Laser profiling of sewer pipes
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Analysis of concrete egg shaped sewer pipes

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Abstract

Introduction
In developed countries like the Netherlands there is an extensive and well functioning sewer system. Over the years 111,000 kilometres of sewer pipes were constructed in the Netherlands. With an effective management proper serviceability of the asset can be achieved on the long-term, which will minimize adverse effects on human health and environment. Moreover, cost-effective sewer asset management is necessary to attain a preferred service level at lowest public costs.

Problem definition
To enable effective sewer asset management a reliable source of information has to be available about the state of an asset. Nowadays CCTV inspections and pipe age are the main sources of information about the state of sewer pipes. These techniques don’t always provide conclusive information. Laser profiling is a relatively new technique which can aid to gain information about the state of. A laser profiler, as an adjunct to CCTV, can identify the profile of a sewer and also wall loss from corrosion compared to an assumed initial situation.

Research
The goal of the research is to determine the potential of laser scanning methods for accurate, non-invasive assessment of the changes in the inner pipe profile of concrete sewer pipes. The main research question is: ‘How accurate is the laser profiler when measuring deteriorated sewer pipes?’

In the research egg shaped concrete sewer pipes were measured under laboratory conditions. The used experimental setup consists of an old concrete, egg shaped sewer pipe. At the front and back of the pipe a ramp is placed to ensure a smooth entrance and exit of the inspection camera. The recordings from the laser profiler are analyzed with Matlab to determine the accuracy.

Results
The accuracy of the laser profiling remained within 0.5% while stationary. However when the camera with the laser profiler is moving through the pipe the accuracy is reduced drastically. In fact when corrected for movement the values deviated up to 15.9mm in one axis. Also an attempt to link the corrosion to the wall thickness was inconclusive due to difference in theoretical and actual shape of the egg shaped sewer pipes.

Conclusions and Recommendations
It is a technique with potential to deliver 3D information about the inside of a sewer pipe. However for that use the accuracy has to be improved while moving. In the future it can be used to objectify inspection techniques and can be used in sewer renovation. In this process the aspect of determining the remaining wall thickness with laser profiling will always remain difficult due to unknown starting conditions.

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Preface

The reason to attend the Master’s study Water Management at the TU Delft is because the sewer is a neglected but very important issue in the Netherlands, or as my friends would explain to me: “My shit is your job”.

I started studying civil engineering at the University of Twente, where I received my bachelor’s degree. However, my love for the field of sanitary engineering arose a few years back when I did my internship at the engineering agency MWH in Delft. The subject of my internship was “Asset management as part of sewer management at municipalities”. This was my first acquaintance with sewer management and the subject intrigued me.

It lead to an easy decision to continue my Master’s study at the TU Delft on the subject of Water management. After another internship at civil contractor GMB where I constructed new sewers at the Maasvlakte II, I found a suitable thesis topic subject at the sanitary department.

The thesis was about testing and measuring the geometry and pipe characteristics of deteriorated concrete sewer pipes. It was a very educational experience which, being executed partly next to my job at GMB has taken much more time to finalise than what was expected.

Along the way to the finalisation of my research a lot of people have supported me, All the PhD student were familiar with the research and have contributed somewhere in the process. This is very much appreciated, and I would like to thank them for their input. I like to thank Nikola Stanic for the interesting discussions and input during the thesis. Special thanks goes to Francois Clemens who was my counsellor during the internship and master thesis.

Besides the people at the TU Delft, I would also like to acknowledge and thank the companies “Van der Valk en de Groot” for providing the means necessary to execute the experiments. On top of that special thanks to their employees who did a fantastic job enabling all the experiments with their support. Especially Bert Kuier, who helped out with the experiments and contributed extraordinary in the overall process.
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1 Introduction

In developed countries like the Netherlands there is an extensive and well functioning sewer system. Over the years 111.000 kilometres of sewer pipes were constructed and 99.8 % of the population is connected to a sewer system. This is in fact the highest percentage of connected households of all the countries of Europe. The performance of the system can be illustrated in by the comparison of the average downtime (time not functioning). The downtime of the sewer system in the Netherlands is only 0.6 minute per household per year. In comparison, the downtime of electricity is 14 minutes per household per year (Feitencommissie, 2010).

With time the sewer system deteriorates due to aging, overloading, misuse and mismanagement. The Municipalities in the Netherlands are responsible for the maintenance of the sewer system; they finance the sewer maintenance mostly from the sewer taxes which every household has to pay. With an effective management proper serviceability of the asset can be achieved on the long-term, which will minimize adverse effects on human health and environment. Moreover, cost-effective sewer asset management is necessary to attain a preferred service level at lowest public costs.

1.1 A need for sewer asset management

The main issue is that the sewer maintenance costs have increased over the last 10 years. Urban drainage systems are viewed as a capital intensive infrastructure. For instance, the estimated value of the existing urban drainage infrastructure in the Netherlands is around 77 billion euro’s. To be able to pay for the maintenance of this infrastructure, the total amount of sewer taxes has been doubled between the year 2000 and 2010. In 2010 it was around 1.3 billion euro’s per year. In 2012 the cost already rose to 1.4 billion and it is expected that the costs will increase further to 1.7 billion in the year 2020. The main cause for this increase is the aging of the sewer systems. A total of 88% of the system is constructed after the 1950’s and with an average technical lifespan of around 60 years an increasing part has to be replaced or repaired in the near future (Feitencommissie, 2010).

To limit this increase in costs the various actors in the water sector want to increase their efficiency. In order to achieve this The Provinces, The Municipalities, Drinking Water companies and Waterboards joined forces in the commission “Feitenonderzoek” which looked at possible savings in the entire water sector. Their report states that till the year 2020 a saving of 8% in the sewer management is feasible. One of the main pillars to achieve this is the structural application of asset management within the sewer management (Feitencommissie, 2010). However, saying is one thing and doing is another.

Asset management is not an exact science and there are many interpretations and definitions available. The one used in this report is the definition according to PAS 55-1:2008: “Systematic and co-ordinated activities and practices through which an organization optimally and sustainably manages its assets and asset systems, their associated performance, risks and expenditures over their life cycles for the purpose of achieving its organizational strategic plan.” (Institution, 15 September 2008) Overall, asset management consists of multiple steps and processes to manage assets. These processes are depicted in Figure 1. The field of interest of this thesis is the determination of objectives, in other words the information needed to make decisions about an asset.
Since 1993 the Municipalities are obliged by The Dutch Government to apply asset management (article 4.22, Wet milieubeheer). They have to report their actions in the Municipal Sewer Plan (Gemeentelijk Riolerings Plan).

The goal of the sewer asset management is to provide optimum decisions on the provision for maintenance, on-going operation and on the provision of the large investments, associated with sewer rehabilitation and replacement. The schematic diagram of the sewer system management process is given in Figure 1. The investigation and assessment, the first two stages, are important factors in the sewer system management due to the fact that they have direct impact on all further stages (Nederlands Normalisatie-instituut, 2008).

1.2 Problem definition

Today, it is still difficult to assess the actual condition of the sewer pipes. Decisions on rehabilitation and maintenance of sewers should be made based on reliable information on the physical status of the sewer system and on its serviceability. The primary sources of information used in decision making (e.g. necessary replacement) are pipe age and Closed Circuit Television (CCTV) inspections. The difficulty with pipe age is that it is only one of many factors influencing the deterioration of sewer pipes. For example in The Municipalities
with soft soil the sewer system has to be replaced more often than in municipalities which are located on solid soils. The setting of the soft soil influences the service life of the sewer pipes more than the pipe age. A few other factors that influence the service life are the installation method, surface use, groundwater level and section length influence the deterioration. In conclusion, information on the pipe age is insufficient to provide knowledge on the actual condition of the sewer pipes.

The visual inspection with CCTV has disadvantages as well. Recent research of Dirksen et. al., (2011) shows that there are inconsistencies in the assessment of the visual data from CCTV inspections. In the research the same stretch of pipe was assessed by different qualified inspectors and the assessment of the recorded damages differed per person. This could mean that in some cases the municipality would replace the pipe and in another case they wouldn’t. Even so with severe damage to the pipe or obvious clogging the CCTV inspections will give a conclusive answer. Overall, research shows that the quality of visual inspection data is insufficient to make proper decisions about sewer renewal. In order to overcome the limitations of visual inspection, several new techniques have been developed over the past two decades and are applied in practice, like radar (e.g. Olhoeft, 2000), acoustic techniques (e.g. Feng, Horoshenkov, Tareq, & Tait, 2012), sonar (Kirkham et al., 2000), or laser profiling (Duran, Althoefer, & Seneviratne, 2003).

Laser profiling of (sewer) pipes is a technology that is introduced and applied in practice for some years. A laser profiler, as an adjunct to CCTV, can identify the profile of a circular sewer and also wall loss from corrosion (Thomson et al., 2010). Some research claim that the laser profiling technique is capable of measuring the wall losses due to corrosion (Kirkham et al., 2000) with a relative uncertainty of 0.5%. However, Duran et al. (2003) state that the main difficulty in laser profiling is the alignment and orientation of the sensor in the harsh sewer environment.

In summation, to authors’ knowledge no attempt to measure actual pipe wall thickness of deteriorated sewer pipe was reported so far, as well as to quantify uncertainties related to the laser profiling inspection technique. For the aforementioned reasons, further studies need to be carried out in order to fill the gap of previously carried out research and provide reliable information on the condition of the sewer assets.
1.3 Scope and goal of the research
This thesis is part of a PhD research which aims at a better understanding and gaining advanced knowledge on the collapse of deteriorated sewer pipes. Part of the PhD research is to determine physical and structural properties of deteriorated concrete sewer pipes. With this data a model for the probability of pipe collapse can be created, which will contribute to better estimate the probability of collapse of sewer pipes. Consequently, if the remaining life span of concrete sewer pipes can be predicted better than based on CCTV inspections and pipe age, the investments associated with sewer rehabilitation and replacement can be optimized even further.

Input for the numerical model in the PhD will be the pipe dimensions and material characteristics, or summarized, the following data will be collected:

1. Dimensions of the pipe/the remaining wall thickness
2. Determine the characteristics of the material
   - Crushing strength - Cracking the pipes
   - Material properties - Drill core analysis
3. Numerical model

The goal of this research is to determine the potential of laser scanning methods for accurate, non-invasive assessment of the changes in the inner pipe profile of concrete sewer pipes. The main research question is: ‘How accurate is the laser profiler when measuring deteriorated sewer pipes?’

The detailed objectives of the research are:

- To quantify measuring uncertainties.
- To measure the shape of the pipe interior and exterior.
- To post-process raw data in Matlab platform.

