>104.26</td>
</tr>
</tbody>
</table>
Additionally, explosion probability was checked for the most popular pipes 150 mm diameter and 100 mbar pressures. It turned out that mean explosion probability in these pipes is 0.00026 per km/year and there is about 364.5 kilometers of such pipes.

### 4.4 Pipes with the worst performance

The study presented in this section is about the worst performing pipes. For each pipe mean probability of explosion was calculated.

The most dangerous pipes are the ones situated in distance smaller than 1m to nearby property. Only for these pipes model assumes that released gas can accumulate. Pipes which are in larger distance to the buildings can have a leakage, but released gas will disperse due to lack of opportunity to get storage.

If we consider probability of explosion per pipe, the biggest probability has pipe with ID 35705037 (0.0035). It is a pipe which is situated in post code with high traffic. This yields high value of explosion probability due to ground movement (5.53E-04). It is also one of the longest pipes (256.59m where mean length of the pipe is about 21 m.) Thus explosion probability due to connection failure is also high (0.0029). The pipe is young (35 years) thus explosion probability due to corrosion is equal to 0. Contribution to overall explosion probability has 3rd party damage, which depends on pipe’s length.

To see results that are not dependent on pipe’s length we calculated the explosion probability of each pipe per 1 km. In this case the worst performance has the pipe with ID 385798485. Explosion probability per 1 km. of such pipe is equal to 0.0228. Whole explosion probability constitutes probability of leakage due to corrosion because the pipe has small wall thickness (8.25) and is relatively old (53 years). The pipe is short (0.133m), thus there were no connections in this pipe and no leakage due to 3rd party damage. The pipe is situated in area with low traffic.

In figure 29, distribution of explosion probability for pipes with leak which are located close to the nearby property is shown.
2848 out of 2959 pipes has probability of explosion smaller than 0.00037. Thus, we set the critical value of explosion risk as level 0.00037 and checked which pipes have explosion probability higher than this critical value. There are 111 such pipes and their ID can be found in appendix 3.

In this chapter we showed results of the model. It is said that no model is perfect, but most of them are useful. We calculated that our model probably overestimates the probability of explosion due to overestimation of leakages caused by corrosion. In the next chapter recommendations about improvement of the data collection as well as possible model improvements can be found.

### 4.5 Sensitivity Analysis

Sensitivity Analysis is a study about relations between the input and the output of a model. It is concerned with identifying "important parameters". Thanks to sensitivity analysis we can simplify, optimize and validate the model or check its robustness. SA allows us to recognize factors that contribute the most to the output variability.

The following figure shows parameters which affect the final result:
Let us introduce the following notation:

- \( pl_{con} \) – probability of the leakage due to connection failure in distance to nearby property smaller than 1 m
- \( pl_{cor} \) – probability of the leakage due to corrosion in distance to nearby property smaller than 1 m
- \( pl_{3rd} \) – probability of the leakage due to 3\(^{rd}\) party damage in distance to nearby property smaller than 1 m
- \( pl_{gm} \) – probability of the leakage due to ground movement in distance to nearby property smaller than 1 m
- \( pe_{con} \) – probability of the explosion caused by leakage due to connection failure in distance to nearby property smaller than 1 m
- \( pe_{cor} \) – probability of the explosion caused by the leakage due to corrosion in distance to nearby property smaller than 1 m
- \( pe_{3rd} \) – probability of the explosion caused by the leakage due to 3\(^{rd}\) party damage in distance to nearby property smaller than 1 m
- \( pe_{gm} \) – probability of the explosion caused by the leakage due to ground movement in distance to nearby property smaller than 1 m
- \( f_1 \) – probability of explosion given small leakage in distance to nearby property smaller than 1 m.
- \( f_2 \) – probability of explosion given big leakage in distance to nearby property smaller than 1 m.
- \( PE \) – overall probability of explosion
For the analysis, which will provide us with the knowledge about relations between above probabilities, Unigraph and Unisense software was used. Unigraph is graphical tools to analyze represent high dimensional data sets. We will use it to investigate the sample file created by the explosion probability model. In our case we took 10 000 samples of eleven dimensional random vector with elements described above. Unigraph allows us to visualize distributions of each variable (margins, histograms) as well as to study relationships between these variables (scatter plots, cobweb plots). Scatter plots allow visualization of bivariate relationships whereas cobweb plots are very useful in analyzing multidimensional data sets. Cobweb plot uses vertical lines as a representation of random variables. They can be shown in natural and percentile scale. For each sample of the dataset values for variables are found on the vertical lines and connected with each other forming a jugged line. This representation allows us to observe if high values of one variable tend to appear with high values of other variable. If this is the case then these two variables are strongly related. If on the other hand high values of the variable appear with low as well as with high values of the other variable then these variables are not strongly correlated.