1.4 Structure of the report
This introduction chapter describes the context of sewer asset management and current sources of information used in decision making. It identifies a number of shortcomings in existing approaches and addresses some. Chapter 2 describes the used equipment materials and methodology. Chapter 3 sums up the results in graphs and tables together with a discussion of it. At the end of the thesis the summary and conclusions of this study are presented. Furthermore, in the annexes background information can be found about the process of deterioration of concrete sewer pipes, as well as information on the original location of the used pipes.
2 Approach and methods

2.1 Used equipment and material

Sewer pipes
In the research, egg shaped sewer pipes are used with dimensions 300/450 mm and 400/600 mm, the regular shape is shown in Figure 2. The pipes come from regular sewer renovation projects in the Hague and Breda. The location and properties of the pipe, such as years in service, ground water level and soil type are recorded for both locations in Table 1 and described in detail in annex B.

Table 1. General characteristics of the studied sewer pipes

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Breda</th>
<th>The Hague</th>
</tr>
</thead>
<tbody>
<tr>
<td>Years in service</td>
<td>61</td>
<td>89</td>
</tr>
<tr>
<td>Groundwater level (m)</td>
<td>Mostly above</td>
<td>Below invert level</td>
</tr>
<tr>
<td>Soil type</td>
<td>Peat, clay, sand</td>
<td>Sand</td>
</tr>
<tr>
<td>Surface load</td>
<td>35 years of high traffic load</td>
<td>Only domestic</td>
</tr>
<tr>
<td>Inspection results</td>
<td>Surface damage BAF 3</td>
<td>Surface damage class BAF 4</td>
</tr>
</tbody>
</table>

A detailed characteristic of each studied pipe is given in Table 2. Prior to excavation visual inspections were performed to determine the condition of the inner surface of the sewer i.e. surface damage by internal chemical (corrosion) or mechanical action (code BAF). The registration of defects was done according to the visual inspection coding Standard NEN-EN 13508-2, while the Standard NEN 3399 was used to assign a level of severity to each defect – condition assessment (Nederlands Normalisatie-instituut 2003; 2004a).

Table 2. Deterioration characteristics based on sewer inspection prior to excavation of the sewer pipes. Defects are reported based on the coding from NEN 3399.

<table>
<thead>
<tr>
<th>No.</th>
<th>Origin</th>
<th>Year of construction</th>
<th>Surface damage class (BAF)</th>
<th>BAF class description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>De Hamer factory</td>
<td>new</td>
<td>-</td>
<td>Missing aggregates or reinforcement outside the surface protrudes</td>
</tr>
<tr>
<td>2</td>
<td>The Hague</td>
<td>1924</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>The Hague</td>
<td>1924</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Breda</td>
<td>1952</td>
<td>3</td>
<td>Aggregates that protrude beyond the surface or visible reinforcement</td>
</tr>
<tr>
<td>5</td>
<td>Breda</td>
<td>1952</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

Panoramo camera
During the research the sewer pipe conditions were assessed using the IBAK PANORAMO camera system/optoscanner, a relatively new concept in the field of pipeline inspection (Figure 3). The IBAK PANORAMO 360 utilizes two high-resolution, 186°, wide-angle camera lenses to captures a complete, 360° spherical image of the pipe. The video recording can be unfolded and assessed in real time or at a later date and permits computer-aided measurement of the positions and sizes of objects or pipe defects. Furthermore, the system
has no external moving parts - hence it is robust and has less chance to fail; the captured images are always sharp, regardless of the recording.

**Laser profiler**

The change in shape of the sewer pipe interior was assessed by a concept employing a CLEARFLOW Clearline laser profiler coupled to a PANORAMO optoscanner (Figure 5). A laser profiler, as an addition to the camera, can identify the profile of a pipe and also wall loss from corrosion (Thomson et al., 2010). The laser profiler mode of operation is based on a laser ring, which is projected onto the pipe wall and subsequently recorded by the connected camera. Figure 4 shows the principle of the laser based inspection concept.

The laser profiler mode of operation is based on a laser ring, which is projected onto the pipe wall and subsequently recorded by the connected camera (Figure 7). The software calculates the data received and creates a 3D model of the pipe geometry. As an illustration an image of a round pipe is shown in Figure 6.
2.2 Measuring setup

The experimental setup (Figure 8) consists of an old concrete, egg shaped sewer pipe. At the front and back of the pipe a ramp is placed to ensure a smooth entrance and exit of the inspection camera. With a frame over these ramps the setup is darkened to ensure good visibility of the laser. As described the profiler projects a laser ring on the pipe wall that is captured by the camera and identifies the shape of the pipe interior.

![Figure 8. Measuring setup which is used to perform the measurements. To create situations comparable to the sewer the setup is covered with a large black plastic film.](image)

Secondly, the shape of the pipe exterior was determined by measuring the wall thickness at 4 selected locations on both ends of the pipe (Figure 9). This was done with a calliper gauge and a frame clamp. Cylinder-shaped objects were used as indicators of the selected location for the measurements.

![Figure 9. in each pipe several reference shapes are placed for measurements. The locations of the reference shapes have a unique coded and in total eight locations shapes are placed per pipe.](image)
To create a reference point a semicircle wooden shape with dimensions 35 x 40 x 9.5 mm is glued to the pipe at each location shown in Figure 9. To increase the visibility the shapes are sprayed white. Figure 10 and Figure 11 show the reference shape in practice on a recorded video frame and with the laser projected on it.

![Figure 11. A white painted and placed reference shape, the shapes were painted white to increase the visibility on video.](image1)

![Figure 10. Reference shape as recorded by the Panoramo camera](image2)

### 2.3 Experimental method

The study was conducted on all eight egg-shaped concrete sewer pipe with dimensions of 400/600 mm. Figure 12 describes the applied experiment protocol. Before experiments were carried out on a full scale, tests were conducted in order to determine measuring and systematic errors within the method – the stationary measuring accuracy. Furthermore, the PANORAMO system was calibrated. The measurements were carried out in two stages: measuring the shape of the pipe interior and manually measuring the shape of the pipe exterior. The results where combined in order to determine the remaining pipe wall thickness. Additionally, the effect of camera velocity on the final results was verified by comparison of measuring results obtained under normal inspection velocity (around 20 cm/s) and at a velocity of 4 cm/s. Moreover, Matlab code was written and applied as a post-process on the raw data – data processing.

![Figure 12. The schematic diagram of experiments protocol.](image3)

### 2.4 Measuring uncertainties

The noise level (measuring error) that originates from the measuring inaccuracy of the laser profiler was determined by repeating measurements 80 times at a single location within the sewer pipe. In order to validate the test results the same test was conducted on a specially constructed, for the purpose of the experiment, round iron 300 mm diameter pipe.

Systematic errors in the measuring principle or by the apparatus (e.g. improper distance measurement, misalignment of the camera within the sewer pipe, improper operational velocity of the camera, improper wall thickness measurements) were checked. First it was checked if an error was made in the distance measuring by the laser profiler. This is verified
using a simple laser distance meter at the exact location where the profiler projects its laser beam at the reference locations described in 2.2.

Due to an uneven surface of the pipe and possible freedom of movement of camera misalignment can occur along the vertical and horizontal axis. The amount of error due to misalignment was quantified by mathematical calculations.

At each reference location the wall thickness is measured manually as a reference location to link the inside and outside of each pipe. Errors caused by human error during the measuring process of wall thickness were checked by re-measuring. The measuring accuracy is defined as the 95% accuracy interval (4σ).
2.5 Future research

Results from the previously described measurements showed that movement of the camera influences the measurements. A setup to determine the uncertainties due to movement during measurements was created as a part of further research comprising all the uncertainties associated with the laser profiler. The research is described in the published article: "Uncertainties associated with laser profiling of concrete sewer pipes for the quantification of the interior geometry" (Clemens, Stanić, Van der Schoot, Langeveld, & Lepot, 2014). Measurements for this article are executed as part of this thesis. The software to analyse the pixel intensity on page 4 and 5 of the article is developed during the thesis and the setup to measure the movement as well. The measuring setup is developed during the thesis together with Francois Clemens and Nikola Stanic.

Measuring setup for measurements with moving camera

A setup with three distance measuring lasers is used. The distance lasers are altered to measure and record the distance continuously. A screen is attached to the panorama camera to catch the laser projections. At the same time the location of the three lasers on the screen is recorded by a second camera attached to the panorama as well. Together with elaborate mathematical calculations these recorded values determine the movement in all three directions, the so called pitch, roll and rotation.

In the end the determined movement is then used to rearrange the recorded data points to its actual position.

![Figure 13. Sketch of the setup, top figure shows the dimensions (mm) of the device attached to the panorama camera. It has an additional camera and screen to capture three distance lasers. The three distance lasers are used to measure all movements, the location of the laser in the entire setup is depicted in the bottom figure.](image)
Aligning the lasers

An important step to reduce uncertainties is the alignment of the three lasers. To align the three lasers a board with mm paper is put thirty meters away from the lasers. With small adjustments to the setup each laser is aimed at the same point as where it should be when the board is put in front of the three lasers.

At first this is done in the hallway, Figure 15 but at the v.d. Valk company a special straight line is used to align the inspection camera. This line is used to align the lasers before executing the measurements. With this method a deviation of +/- 3 mm in thirty meters was achieved, based on the mm paper.

Figure 15. These photographs give an indication of the process to align the three lasers, the photographs are taken in the hallway of an apartment building.
2.6 Preparation of the pipes for further experiments

Besides the reference points and the manual measurement, each pipe is photographed for analyses in the future. With these photographs any abnormalities at the inside of the pipe might be linked to the outside of the pipe. To create a complete image of each pipe, six pictures are taken, as an illustration the pictures of one pipe are depicted in Figure 16.

![Figure 16](image)

Figure 16. Of each pipe six photographs are taken to record the outside and inside of each pipe. The photographs shown are from pipe number one, the house number was painted on each pipe when excavated to determine the location.

After the pictures are taken, the pipes are painted in three colours and numbered square planes(Figure 17). These colours show the crown, side and invert level of the pipe. At the same time the numbers in the squares determine the position along the length of it. This is done to make the pipes ready for further analysis with drill cores and to create a link between the inside and outside of the pipe, but this is out of the scope of the thesis report.

![Figure 17](image)

Figure 17. A pipe before and after painting for future research, the colors depict the crown, side and invert level, each square is numbered to create a specific location on each pipe.
2.7 Data processing

The raw data need to be processed to obtain the information sought after. Although the laser profiler comes with a software programme it was necessary to write a Matlab code, because the original software does not support egg-shaped sewer pipes nor produces enough data points. The full Matlab scripts are available on request. Instead the process is described and illustrated based on eight different steps. The data processing encompasses the following steps:

**Step 1**
Firstly, an avi video is recorded with the PANORAMO system. Figure 18 shows a single frame/image from one of the video’s.

![Figure 18. Step 1: Original frame from a measurement with the laser profiler, recorded with the panorama camera.](image)

**Step 2**
Determine the x, y position of the laser projection from the recorded image using Matlab.

![Figure 19. Step 2: The data points obtained from the frame with Matlab, the blanks are missing data points.](image)
Step 3
Further, interruptions in the laser signal due to unevenly deteriorated pipe surface occurred, and these gaps were filled in with interpolation technique. Linear interpolation was adopted due to small interruptions in the signal. The code filled in the gaps if the distance was more than the average distance between the measured points. This comes down to every 2.4 pixel, which corresponds to an average distance of 2.2 mm.

![Figure 20. Step 3: Interpolation is used to fill in the gaps.](image1)

Step 4
The loss of wall thickness can be quantified by overlapping the measured and theoretical profile of the pipe. Therefore, a theoretical profile of the pipe is created, based on the dimensions defined by Standard NEN 7126.

In this step mm to pixel factor is added in order to correctly scale the theoretical pipe profile. This factor is determined during PANORAMO system calibration.

![Figure 21. Step 4: A perfect theoretical pipe is used as a reference shape to determine corrosion.](image2)
**Step 5**

Due to an uneven surface of the pipe and possible freedom of movement of camera misalignment can occur along the vertical and horizontal axis. In order to correct for these movements during recording and to be able to compare the theoretical pipe with the recorded one, the recorded profile is repositioned in several steps:

5.1

Based on the location of the centre point of the values the data set is moved in the axis system towards the centre of the perfect profile.

![Figure 22. Step 5.1: The recorded image is placed over the perfect pipe, the shift is based on the centre point of each pipe. Consequently the area between the boundaries is used to rotate the recorded image for a better fit.](image)

5.2

Furthermore, there is still the problem of rotation - roll and translation in x direction. This is corrected by fitting two circles within the boundaries as shown in Figure 22. Based on the location of the centre points of these two circles the dataset is rotated and moved along the x-axis. This process is iterated twice by the Matlab code in order to correct translation in x direction and rotation.

![Figure 23. Step 5.2: Two circles are fitted through the data points between the boundaries from figure 22. The centre points of these circles are used for correcting rotation.](image)
5.3
At the end, the measured profile needs to be properly fitted to the theoretical one. Errors in vertical positioning will lead to wrong estimation of loss of wall thickness. Any translation in the y direction is corrected using two fitted polynomial equations through the invert level of the perfect pipe and the imperfect pipes' data set.

Figure 24. Step 5: This is the initial fit before any correction for rotation and vertical movement. The figure shows the data points from perfect pipe and the recorded one.

Figure 25. Step 5: The final result after correcting for movement and rotation. The difference between the perfect and recorded pipe is used to determine the wall loss.

Step 6
The loss of wall thickness is quantified by determining the shortest distance between the theoretical and measured profile for each point.
Step 7
At the end, a contour figure of the whole pipe is created based on obtained results from the Matlab code, the measured length between reference shapes and the number of frames in each video.

Figure 26. Step 7: Example of a cut-out from pipe one, a darker colour means less corrosion. The length of the pipe is along the y-axis and the perimeter is along the x axis. The middle of the invert level is at $x = 0$.

Step 8
In addition, a contour figure is created that shows which points are created by interpolation and which ones are the measured points.

Figure 27. Step 8: Example of the origin of data points in the cut-out from pipe one (Figure 26) the black dots are the added data points.
3 Results and discussion

3.1 Measuring uncertainties

Multiple measurements at the same location
Several stationary measurements are executed to get a first indication about the accuracy of the laser profiling. One setup with a smooth iron tube, diameter 300mm, and one setup with a deteriorated egg shape sewer pipe, dimensions 400/600mm. In each setup a location is recorded about eighty times to determine the variation in the data while stationary. The measured values consist of the radius recorded by the laser profiler in combination with the original laser profiler software. As an indication for the accuracy the standard deviation is calculated for each data point, based on the values during the recording. Table 3 shows the values for the perfect round pipe. And table 4 the values for the deteriorated egg shaped pipe.

Table 3. Standard deviation and relative error while performing a stationary measurement in a round ø 300mm pipe

<table>
<thead>
<tr>
<th>Measurement</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processed points</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Times measured</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average value r</td>
<td>150.0833</td>
<td>150.0292</td>
<td>150.2850</td>
</tr>
<tr>
<td>Average standard deviation</td>
<td>0.4949</td>
<td>0.4290</td>
<td>0.1845</td>
</tr>
<tr>
<td>Smallest standard deviation</td>
<td>0.1706</td>
<td>0.1613</td>
<td>0.0799</td>
</tr>
<tr>
<td>Largest standard deviation</td>
<td>2.1508</td>
<td>1.3456</td>
<td>0.3957</td>
</tr>
<tr>
<td>Average relative error %</td>
<td>0.3297</td>
<td>0.2860</td>
<td>0.1228</td>
</tr>
<tr>
<td>Smallest relative error %</td>
<td>0.1137</td>
<td>0.1075</td>
<td>0.0531</td>
</tr>
<tr>
<td>Largest relative error %</td>
<td>1.4331</td>
<td>0.8969</td>
<td>0.2633</td>
</tr>
</tbody>
</table>

In total four stationary measurements are executed in the egg shaped pipe. Measurement one and two are executed at the front and measurement three and four at the back of the pipe.

Table 4. Standard deviation and relative error while performing a stationary measurement in an egg shaped concrete sewer pipe

<table>
<thead>
<tr>
<th>Measurement</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processed points</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Times measured</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average value D</td>
<td>240.1926</td>
<td>239.0891</td>
<td>241.2223</td>
<td>241.2878</td>
</tr>
<tr>
<td>Average standard deviation</td>
<td>1.3062</td>
<td>1.2837</td>
<td>0.7808</td>
<td>0.8263</td>
</tr>
<tr>
<td>Smallest standard deviation</td>
<td>0.5244</td>
<td>0.6260</td>
<td>0.3505</td>
<td>0.3725</td>
</tr>
<tr>
<td>Largest standard deviation</td>
<td>3.1990</td>
<td>3.0053</td>
<td>1.6980</td>
<td>1.6650</td>
</tr>
<tr>
<td>Average relative error %</td>
<td>0.5438</td>
<td>0.5369</td>
<td>0.3237</td>
<td>0.3424</td>
</tr>
<tr>
<td>Smallest relative error %</td>
<td>0.2183</td>
<td>0.2618</td>
<td>0.1453</td>
<td>0.1544</td>
</tr>
<tr>
<td>Largest relative error %</td>
<td>1.3318</td>
<td>1.2570</td>
<td>0.7039</td>
<td>0.6901</td>
</tr>
</tbody>
</table>

The first striking difference is the number of data points recorded. While at the perfect round pipe around 170 data points are recorded per measurement, the deteriorated sewer pipe records only around 135 data points per measurement. This is a reduction of 20 percent, despite that the diameter of the sewer pipe is larger. In fact this comes down to, on average, a data point every 11,8mm in the sewer pipe compared to one every 5,5 mm in the iron pipe. This implies that the reflection influences the amount of data points being recorded.
The second distinct result is the difference in relative error. In the sewer pipe measurements one and two are executed at the front and measurements three and four at the back of the pipe. Although the measurement at the back of the sewer pipe have the same relative error as the iron pipe (around 0.3 %), measurements one and two have a larger relative error (around 0.5%). To put this in perspective, this is a reduction of 40% in the relative error even though the way of measuring didn't change, only the location.

The location of the camera with laser profiler during the first two measurements was outside the pipe due to the relative short length of the pipe (1m). During these measurements outside the pipe, the IBAK panorama camera did not yet enter the pipe, but was still placed on a wooden support structure, which causes some vibrations. However the second two measurements are executed in the pipe itself, this might have been a more stable base. The described difference can indicate that small vibrations may already have a relatively large effect on the measurements.

In short: the number of recorded data points decreased with 20% and the error expressed as standard deviation is small, but is influenced easily with a change of 40% between the same kind of measurements.

Comparing the measured distance with laser profiler values
The distance between reference shapes is measured manually with a laser distance meter and with the laser profiler, table 5 shows the results of these measurements. The measurement is performed several times, however the results from this measurement are not conclusive.

<table>
<thead>
<tr>
<th>Measured with laser (mm)</th>
<th>Vertical Distance</th>
<th>Horizontal Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Profiler (mm)</td>
<td>#</td>
<td>581</td>
</tr>
<tr>
<td>Profiler (mm)</td>
<td>1</td>
<td>578,03</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>577,77</td>
</tr>
<tr>
<td>diff(%)</td>
<td>1</td>
<td>0,51</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0,56</td>
</tr>
<tr>
<td>diff(abs)</td>
<td>1</td>
<td>-2,97</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-3,23</td>
</tr>
</tbody>
</table>

The measurements show a difference between the measurement with the laser distance recorder and the values from the laser profiler. Unfortunately the accuracy of the measuring device was more than the half percent difference recorded in the experiment. On top of that, the values obtained from the software can be influenced easily. The values depend on manual input for the diameter, and this is based on the calibration video.
3.2 Manual wall thickness measurements.

The wall thickness is measured at four locations in the ten pipes available. In the end not all pipes are used for further research. Manually measuring was a painstaking and long effort but in the end rewarding, because the results are not as expected. The difference in wall thickness at the top and sides, as well as the difference between the pipes from Breda and the Hague are quite interesting.

Figure 28. manually measured wall thickness in the pipes from Breda, measured at the front (white bars) and at the back (black bars).

Figure 29. Manually Measured wall thickness in the pipes from The Hague, measured at the front (white bars) and at the back (black bars).

There are hardly any differences in values between pipes which come from the same location. Figure 29 shows the average values for 400/600 mm pipes from the Hague and Figure 28 the average values from Breda. The values at the front and at the back show small difference.

However comparing the pipes per location shows differences in measured values. This is illustrated in Figure 30, which shows that the wall thickness of the pipes from Breda are less than those from The Hague. Not a big difference, but still a difference while the pipes from the Hague has been in service for almost thirty years more.
This can be explained because there are local differences which can influence the state of the pipes, these differences are described in annex A. The recorded difference in wall thicknesses emphasises the role of local influences on deterioration in concrete sewer pipes. It also satisfies the idea that pipe age in itself is not a good indicator for the state of a concrete sewer pipe.

Figure 30. Manually measured wall thickness the Hague (white bars) vs. Breda (black bars).

Another unexpected result, based on these measurements, is the large wall thickness at the top of all the measured pipes. It is not abnormal but, according to the described deterioration process (annex B), under normal conditions corrosion would take place as well at the sides as at the top. So when the deterioration would progress normally the corrosion should be comparable at the sides and top, while in the measurements the wall thickness is significantly larger at the top.

A possible explanation is found in the measuring method and the construction of the pipes. When measuring the wall thickness, it was exactly at the top. The top itself was not a smooth circle but more at an angle, this might have increased the measured values. Also based on the age of the pipe the construction took place in 1952 and 1924. Back then the construction was on site and with a template which was not standardized. As a consequence the shape itself depends on the person who constructed the pipe itself. Even nowadays the dimensions are standardized but still variations in wall thickness are accepted, for example the NEN 7126 allows a tolerance between -4,4 mm and +6,8 mm of the nominal wall thickness in new 400/600mm egg shaped sewer pipes.
3.3 Measuring variations

Distance and number of frames

The created cut-out and origin image of pipe P1 consist of 52 frames which are evenly distributed over the distance between the reference points in the pipe, which is 796 mm. At the same time pipe P2 consists of 73 frames evenly distributed over a distance of 826 mm. The resulting distance between frames, or as you might state the density of the data points along the length of the pipe (vertical axis in the cut-outs) varies between 15.3 mm and 11.3 mm.