In Figures below we see cobweb plots of probability of leakage and probability of explosion due to connection failure, corrosion, 3rd party damage and ground movement. The cobweb plots are shown in percentile scale so the minimum and maximum values of each variable are 0 and 1, respectively.

Samples selected: 150

(a) connection failure  
(b) corrosion
As we can see, in case of connection failures and ground movement we cannot distinguish significant relation between probabilities of leakages and probabilities of explosion due to these leakages. Low values of leakage probabilities are not always associated with low values of probability of explosion. The same applies for other values. In two other cases (corrosion and 3rd party damage) the relation is stronger, but still not that high as one could expect. For that reason, Factor 1 and Factor 2 have to be investigated, because they influence explosion probability.

The following figures show the same relations, but Factors are also depicted.
Figure 31: Cobweb plots of plcon & pecon & f1, plcorr & pecorr & f1, pl3rd & pe3rd & f2, plgm & pegm & f2
This analysis shows significant influence of both Factors on the final result. This was of curse easy to predict as these factors determine the probability of explosion in case when the leak occurs.

This analysis shows that only extremely low values of leakages probabilities are not sensitive to factors and yield small probabilities of explosion due to these leakages. In all other cases, we can observe lack of correlation between leakage probability and probability of explosion due to this leakage because of multiplication by factor 1 or 2. Hence, the model is very sensitive to parameters f1 and f2. High probability of leakage not necessarily leads to high probability of explosion. This probability is high if also there are conditions for gas to accumulate and ignite. This is exactly what factors indicate.

The graphical tools are very useful. They help us analyze and understand the model and allow us to gain confidence in the model performance. There are also other tools that represent relationships in numerical way. The most known is the product moment correlation which range from -1 to 1. Value 1 means that there is a linear relationship with positive slope between two variables. -1 implies the liner relationship with negative slope. If the value is equal to 0, then there is no linear correlation between two variables. Cohen[37] proposed a guideline for the interpretation of a correlation coefficient:

<table>
<thead>
<tr>
<th>Correlation</th>
<th>Positive value</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>0-0.09</td>
</tr>
<tr>
<td>Small</td>
<td>0.9-0.3</td>
</tr>
<tr>
<td>Medium</td>
<td>0.3-0.5</td>
</tr>
<tr>
<td>Large</td>
<td>&gt;0.5</td>
</tr>
</tbody>
</table>

*Table 22: Interpretation of a correlation coefficient, Cohen[37]*

In our case the product moment correlations calculated in Unisense are as follows:

<table>
<thead>
<tr>
<th>First variable</th>
<th>Second variable</th>
<th>Product moment correlation</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>peconn</td>
<td>PE</td>
<td>0.9552</td>
<td>Large correlation</td>
</tr>
<tr>
<td>pecorr</td>
<td>PE</td>
<td>0.6378</td>
<td>Large correlation</td>
</tr>
<tr>
<td>pe3rd</td>
<td>PE</td>
<td>0.1742</td>
<td>Small correlation</td>
</tr>
<tr>
<td>pegm</td>
<td>PE</td>
<td>0.3425</td>
<td>Medium correlation</td>
</tr>
</tbody>
</table>

*Table 23: The product moment correlations calculated in Unisense*

The result shows that as measured with the product moment correlation the biggest impact on the overall explosion probability has explosion due to connection failure and the smallest the one due to 3rd party damage. The figures below show graphical interpretation of the results - the linear fit to the data points for both cases:
The cobweb plot below proves that in fact there is a strong correlation between explosions due to leakage caused by connection failure and overall explosion probability.

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Figure 32: Linear regression of pecon on PE

Figure 33: Linear regression of pe3rd on PE

Figure 34: Cobweb plot of pecon and PE
Looking at the density of the explosion probability due to connection failure, one can observe that it is very similar to the density of the overall explosion probability (in comparison to three other densities—small figure).