This discussion is based on the number of frames, distance between reference points and the corresponding average speed of the panorama camera with laser profiler. In this case the average speed is calculated based on the measured distance between reference points, frames per second and the number of recorded frames between the reference shapes.

As is visible in the graphs there is a very large difference in measuring speed and number of frames while the distance between reference shapes is more or less the same for every pipe. This comes down to a variation in average moving speed between 25 and 5 centimetres per second. The variation in the number of frames lies between 50 and 200 frames. If evenly distributed over the distance between reference points this comes down to a variation in distance between frames of 5 mm to 23 mm.

![Figure 31. Average distance (y-axis) between frames along the length of a pipe. In total 30 measurements (x-axis) are executed and displayed. The horizontal line shows the average distance in mm between frames during all measurements.](image)
Figure 32. The average speed (y-axis) during the measurements. In total 30 measurements (x axis) are executed and displayed. The horizontal line shows the average speed during all measurements.

These large variations in distance between frames and measuring speed makes it hard to compare the measurements. Unfortunately this became apparent after the measurements. The cause for these large variations lies in the used measuring equipment. Moreover the panaromo camera system is developed for practical use in sewers, where the operating speed is not an issue. The device is not build to accurately keep a constant speed during measurements. In fact the speed is regulated by hand with a small joystick.
3.4 Data processing

The measured pipes are processed with the described Matlab code. Unfortunately it was not possible to create usable output from all measured pipes. This was caused by difficulties during the analysis and during the measurements itself. The discussion presented here is thereby based only on the measurements of pipe P1 and P2. Even though not all pipes are analyzed this still provides an insight in the laser profiling process and results.

Number of data points

Figure 33. The graphs show the number of data points in combination with the number of added data points. In the processing with Matlab data points are added to fill in any blank locations. The graphs show for every frame (x-axis) the amount added versus the total amount of data points (y-axis). The top graph displays pipe P1 and the bottom graph displays pipe P2.
Figure 34. The graphs show the percentage of added data points. In the processing with Matlab data points are added to fill in any blank locations. The graphs show for every frame (x-axis) the percentage of added versus data points compared to the total amount of data points. The top graph displays pipe P1 and the bottom graph displays pipe P2.

The number of data point per frame in each pipe is more or less the same, around 1400 in every frame. The amount of data points added shows similar numbers with around 400 data points added per frame. To elaborate on this, with an estimated perimeter of 1600mm in the sewer pipe there is a data point every 1,1 mm, which allows a detailed picture of the inner surface of the sewer pipe.

On the contrary, the fact that 30% of the data points are added by the interpolation indicates that 30 % of the inner surface is not recorded. Of course there is a part that prevents the camera from recording the entire laser projection. The mounting frame of the laser profiler itself, which holds the laser emitter, is always in the recording. Figure 7 and 18 show this. Furthermore the exact distribution of the data points along the perimeter isn't investigated, the interpolation software/code creates an even distribution of data points on locations where the initial distance is too large. But how this exactly distributes the data points along the perimeter is not certain. Taking this into account it might be a preliminary conclusion but the average adding of 30% of the data points does show that not the entire perimeter of the pipe can be recorded. The reason for this might be bad reflection or just the laser disappearing out of sight behind large concrete aggregate at heavily deteriorated positions.
Movement during measurements

The difficulties with processing the data are movements during the measurements. All recorded videos show leaps and shocks in the recordings. As an example, Figure 35 illustrates the movement between frame 172 and 182 of pipe 7. The figure combines the two frames with two equally sized white rectangles. The recorded red laser projections should remain at the same position. This is however clearly not the case.

Another indication of the movement during measurements is found in the black and white figures (Figure 36 and 37) which show the origin of data points (original vs. Added) shows signs of these disturbances as well. If the movement was constant and smooth the two black lines (added data points) would be more or less straight. However this might also be caused by the processing of the data with Matlab, but at the same time the processing steps are the same for every frame.

Corrosion / Remaining wall thickness

As described in 2.7 the corrosion in the cut-outs is based on the comparison of the measured recorded pipe wall with a theoretical perfect egg shaped pipe. The figures 36 and 37 show the most deterioration at the top and sides of the pipe. This does coincide with the theory as described in Annex A.

The manual wall thickness measurements showed that the exterior shape of the egg shaped sewer pipe differs from the theoretical egg shaped sewer pipe. Based on this an accurate estimation the remaining wall thickness is impossible. At least not without additional information on the exterior shape of the pipe to create a link between the in- and exterior of the pipes. For the experimental measurements the pipes are accessible and this link might be created with wall thickness measurements. But especially when the pipes are still in the ground there is no cost efficient option to determine the outer shape of an egg shaped sewer pipe.

On the other hands the described issue with the exterior shape of the egg shaped concrete sewer pipes might be less with round pipes. Due to the simpler shape of these pipes the exterior will be more similar than those of the egg shaped sewer pipes. However round sewer pipes are out of the scope of this thesis.
Figure 36. Top figure: cut-out from pipe P1, a darker colour means less corrosion. The length of the pipe is along the y-axis and the perimeter is along the x axis. The middle of the invert level is at t x =0.

Bottom figure: Example of the origin of data points in the cut-out from pipe two. The black dots are the added data points.
Figure 37. Top figure: cut-out from pipe P2, a darker colour means less corrosion. The length of the pipe is along the y-axis and the perimeter is along the x-axis. The middle of the invert level is at $t \times = 0$.

Bottom figure: Example of the origin of data points in the cut-out from pipe two. The black dots are the added data points.
Further research
In the article (Annex E) an analysis for all uncertainties is performed and the recorded data is corrected for movement during measurements.

The measurements from the article are performed with the setup developed during this thesis. Afterwards, with a much more powerful computer, the recordings are corrected for movement during the measurements. As shown in Figure 38. The correction can count for as much as 15.9 mm in one axis (Clemens et al., 2014).

In this figure 38, the lighter the area, the more deterioration is measured. The corrected version (bottom figure) shows much less deterioration and also at a different location. This shows that the movement during the measurements caused a difference in the spatial distribution of the deterioration and a difference in the amount of deterioration.

![Figure 38](image)

*Figure 38. Image from the article (Clemens et al., 2014) it shows an cut-out uncorrected (top) for movement and corrected (bottom) for movement. An important difference is that the correction in this image is performed with actual measured movements, while the correction for movement in the cut-outs from figure 36 and 37 are only based on the corrections in the Matlab code.*
4 Conclusion and recommendations

As a reminder, the main research question is:

‘How accurate is the laser profiler when measuring deteriorated sewer pipes?’

Even though there is no conclusive answer on that main question, the research gives an estimation and showed a clear difference between stationary measurements and measurements while moving.

Accuracy

While stationary the accuracy of the measurements with the laser profiler remained within the 0.5% error as stated by the manufacturer. However during measurements with the moving profiler, variations in speed, vibrations and shocks disturbed the recordings. Although these influences were mainly caused by the used set up of the testing equipment it is to be expected that these kind of movements will occur in practice as well. During the research these disturbances resulted in unusable data and caused unpredictable and inaccurate results.

Just as in the experiments the recorded movements will influence recordings in practice in the same manner. Therefore to create a correct image of the inner perimeter of a sewer pipe these motions have to be measured and analyzed. Rearranging the recorded data points using positioning measurements will result in a more accurate image. To emphasize this, correcting the data showed that the location of data points might deviate up to 15.9 mm in one axis’ direction.

Remaining wall thickness

Some problems arise if laser profiling is used for the purpose of determining the remaining wall thickness in comparison with the original wall thickness of an old concrete sewer pipe. The main problem is that for old pipes the wall thickness at the moment of construction is unknown. Due to the fact that the used pipes are egg shaped this aspect showed to be a crucial uncertainty. So for the old concrete egg shaped sewer pipes comparing the pipes with a perfect situation is prone to wrong assumptions.

However the shape of the exterior might have less influence in round pipes due to the simpler shape. Therefore it is very well possible that the uncertainty in the initial wall thickness is less for round pipes, however these are outside of the scope of this research. Not only for old pipes, also for new ones this unknown factor remains an issue. The reason for this is that even the current margins in wall thickness during production are relatively large.

Future use

Laser profiling might prove to be useful in the near future if the influences of motions during measurements are reduced or incorporated in the data. The technique can be used to objectify aspects of the current sewer inspection technique and be an aid in sewer renovation.

Laser profiling as a inspection technique can improve the objectivity of current sewer inspection. Laser profiling can be used to actually measure the deterioration instead of estimating it. Currently the deterioration is estimated by inspectors based on visual observations and experience. This practice is very subjective, but the result is often a reason for renovating the sewer. With an improved laser profiling system the actual deterioration can be determined which.

Another use is to measure the end result of sewer renovation products, like glass fibre linings within the sewer. This is an increasingly used method of sewer renovations from within the pipe. The device can actually measure if the required rehabilitation is achieved. It can also limit discussions about unwanted reductions in diameter or the size of folds in the material.
List of references


Feitencommissie. (2010). *Doelmatig beheer waterketen eindrapport commissie feitenonderzoek*


Annexes
Annex A Theoretical degradation
Annex B In situ information
Annex C Dimensions movement measuring device
Annex D Article
Annex A  Theoretical degradation

Keneth and Karle identified two major causes for corrosion inside concrete sewer pipes (Keneth & Karle, 1991). The first is caused by the discharge of industrial waste(water) which has a low pH thus affecting the acidity of the sewage and with it the concrete. The second situation is a process known as sulphide corrosion or sulphide attacks. The difference between the two types of deterioration is in the location of occurrence. The sulphide attack causes corrosion above the sewage level and a low pH sewage will cause corrosion below the sewage level.

A1. Sulphide corrosion

This sulphide corrosion doesn’t start instantly. It is a microbiological process which takes time and involves different species of bacteria as well as fungal species. In the microbiological corrosion process Wells et all identified four stages (Wells, Melchers, & Bond, 2009). The following paragraphs describe each stage consecutively. Figure 39 summarises the entire microbiological process.

![Figure 39. Overview microbiological corrosion process](image)

Figure 39: Stage 1. A biotic neutralization of the concrete surface

The first stage starts at the moment that a new concrete sewer pipe is installed, at that time the pH at the concrete surface is approximately 12-13. Such a high pH makes any microbiological activity impossible. But, in time, the pH will change due to anaerobic sulphate reducing bacteria (SRB). Colonies of these bacteria are present in the sewage and will start to grow in layers of bio film below the sewage level, as depicted in Figure 39. The SRB produce hydrogen sulphide and carbon dioxide by reducing sulphates and oxidising biodegradable organic carbon, these components are present from sources like excreta and detergents (1).

\[
\text{Organic matter} + \text{SO}_4^{2-} \xrightarrow{\text{SRB}} \text{H}_2\text{S} + \text{CO}_2 \quad (1)
\]

The produced hydrogen sulphide and carbon dioxide transport through the bio film layers into the wastewater and, at the water level, part of the hydrogen sulphide and carbon dioxide volatilises into the pipe’s atmosphere. With time these gaseous substances form a condensate layer along the perimeter of the sewer pipe. At the formed condensate layer the \(\text{H}_2\text{S}\) and \(\text{CO}_2\) dissolve back into a liquid form. The \(\text{H}_2\text{S}\) re-dissociates to form \(\text{HS}^-\) and \(\text{H}^+\) while the \(\text{CO}_2\) dissolves to various forms of carbonic acid. These formed weak acids react with alkali species in the concrete, and over time this reaction will lower the pH of the concrete surface to a pH of approximately nine.
Figure 39: Stage 2. Colonization by neutrophilic bacteria
Once the concrete pH value drops to around 9 the pipe walls can be colonized by neutrophilic sulphur oxidizing microorganisms (NSOM), as long as there is sufficient oxygen, nutrients and moisture present. Just like the bacteria in stage one these organisms oxidize $\text{H}_2\text{S}$, but these organisms produce $\text{H}_2\text{SO}_4$ instead of $\text{H}_2\text{S}$ and $\text{CO}_2$. The produced acids diffuse into the condensate film and there it reacts with the concrete surface, hence further lowering the pH of the concrete surface.

Figure 39: Stage 3. Colonization by Acidophilic bacteria
The third stage of sulphuric acid attack starts at the moment the pH value is lowered by the NSOM to a pH value of four. At this pH value the conditions are favourable for acidophilic sulphur oxidizing microorganisms (ASOM). The acidophilic bacteria will oxidize $\text{H}_2\text{S}$ to sulphuric acid, in a similar manner like NSOM. The difference between the two is that these neutrophilic bacteria can oxidize $\text{H}_2\text{S}$ as well as thiosulphate and elemental sulphur, which are deposited on the pipe’s perimeter after gaseous $\text{H}_2\text{S}$ is oxidized directly by any present oxygen. Eventually the activities of the acidophilic bacteria further lowers the pH value to around 1-2.

Figure 40. Corrosion and processes inside a pipe

Figure 39: Stage 4. Loss of concrete mass
In the fourth and final phase the concrete itself is affected. In this phase the sulphuric acid reacts with the silicate and carbonate compounds from the cement component of the concrete. In this reaction, which is described below, gypsum is formed (2-4).

\[
\begin{align*}
\text{H}_2\text{SO}_4 + \text{CaO} \cdot \text{SiO}_2 \cdot 2\text{H}_2\text{O} & \rightarrow \text{CaSO}_4 + \text{Si(OH)}_4 + \text{H}_2\text{O} \\
\text{H}_2\text{SO}_4 + \text{CaCO}_3 & \rightarrow \text{CaSO}_4 + \text{H}_2\text{CO}_3 \\
\text{H}_2\text{SO}_4 + \text{Ca(OH)}_2 & \rightarrow \text{CaSO}_4 + 2\text{H}_2\text{O}
\end{align*}
\]

The gypsum, however, has a bigger volume than the original silicate and carbonate compounds. Consequently the formation of gypsum increases the volume by 124%, which weakens the concretes’ cement component. Consequently the mineral Ettringite is formed by a reaction of the formed gypsum with tricalcium aluminates from the cement (5). The formation of this mineral is even more destructive as it gives a volume expansion with estimates ranging from 227% up to 700%.

\[
\text{CaSO}_4 + 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{H}_2\text{O} + 25\text{H}_2\text{O} \rightarrow 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaSO}_4 \cdot 31\text{H}_2\text{O}
\]

Finally the volume expansion of Ettringite leads to cracking and pitting of the concrete, which increases the surface area. And in addition the increased surface area speeds up the process because it facilitates the further penetration of moisture, acid and microorganisms.
A2. Timescale and size of the corrosion

The timescale of the described microbiological process depends on local factors in the sewer pipes. The estimates for different stages range from months up to years. For example, the corrosion rate depends among others on the sewage temperature, detention time, concrete type, turbulence in the pipe, sewage pH and biological-oxygen-demand (Mori et al., 1992).

In the research described in "interactions of nutrients moisture and ph on microbial corrosion of concrete sewer pipes" the corrosion rates of 12 year old pipes near a wastewater treatment plant were investigated. The highest measured corrosion rate is 4.7 mm/year at the sewage level.

What is interesting however is the corrosions' location and rate distribution above the sewage level. With 4.7mm/year the highest corrosion rates were found at the sewage level, while the rates diminished further from the sewage level to about 1.4 mm/year at the crown level. Furthermore there was no sign of corrosion below the sewage level, which indicates that the only cause for corrosion was sulphide corrosion.

As a conclusion, from this theoretical analysis only a prediction on the location of the corrosion is possible and not a prediction of the corrosion rate or timescale. The corrosion is expected to occur above the sewage level, especially at the crown and near the sewage level while hardly any corrosion occurs below the sewage level. On the other hand it is difficult to make a realistic prediction regarding the corrosion rate, due to the influence of too many factors.
Annex B
Case study characteristics
Since the influence of local conditions on the concrete sewer pipes is substantial, information on the local environmental conditions of the studied pipes is provided in this chapter. The study was conducted on the four excavated concrete sewer pipes, of the same shape and size, that were scheduled for replacement, according to the municipal sewer rehabilitation plans of The Hague and Breda. Furthermore, a new concrete sewer pipe of the same shape and size, from De Hamer factory, was used to validate the experimental results.

3.1 Municipality of The Hague
For research purposes, two sewer pipes scheduled for replacement at the Visserhavenstraat, Municipality of The Hague (Figure 41) were excavated. Pipes are from combined sewer systems; they are egg-shaped with dimensions of 400/600 mm, 1m long and made of concrete. The sewer was constructed in 1924, thus pipes are 89 years old.

Figure 41. Location of excavated pipes in the Visserhavenstraat in The Hague, the location was indicated based on the house numbers painted on each pipe.

The sewer in The Hague is located in a domestic housing area around old dunes. There was no detailed information available about the soil structure, but because it is in an old dune area it is assumed that soil is sandy. The area is subject to relatively low settling rates of maximal 2cm till the year 2050 (Rijkwaterstaat Klink en bodemdaling). Further, the groundwater level this area is maximum +1.40m NAP, while the invert level of the sewer pipes is around +5.80m NAP. (bodemdata.nl) Therefore, in this area the groundwater is below the sewer invert level.
3.2 Municipality of Breda

For this research, two pipes were excavated at the Talmastraat in the Municipality of Breda (Figure (42)). As in the case of the Municipality of The Hague, pipes are from combined sewer systems; they are egg-shaped with dimensions of 400/600 mm, 1m long and made of concrete. The sewer was constructed in 1952, thus pipes are 61 years old.

Currently around Talmastraat it is domestic housing area. In contrast to the pipes from the Hague the area in Breda used to be part industrial and part domestic. As a consequence, this sewer was under a constant high traffic load for approximately 35 years. In this area, the surrounding soil is a combination of peat, clay and sand. Table (6) shows the soil structure of the area surrounding Talmastraat. Similar to the case in the Municipality of The Hague this whole area is subject to relatively low settling rates, the settling is expected to be less than 5mm till the year 2050 (Rijkwaterstaat Klink en bodemdaling). The recorded groundwater level is at an average maximum of +1.75 m NAP and an average minimum of +0.70m NAP, while the invert level of the sewer pipes is at +1.10m NAP. Consequently, in this area, the groundwater is above the sewer crown level (Oranjewoutd, 2009).

Table 6 Soil structure near “Talmastraat” in Breda

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Soil Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 0.75</td>
<td>Weak loamy, coarse sand</td>
</tr>
<tr>
<td>0.75 - 1.75</td>
<td>Peaty clay</td>
</tr>
<tr>
<td>1.75 - 3.00</td>
<td>Fine sand</td>
</tr>
<tr>
<td>3.00 - 4.25</td>
<td>Coarse sand</td>
</tr>
<tr>
<td>4.25 - 4.75</td>
<td>Light clay</td>
</tr>
</tbody>
</table>
3.3 New pipe “De Hamer”
The new concrete sewer pipe, from De Hamer factory, is egg-shaped, with dimensions of 400/600 mm was used to validate experimental results (Figure (43)). The new pipe was 2 m long, being shortened to 0.85 m length to allow testing in the same test facility. The pipe is made out of concrete and is constructed according to the European quality norm NEN-EN 1916, national additional NEN 7126 and certified according the assessment guidelines BRL 9201.

Figure 43 Display of a new pipe from De Hamer factory.
Annex C  Dimensions movement measuring device

Center of the
11.28

25.08

50.11

50.18

50.11
Annex D   Article

"Uncertainties associated with laser profiling of concrete sewer pipes for the quantification of the interior geometry."
Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance

Uncertainties associated with laser profiling of concrete sewer pipes for the quantification of the interior geometry

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Uncertainties associated with laser profiling of concrete sewer pipes for the quantification of the interior geometry

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Structural strength and hydraulic capacity are two essential parameters in the assessment of the need for sewer rehabilitation. Especially concrete pipes suffer from loss of wall thickness due to biochemical corrosion and, consequently, a decreasing structural strength along with an increase of hydraulic roughness. Unfortunately, routinely used visual inspection methods do not allow a quantification of the internal pipe geometry which would enable not only detecting but also quantifying the progress of biochemical corrosion. Advances in laser technology and digital cameras theoretically allow a cost-effective application of laser profilers to measure the interior geometry of sewer pipes. An analysis of associated uncertainties revealed that the position and alignment of the laser are the main source of measurement errors. A full-scale laboratory set-up demonstrated, based on tests on a new and an 89 years old corroded sewer pipe, that laser scanning is indeed capable of measuring the interior geometry accurately enough to determine wall thickness losses for corroded pipes, provided that the position and alignment of the laser and camera are accounted for. The obtained accuracy, however, was not enough to quantify the hydraulic roughness.