The smallest input to the final result has explosion due to 3rd party damage. There is very small correlation between this factor and overall explosion probability, thus pe3rd is relatively unimportant for the final output. If one considers the density of pe3rd, pecorr and pegm it is visible (in small figure above) that pe3rd differs the most from PE density.

The analysis showed that explosion due to connection failure is the most significant for the final result. It is almost completely positively correlated with the output and affects it the most. It means that high values of explosion probability due to connection failure implies high values of overall explosion probability, thus the most attention should be paid in order to reduce risk of explosion caused by this kind of leakages. According to the previous analysis, reduction of leakages is not sufficient. Probability of gas concentration and accumulation should be also reduced, in order to decrease overall risk of explosion due to leakage from connection.

This simple sensitivity analysis showed that very important for each type of failure is probability of accumulation and ignition of the released gas (factor1 or factor2). In other words, big chance of gas storage might lead to explosion even when the probability of leakage is small. The biggest input to the final result has probability of explosion due to connection failure. Liander employees expected such an outcome, thus according to their opinion this result is reasonable.

Figure 35: Densities of pecon, PE, pecorr, pe3rd, pegm
CHAPTER 5

Summary and recommendations

In this chapter we will present possibilities of databases and model improvements as well as summary of the whole study.

5.1 Summary

Liander Company manages grey cast iron pipelines in Amsterdam city. Because of brittle nature of these pipes as well as aging process, there is a high danger of explosion associated with these pipes. In order to reduce the risk and schedule the replacement, the model which calculates explosion probability in the mains was developed.

The model is based as much as possible on available data. Some parameters of this model were not available and Expert Judgment study was used in order to obtain missing data.

The model is a simulation-type model which takes into account uncertainties and provides us with result in form of the sampling probability distribution. The final result is the combination of four probabilities of explosion due to different causes: probability of explosion due to leakage caused by connection failure, corrosion, 3rd party damage and ground movement.

The model was implemented in Matlab and allows selection of various pipes’ sub populations (with respect to area or some particular pipe characteristic) to see how they contribute to the overall probability of explosion.

We applied the model for the whole population of the grey cast iron pipelines in Amsterdam as well as for the following pipes’ sub populations:

- Each post code in Amsterdam (obtaining the risk map of explosion probability);
- Pipes in age: <30, 30-40, 40-50, 50-60 and >60 years;
- Pipes under the pressure of 30,100 and 1000 mbar;
- Pipes with diameter 100, 150, 200 and 300 mm.
Result obtained for the whole population in Amsterdam seems to be reasonable taking into account two explosions which took place in past 10 years and the fact that the model is based on data from 2009.

It turned out that connection failures have the biggest contribution to the overall explosion probability, which was confirmed in the sensitivity analysis. Nevertheless, the results of the model might be slightly overestimated due to overestimation in corrosion model. Thus, databases and model improvement should be carried out in order to obtain more accurate results.

5.2 **DATA AND MODEL IMPROVEMENT**

Main recommendations concerning improvements in data collection, which could have an impact on the model, are given below (for the thesis artificial data have been used):

**Data**

- Data about the pipes should be extended. For each pipe depth and exact wall thickness should be known. Pipes’ environmental surrounding characteristics (ph, soil type, water table level) should be provided.

- Corrosion database should be improved and extended. Corrosion level should be measured not only assessed by eye inspection. Repeated measurements of corrosion level could provide more inside into how the corrosion develops in time. Uniform and pitting corrosions should be better distinguished and measured.

- Good data about traffic should be provided.

- Studies about distribution of obstacles in the ground could be carried out.

- Improvement of database concerning diggings. From KLIC database the information about the area exposed to digging should be known. Moreover detailed information about the digging process (e.g. depth, vibrations, dehydration) should be collected.

- Better data about connections e.g. age, repairs and environmental characteristics around is of interest.

Given better data the model could be improved:

- Model assigns ph randomly from the distribution of ph values obtained from the corrosion database. This could be changed if each pipe’s ph characteristic is known. Soil type and other characteristic could be added to the model.

- Corrosion model could be changed when better data is available.

- Model uses very simple dependence on traffic. It could depend on not only on traffic load but also on traffic type (e.g. light, heavy, industrial).

- Ground movement module of the model does not depend on the presents of underground obstacles and nearby digging activities. This could be improved when more data is known.
• 3rd party damage module of the model could distinguish between diggings carried out under supervision of an inspector from Liander.
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