Keywords: sewer systems; corrosion; inspections; uncertainties; laser profiling

List of symbols

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<th>Symbol</th>
<th>Description</th>
<th>Dimension/ unit</th>
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<tr>
<td>a, b, c</td>
<td>Coefficients defining the plane of the reflection board</td>
<td>L(^{-1}) m(^{-1})</td>
</tr>
<tr>
<td>b(_{\text{CamFRONT}})</td>
<td>x, y coordinates of a point as observed on the optical sensor</td>
<td>L m</td>
</tr>
<tr>
<td>b(_{\text{CamBACK}})</td>
<td>x, y coordinates of a point as observed on the optical sensor</td>
<td>L m</td>
</tr>
<tr>
<td>b(_{\text{CamBACK}})</td>
<td>Sensor of CamBACK</td>
<td>L m</td>
</tr>
<tr>
<td>d(_i)</td>
<td>Distance between stationary laser stand and reflection board for laser distance meters (i = 1, 2, 3) in coordinate system (\mathbb{R}^3)</td>
<td>L m</td>
</tr>
<tr>
<td>d(_{\text{FRONT}})</td>
<td>Distance between laser sheet and lens plane for Cam(_{\text{FRONT}})</td>
<td>L m</td>
</tr>
<tr>
<td>d(_{\text{BACK}})</td>
<td>Distance between laser sheet and lens plane for Cam(_{\text{BACK}})</td>
<td>L m</td>
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<td>e(_{\text{FRONT}})</td>
<td>Distance between optical sensor and lens plane for Cam(_{\text{FRONT}})</td>
<td>L m</td>
</tr>
<tr>
<td>e(_{\text{BACK}})</td>
<td>Distance between optical sensor and lens plane for Cam(_{\text{BACK}})</td>
<td>L m</td>
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1. Introduction

Sewer systems are very capital-intensive infrastructure systems with a long service life. In many countries around the world, sewer operators are under pressure to minimise their maintenance costs, while keeping the risk of failures at an acceptable level. This requires information on the current status and the evolution of the status by repeated visual inspections, several new techniques have been developed over the past two decades and are applied in practice (Wirahadikusumah, Abraham, Iseley, & Prasanth, 1998), like radar (e.g. Olhoeft, 2000), acoustic techniques (e.g. Feng, Horoshenkov, Tareq, & Tait, 2012) or sonar (Kirkham et al., 2000), laser profiling (Duran, Althoefer, & Seneviratne, 2003) or a combination of these technologies in order to benefit from the strengths of each technology (Duran, Althoefer, & Seneviratne, 2007; EPA, 2010). A recent and comprehensive review of existing techniques for condition assessment of underground infrastructure, including sewer systems, can be found in Hao et al. (2012).

Laser profiling of (sewer) pipes is a technology that is introduced and applied in practice for some years. Main applications are checks on ovality or other significant deformations of the geometry and the detection of damages such as cracks or obstacles (see, e.g. Arsenio, Vreeburg, & Rietveld, 2013; Duran et al., 2003; Gooch, Clarke, & Ellis, 1996). In addition, the 3D picture that is obtained of the pipe interior could, provided that the monitoring accuracy is sufficient, be used to assess the hydraulic roughness of the pipe (Pegram & Pennington, 1996).

It was shown by Stanic, van der Schoot, Kuijer, Langeveld, and Clemens (2013) that for corroded sewer pipes the roughness value, in terms of hydraulic friction factor (HFF), an accuracy of 3.5% is obtainable. To this end a Nikon LC60Dx scanner with a resolution in x and y directions of 7 μm and accuracy in z-direction of 60 μm was applied. Based on the general ‘rule of thumb’ (Clemens, 2001) that the monitoring accuracy should be about 10 times smaller than the time and space scale of the measured process, the monitoring accuracy should be 0.15 mm on a 0.15–0.15 mm grid for new pipes with a typical hydraulic roughness of 1.5 and 2 mm on a 2–2 mm grid for heavily corroded pipes with a typical hydraulic roughness of 20 mm.

In addition, some authors also claim that the laser profiling technique is capable of measuring the wall losses due to corrosion (Kirkham et al., 2000) with a relative uncertainty of 0.5%. This implies that in a 600 mm circular sewer, wall losses higher than 3 mm could potentially be measured. Given the typical wall thickness of 80 mm for a 600 mm concrete sewer, this 3 mm seems to be sufficiently

<table>
<thead>
<tr>
<th>Symbol</th>
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<th>Dimension/ unit</th>
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<tbody>
<tr>
<td>$s_{\text{FRONT}}$</td>
<td>Scaling factor for Cam$_{\text{FRONT}}$</td>
<td>–/–</td>
</tr>
<tr>
<td>$s_{\text{BACK}}$</td>
<td>Scaling factor for Cam$_{\text{BACK}}$</td>
<td>–/–</td>
</tr>
<tr>
<td>$V$</td>
<td>Vector containing all the measured variables for the uncorrected projected points</td>
<td>Various</td>
</tr>
<tr>
<td>$V_c$</td>
<td>Vector containing all the measured variables for the corrected projected points</td>
<td>Various</td>
</tr>
<tr>
<td>$x, y, z$</td>
<td>Coordinates</td>
<td>L m</td>
</tr>
<tr>
<td>$x_i, y_i$</td>
<td>x, y location of laser $i = 1, 2, 3$ in the reference coordinate system $\mathbb{R}^{(3)}$</td>
<td>L m</td>
</tr>
<tr>
<td>$\phi_x$</td>
<td>Rotation angle around x-axis</td>
<td>Angle rad</td>
</tr>
<tr>
<td>$\phi_y$</td>
<td>Rotation angle around y-axis</td>
<td>Angle rad</td>
</tr>
<tr>
<td>$\phi_z$</td>
<td>Rotation angle around z-axis</td>
<td>Angle rad</td>
</tr>
<tr>
<td>$\Delta_x$</td>
<td>x-shift of the camera platform in $\mathbb{R}^{(2,3)}$</td>
<td>L m</td>
</tr>
<tr>
<td>$\Delta_y$</td>
<td>y-shift of the camera platform in $\mathbb{R}^{(2,3)}$</td>
<td>L m</td>
</tr>
<tr>
<td>$\Delta_z$</td>
<td>z-shift of the camera platform in $\mathbb{R}^{(3)}$</td>
<td>L m</td>
</tr>
<tr>
<td>$\sigma_{\text{ref}}$</td>
<td>Standard deviation in parameter $i$</td>
<td>–</td>
</tr>
<tr>
<td>$\mathbb{R}^{(2)}$</td>
<td>Reference coordinate system in two dimensions ($z = 0$)</td>
<td>–</td>
</tr>
<tr>
<td>$\mathbb{R}^{(3)}$</td>
<td>Reference coordinate system in three dimensions</td>
<td>–</td>
</tr>
<tr>
<td>$\Psi^{(2)}$</td>
<td>Moving platform coordinate system in two dimensions ($z = 0$)</td>
<td>–</td>
</tr>
<tr>
<td>$\Psi^{(3)}$</td>
<td>Moving platform coordinate system in three dimensions</td>
<td>–</td>
</tr>
<tr>
<td>$o, r, n$</td>
<td>Three vectors define the orthogonal base for the coordinate system $\Psi^{(3)}$</td>
<td>L m</td>
</tr>
<tr>
<td>$o_{xy}, r_{xy}, n_{xy}$</td>
<td>Normalised orthogonal basis for the coordinate system $\Psi^{(3)}$</td>
<td>–/–</td>
</tr>
</tbody>
</table>

Changes in exact position and orientation of a pipe due to subsidence and information on the hydraulic roughness. As a consequence, sewer operations experience a lack of suitable information on the status of the sewers for adequate sewer asset management (van Riel, Langeveld, Herder, & Clemens, 2012).
accurate as input for the purpose of assessing the constructional strength and stability.

However, amongst others, Duran et al. (2003) state that the main difficulty in laser profiling is the alignment and orientation of the sensor in the harsh sewer environment. Even small misalignments and shift in position can cause a significant systematic error in the measured internal geometry (Stanić et al., 2013; van der Schoot, 2014). In current practice, uncertainties due to unknown misalignments remain unnoticed, rendering the laser profiling technique without correction of the alignment and position unsuitable for measuring the exact internal geometry.

In this article, the uncertainties associated with the application of laser profiling in order to obtain a 3D profile of corroded concrete (sewer) pipes are analysed. The uncertainty analysis revealed the significance of the different sources of errors in the laser profiler monitoring results. Based on this, an improvement of the available laser profilers is proposed and tested in a full scale pilot using a corroded egg-shaped concrete sewer pipe and one new egg-shaped pipe that has not been in service. Based on laboratory experiments and theoretical analysis, future developments are defined.

2. Laser profiling: measuring uncertainties

Laser profiling of sewer pipes is based on a combination of projecting rings of light on the sewer pipe wall and capturing the images by a digital camera. Laser profilers are commonly placed on top of a CCTV camera tractor in order to be able to move them through the sewer pipe, as shown in Figure 1.

The accuracy of the results obtained by laser profiling is determined by: (1) the quality of the camera, i.e. the number of pixels, the pixel size and the number of frames per second that can be recorded, (2) the quality of the circular laser projection, which determines the width of the projected rings of light, (3) the method used to determine the position of the camera during its movement through the sewer, which determines the position of each recorded frame and consequently the distance between the frames and (4) the alignment of the laser and camera, which determine the angle of the projection and consequently the extent of deformation of the projection.

The impact of the quality of the camera and lasers on the uncertainties can be assessed by checking the specifications of the equipment by practical tests. The position of the camera and laser is normally determined by measuring the rotation of the wheels of the camera tractor or of the cable that is used to pull the camera tractor through the sewer. As the wheels of the camera tractor are likely to skid in the sewer, the position of the laser and camera can be rather imprecise (Dirksen, Pothof, Langeveld, & Clemens, 2014). Another bias could be introduced by the use of the cable to estimate distance: the cable follows the path of the tractor (not necessarily parallel to the pipe) and the flexion of the cable. Moreover, the alignment of the camera and laser is normally not accounted for. As a consequence, this adds to the unknown bias related to the position.

3. Material and methods

3.1. Measuring set-up

To assess the uncertainties associated with laser profiling, the measuring set-up shown in Figure 2 has been designed with all the monitoring equipment placed on a mobile platform. The set-up consists, like for ordinary laser profilers, of a laser projector combined with a camera, referred to as camFRONT. The laser uses a reflecting cone to produce a laser sheet which projects a line perpendicular to the main axis of the platform on the inner pipe wall. The mobile platform moves at a, not necessarily constant, speed of approximately 0.05 m/s through the pipe, the recording frequency of camFRONT is 30 frames/s, implying that each frame is about 1.7 mm apart along the length of the pipe. The images recorded by camFRONT are stored on a measuring computer for further processing.

Accurately measuring the position and alignment of the camera and laser requires that information is available on the $x$, $y$ and $z$ positions and rotation around these axes. In the experiments, this information is obtained by using a set-up comprising three parallel lasers with a fixed position, each measuring the distance between the parallel lasers and a reflection board. A second camera, referred to as camBACK, records the position of the three points projected by the parallel lasers on the reflection board. The frame rate of camBACK is 8 frames/s, implying that every 6.25 mm there is a recording of the distance between reflection board and the three lasers.
The three parallel lasers have a fixed position and define a reference coordinate system, with the $z$-axis being parallel to the main axis of the pipe. A left-handed coordinate system is applied, while the rotation angles are defined in the Tait-Bryan formalism (Figure 3), see e.g., Baranowski (2013). The images recorded by cam BACK and the readings from the laser distance meters are stored on the same measuring computer as camFRONT.

For each frame recorded by the front camera, the exact position and orientation of this camera should be known; therefore, for each frame, the position of the three laser points projected on the reflection board has to be known. It is important that the synchrony of the images recorded with the front camera and the back camera is guaranteed. Synchrony is guaranteed by the fact that both cameras were connected to the same data-acquisition system, which enforced both data sources into the same time base.

### 3.1.1. Accuracy of camera sensors

The measuring error of the 2D projection of the wall of the pipe is calculated using the average number of pixels that are illuminated on the sensor of camFRONT, depending on the scale factor, defined by the ratio between the distance between the laser sheet and the lens and the distance between the lens and sensor plane. The sensor used in camFRONT is a 2/3" sensor with $1024 \times 760$ pixels, pixel dimensions are $6.45 \times 6.45 \, \text{m}$. Based on an analysis of 20 repetitive samples in 20 different video frames, in which the measuring system was stationary, all rotation angles were equal to zero and the camera positioned in the axis of the conduit revealed that the laser sheet illuminated about $9 \sim 10$ pixels. Figure 4 shows the results of the distribution of the recorded light intensity across the projected line on the camera sensor. Based on these experiments, the standard deviation in the position was estimated to be $\sigma_{x,y,\text{camFRONT}} = 13 \, \mu\text{m}$.

Cam BACK is used to keep track of the position of the three points projected on the reflection board by the three stationary lasers. The obtained image of these points is transferred into contour lines using standard image processing routines. On these contour lines, an ellipse is fitted from which the intersection point of both axes defined as the $x$ and $y$ location of the point (in sensor

---

### Table 1. Specifications and their standard uncertainties (obtained by repeated measurement) of the instrumentation.

<table>
<thead>
<tr>
<th>Brand/model</th>
<th>Standard uncertainty $\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>camFRONT and the tractor, Panorama/3D</td>
<td>13 $\mu$m</td>
</tr>
<tr>
<td>optical Pipeline scanner</td>
<td></td>
</tr>
<tr>
<td>camBACK, D link/DCS 2310 L</td>
<td>5.6 $\mu$m</td>
</tr>
<tr>
<td>Laser distance meters Fluke/414D</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>Circular projected laser, Ibak/ILP</td>
<td>–</td>
</tr>
<tr>
<td>Dimensions of the measuring set-up</td>
<td>0.25 mm</td>
</tr>
</tbody>
</table>

Note: The figures between brackets for the camera offset values are valid for the old pipe, and the other values are valid for the new pipe.

### Table 2. Dimensions of the measuring set-up.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Value (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_{\text{camFRONT}}$</td>
<td>0.4760</td>
</tr>
<tr>
<td>$d_{\text{camBACK}}$</td>
<td>0.3540</td>
</tr>
<tr>
<td>$e_{\text{camFRONT}}$</td>
<td>0.003440</td>
</tr>
<tr>
<td>$e_{\text{camBACK}}$</td>
<td>0.002860</td>
</tr>
<tr>
<td>camoff$_x$</td>
<td>0.0020 (0.0022)</td>
</tr>
<tr>
<td>camoff$_y$</td>
<td>$-0.2307$ ($-0.2248$)</td>
</tr>
<tr>
<td>camoff$_z$</td>
<td>0.1647 (0.16466)</td>
</tr>
</tbody>
</table>
coordinates) is derived. Analysing 30 independent frames resulted in a standard deviation in both x and y directions of about 2 pixels. The sensor of cam\(_{\text{BACK}}\) is a 1/4" sensor with a resolution of 1280 × 800 pixels with a pixel width of 2.8 \(\mu\)m × 2.8 \(\mu\)m, resulting in estimated standard deviation of \(\sigma_{x,y,\text{camBACK}} = 5.6 \mu\)m. The cameras were tested on lens distortion effects (e.g. barrel distortion), for cam\(_{\text{FRONT}}\) these proved to be not observable, for cam\(_{\text{BACK}}\) there was some distortion at the far corners of the image. During the experiments, care was taken to avoid that the laser dots were recorded in these (slightly) distorted areas.

### 3.1.2. Accuracy of laser alignment

The alignment of the lasers was determined by repeated measurement of the distance between the three projected points at a distance of 30 m, the maximum mutual deviation over this distance between the projected points was ±3 mm (95% confidence interval in 30 repeated measurements) when compared with their position at the origin. This implies that the standard deviation of the alignment was estimated to be \(2.5 \times 10^{-3}\) radials.

![Figure 4. Distribution of the light intensity on the sensor of cam\(_{\text{FRONT}}\).](image)

![Figure 5. Definition sketch coordinate systems.](image)
3.2. Data processing

Processing of raw data consists of five steps as follows:

1. Determine the $x$, $y$, and $z$ positions of the three laser points projected on the reflection board.
2. Determine the position and orientation of the mobile platform.
3. Correct the recorded image from camFRONT for misalignment and orientation.
4. Calculate the inaccuracy interval for each recorded point in $x$, $y$, and $z$ directions.
5. Generate images.

These steps have been incorporated in Matlab® platform for post-processing the raw data.

3.2.1. Correction for misalignment and orientation of the camera/profiling systems relative to the pipe coordinate system

The recorded 2D images on the camera sensor have to be translated into 3D information based on the exact position of camFRONT and the orientation of the mobile platform (i.e. the exact position and the axis along which the system is ‘looking’). The three stationary laser distance meters (having known and fixed positions $p_{Ri} = [x_i, y_i, 0], i = 1, 2, 3$) define a reference coordinate system $\mathbf{R}^{(3)}$ see Figure 5.

From the projected three points and their measured distances along the $z$-axis ($d_1$, $d_2$ and $d_3$), between the fixed stand and the projection board, the position and orientation of the mobile platform and especially that of camFRONT can be calculated. The three laser points define a plane in the reference coordinate system $\mathbf{R}^{(3)}$ with a normal vector $\mathbf{n}$:

$$
\begin{bmatrix}
  a \\
  b \\
  c
\end{bmatrix} = \begin{bmatrix}
  x_1 & y_1 & d_1 \\
  x_2 & y_2 & d_2 \\
  x_3 & y_3 & d_3
\end{bmatrix}^{-1} \begin{bmatrix}
  1 \\
  1 \\
  1
\end{bmatrix} \mathbf{R}^{(3)},
$$

which is normalised:

$$
\mathbf{n}_n = \frac{\mathbf{n}}{||\mathbf{n}||}
$$

Additional to this normal vector, a normalised orthogonal basis for the rotated camera system is defined with two vectors $o_n$ and $r_n$ (see, e.g. Gruber, 2000):
Figure 7. Difference between theoretical and measured geometry for the new pipe. The upper chart shows the uncorrected result, and the lower chart shows the result after correction for position and orientation of the measuring platform.

Figure 8. Difference between theoretical and measured geometry for the old pipe. The upper chart shows the uncorrected result, and the lower chart shows the result after correction for position and orientation of the measuring platform.
\[
\begin{align*}
\mathbf{a} &= j - (j \cdot \mathbf{n}) \times \mathbf{n}, \\
\mathbf{j} &= \begin{bmatrix} 0 & 1 & 0 \end{bmatrix}, \\
\mathbf{r} &= \mathbf{a} \times \mathbf{n}, \\
\mathbf{\alpha}_n &= \frac{\mathbf{r}}{\| \mathbf{r} \|}, \\
\mathbf{L}_n &= \begin{bmatrix} \mathbf{L}_n(1) & \mathbf{L}_n(2) & \mathbf{L}_n(3) \end{bmatrix}.
\end{align*}
\] (3)

These three vectors define a transformation matrix \( \mathbf{R}_{\Psi^{(3)}} \) for the camera space \( \Psi^{(3)} \):

\[
\mathbf{R}_{\Psi^{(3)}} = \begin{bmatrix} \mathbf{L}_n(1) & \mathbf{\alpha}_n(1) & \mathbf{\beta}_n(1) \\
\mathbf{L}_n(2) & \mathbf{\alpha}_n(2) & \mathbf{\beta}_n(2) \\
\mathbf{L}_n(3) & \mathbf{\alpha}_n(3) & \mathbf{\beta}_n(3) \end{bmatrix}.
\] (4)

Since the projection on the reflection board is in a plane, the transformation of the position of the laser points as recorded by \( \text{cam}_{\text{BACK}} \) to the \( xy \) plane in \( \Psi^{(2)} \) (transformation \( \Psi^{(2)} \rightarrow \Psi^{(2)} \)) uses the following transformation matrix \( \mathbf{R}_{\Psi^{(2)}} \):

Figure 9. Definition sketch for the angles indicated in Figures 10–17, \( 0^\circ \) is the invert level going counterclockwise the crown is at \( 180^\circ \).

Figure 10. Difference between corrected and uncorrected profiles for one frame obtained from the new pipe.
Using this matrix, coordinate transformations between spaces $\mathcal{R}^{(2)}$ and $\Psi^{(2)}$ for a point $p_{\text{c BACK}} = [b_x \text{BACK}, b_y \text{BACK}]$ as recorded on the sensor of cam\text{BACK} can be made, taking into account the scaling factor ($s_{\text{BACK}}$) of cam\text{BACK}:\footnote{Note that this is a non-orthogonal transformation, i.e. angles and distances are not conserved. This is due to the fact that the laser beams are stationary and the reflection board is shifted and rotated. As a consequence, a deformation (stretch) of the original positions of the projected points occurs. Therefore, prior to rotation, the shift and scale should be applied. As a first step, it is necessary to do a coordinate transform from the projected points in the coordinate system $\Psi^{(2)}$ to the reference coordinate system $\mathcal{R}^{(2)}$:}

$$s_{\text{BACK}} = \frac{d_z \text{BACK}}{e_z \text{BACK}} \quad \text{(6)}$$

and

$$p_{\Psi^{(2)};i}^{\text{BACK}} = s_{\text{BACK}}R_{\Psi^{(2)};\mathcal{R}^{(2)};p_{\text{c BACK}}}p_{\text{c BACK}} \quad \text{(7)}$$

Subsequently, the projected points are corrected for the shift in $x$, $y$ and $z$ directions. The correction in the $z$-direction is equal to $1/c$ (being the distance between the reference stand and the reflection board), the shift in $x$ and $y$ directions are made based on the coordinates of the origin $^6 (x_1, y_1)\mathcal{R}^{(2)} = (0, 0)\mathcal{R}^{(2)}$:

$$\left[ \begin{array}{c} \Delta x \\ \Delta y \\ \Delta z \end{array} \right]^{\text{BACK}} = \Delta_{\text{orig}}^{(2)} = p_{\Psi^{(2)};i}^{\text{BACK}}, \quad \text{(9)}$$

where

$$(T)p_{\Psi^{(2)};i}^{\text{BACK}} = p_{\Psi^{(2)};i}^{\text{BACK}} - p_{\Psi^{(2)};i}^{\text{BACK}}.$$  

At this stage, the points are defined in the $z = 0$ plane of the reference coordinate system $\mathcal{R}^{(2)}$, not corrected for the rotation around the $z$-axis however. Two points (e.g. $(T)p_{\Psi^{(2)};i}^{\text{BACK}}$ and $(T)p_{\Psi^{(2)};j}^{\text{BACK}}$, or any other combination of two points) define a vector $(T)p_{\Psi^{(2)};i}^{\text{BACK}}$ that can be used to define the rotation around the $z$-axis:
\[
\theta_z = \text{sign} \left[ \frac{P_{R^{-2}}^{(2)}}{P_{R^{-2}}^{(1)}} (1) - (T) P_{R^{-2}}^{(1)} \right]
\]

\[
\arccos \left( \frac{P_{R^{-2}}^{(2)}}{P_{R^{-2}}^{(1)}} \right). 
\]

\[ (10) \]

The first term determines the direction of rotation (counterclockwise is positive). The next step is to rotate the orientation for \(x\), \(y\) and \(z\) axes as well as the shift of the positions \(x\), \(y\) and \(z\) of the moving camera platform is known, allowing the position of cam\_FRONT to be determined:

\[
\begin{bmatrix}
X_{\text{CamFRONT}} \\
Y_{\text{CamFRONT}} \\
Z_{\text{CamFRONT}}
\end{bmatrix}_{(3)} = 
\begin{bmatrix}
\Delta_{\text{orig}}^{(2)} (1) \\
\Delta_{\text{orig}}^{(2)} (2) \\
c^{-1}
\end{bmatrix},
\]

\[ (13) \]

with

\[
R_{c1}^{(2)} = 
\begin{bmatrix}
\cos(-\theta_z) & -\sin(-\theta_z) \\
\sin(-\theta_z) & \cos(-\theta_z)
\end{bmatrix}
\quad \text{and} \quad
R_{c1}^{(3)} = 
\begin{bmatrix}
\cos(\theta_z) & \sin(\theta_z) & 0 \\
-\sin(\theta_z) & \cos(\theta_z) & 0 \\
0 & 0 & 1
\end{bmatrix}. 
\]

\[ (14) \]

The first term in Equation (13) is the rotation of the camera relative to the origin followed by the shift of the origin along the \(x\)-, \(y\)- and \(z\)-axis of the reference position along the wall in \(\degree\).
coordinate system. Finally, an observed point (reflection from the pipe wall) $p_{c1} = [b_{x1}, b_{y1}]$ on the sensor of camFRONT with camera coordinates $[b_{x1}, b_{y1}]$ translates into the (corrected) $x$, $y$ and $z$ positions in the reference coordinate system $R^{(3)}$:

$$p_{\text{corrected}}^{(3)} = R^{(3)}_z R^{(3)}_y R^{(3)}_x \begin{bmatrix} s_{\text{CamFRONT}} b_{x1} \\ s_{\text{CamFRONT}} b_{y1} \\ 0 \end{bmatrix} + R^{(3)}_z R^{(3)}_y R^{(3)}_x \begin{bmatrix} x_{\text{CamFRONT}} \\ y_{\text{CamFRONT}} \\ z_{\text{CamFRONT}} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \cos(\theta_x)\cos(\theta_y)d_{\text{CamFRONT}} \end{bmatrix} \begin{bmatrix} \Delta_{\text{orig}}^{(2)}(1) \\ \Delta_{\text{orig}}^{(2)}(2) \\ c^{-1} \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ \cos(\theta_x)\cos(\theta_y)d_{\text{CamFRONT}} \end{bmatrix}$$

$$= R^{(3)}_z R^{(3)}_y R^{(3)}_x \begin{bmatrix} s_{\text{CamFRONT}} b_{x1} \\ s_{\text{CamFRONT}} b_{y1} \\ 0 \end{bmatrix} + R^{(3)}_z R^{(3)}_y R^{(3)}_x \begin{bmatrix} x_{\text{offset, CamFRONT}} \\ y_{\text{offset, CamFRONT}} \\ z_{\text{offset, CamFRONT}} \end{bmatrix} + \begin{bmatrix} \Delta_{\text{orig}}^{(2)}(1) \\ \Delta_{\text{orig}}^{(2)}(2) \\ c^{-1} + d_{\text{CamFRONT}}c/\sqrt{a^2 + b^2 + c^2} \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ \cos(\theta_x)\cos(\theta_y)d_{\text{CamFRONT}} \end{bmatrix}$$

with

$$\cos(\theta_x) = \frac{\sqrt{a^2 + c^2}}{\sqrt{a^2 + b^2 + c^2}}, \quad \cos(\theta_y) = \frac{c}{\sqrt{a^2 + b^2 + c^2}},$$

and

$$s_{\text{CamFRONT}} = \frac{d_{\text{CamFRONT}}}{e_{\text{CamFRONT}}}$$

Figure 13. Standard deviation for the new pipe for one frame for the uncorrected profile.
denotes the scaling factor for \( \text{cam}_{\text{FRONT}} \).

The term \( d_{\text{CamFRONT}} \sqrt{a^2 + b^2 + c^2} \) in Equation (15) is the projection of the distance between \( \text{cam}_{\text{FRONT}} \) and the laser sheet on the \( z \)-axis in the reference coordinate system \( R^{(3)} \).

3.2.2. Uncertainties analysis

The overall uncertainty of the position of a point projected on the pipe wall is determined as follows:

\[
\sigma_p^{2,\text{corrected}} = \sum_{i=1}^{19} \sigma_v^{2,(i)} \left( \frac{\partial \xi^{\text{corrected}}}{\partial \xi^{(i)}} \right)^2,
\]

in which

\[
\sigma_v = \left( d_{i=1,2,3}, x_{i=1,2,3}, y_{i=1,2,3}, b_{x1}, b_{x2}, b_{y1}, b_{y2},
\right.
\]

\[
\left. x_{\text{offsetcamFRONT, BACK}}, y_{\text{offsetcamFRONT, BACK}}, z_{\text{offsetcamFRONT, BACK}}, d_{z, \text{FRONT}}, d_{z, \text{BACK}}, c_{z, \text{FRONT}}, c_{z, \text{BACK}}, x_{\text{misal}} \right) .
\]

- The uncertainty of the recorded images in \( \text{cam}_{\text{FRONT}} \) and \( \text{cam}_{\text{BACK}} \).
- The uncertainty of the measured distances \( d_{1,2,3} \).
- The uncertainty of the alignment of the lasers.
- The uncertainty of the fixed distances in the measuring set-up.

Assuming that the measuring uncertainties in the parameters mentioned are mutually independent, hence neglecting covariance terms, the law of propagation of uncertainties (JCGM 104, 2009) applies for the measured points:

\[
\sigma_p^{2,\text{uncorrected}} = \sum_{i=1}^{19} \sigma_v^{2,(i)} \left( \frac{\partial p^{\text{corrected}}}{\partial v_{(i)}} \right)^2,
\]

Figure 14. Difference between corrected and uncorrected profiles for one frame obtained from the old pipe.
where $\alpha_{\text{misal}}$ is the misalignment of the lasers. Due to the very complicated analytical expressions that would result for most of the terms in Equations (18) and (20), the quantification has been done numerically using partial differences estimates.

4. Experimental results

Two concrete sewer pipes were subjected to the analysis as described before, one new egg-shaped pipe with an inner nominal geometry of 400/600 mm$^3$ and one egg-shaped pipe (400/600 mm) that was in service for more than 89 years in the municipality of the Hague, showing clear marks of crown corrosion and concretions of sediments at the sides.

Figure 7 depicts the results for the new pipe. The charts indicate the difference between the profiles measured following the procedures as described before minus the theoretical profile. In the upper chart, the result is shown without correcting for position and orientation of the mobile platform, while in the lower chart, the correction has been applied. As can be seen, the differences between measurement and theoretical profiles are, overall, much smaller for the corrected measurements. It is also noted that both corrected and uncorrected measurements deviate from the theoretical profile with a few millimetres, probably this is due to the allowed tolerance in the production process (see, e.g. Clemens, 2001).

This can also be observed in Figure 8 for the 89 years old egg-shaped pipe. Without correction there are significant differences (loss of wall thickness) at the invert of the pipe, which was not visually observed, while the effect of crown corrosion is exaggerated to have a maximum value of 20 mm. After correction (lower chart in Figure 8), there is no loss of wall thickness at the invert while this reaches a maximum of 15 mm at the top due to crown corrosion. It is also noticeable that a large area at the crown shows significant less loss of wall thickness after correction. It is also observed that at 200 mm along the perimeter of the pipe, along the length a difference of about $-10$ mm occurs, which is shifted to the right along the perimeter in the uncorrected measurement, while in the corrected measurements, this band is more or less parallel to the axis of the pipe.

![Figure 15. Standard deviation for the old pipe for one frame using $\sigma_{\text{misalignment}} = 2.5 \times 10^{-3}$ radials.](image-url)
Figure 10 (definition sketch is shown in Figure 9) illustrates the difference between the uncorrected and corrected profiles for one typical frame obtained from the measurements on the new pipe, while Figures 11 and 12 show $\sigma_x$, $\sigma_y$ and $\sigma_z$ as a function of the perimeter for $\sigma_{\text{misalignment}} = 2.5 \times 10^{-5}$ radials (Figure 11) and $\sigma_{\text{misalignment}} = 8.3 \times 10^{-6}$ radials (Figure 12). $\sigma_{\text{misalignment}} = 2.5 \times 10^{-5}$ is the standard deviation determined for the alignment of the lasers (see Section 3.1.2), the value of $8.3 \times 10^{-6}$ radials, being one-third of this value, is used to illustrate the sensitivity of the accuracy for the misalignment.

Figure 13 shows $\sigma_x$, $\sigma_y$ and $\sigma_z$ for the uncorrected profile of the same frame. Figures 14–17 show the same information for a typical frame as obtained from the old pipe. As can be seen, the difference between corrected and uncorrected profiles as well as the accuracy of the measurements varies along the perimeter of the profile and is strongly influenced by the accuracy of the alignment of the lasers. Figures 18 and 19 present two typical examples of the relative contributions to the measuring uncertainty of the different sources for $\sigma_{\text{misalignment}} = 2.5 \times 10^{-5}$ radials and $\sigma_{\text{misalignment}} = 8.3 \times 10^{-6}$ radials, respectively, for the new pipe. As can be seen, the misalignment is dominant when $\sigma_{\text{misalignment}} = 2.5 \times 10^{-5}$ radials (60–90% of the uncertainty is caused by this factor, while this drops to 15–50% when $\sigma_{\text{misalignment}} = 8.3 \times 10^{-6}$ radials). A similar observation is made for the results for the old pipe shown in Figures 20 and 21.

Tables 3 and 4 summarise the results. A one-sided $t$-test with acceptance level $p = 0.95$ shows that for the new pipe only the differences in the $z$-direction between corrected and uncorrected profiles are significant, even if the alignment of the lasers is improved by a factor of three. For the old pipe, the observed differences are significant, with the exception of the $z$-direction. The results show clearly that results obtained from laser profiling have a tendency to overestimate loss of wall thickness if they are not corrected for position and orientation of the measuring set-up relative to the pipe. Underestimation will not occur, since any deviation of a projection perpendicular to the axis of the pipe will result in an increase in dimension of the profile recorded.

As an example, the observed differences between corrected measured and theoretical profiles for the new pipe at $z = 23$ mm are shown in Figure 22. As can be seen,
a difference between measured corrected and theoretical profiles is visible (though well within the 95% confidence interval). Figure 23 displays the difference between measured corrected and theoretical profiles for the old pipe at \( z = 300 \) mm. At the crown, there is a loss of wall thickness up to 10–14 mm, while at the bottom there is a difference of about 0–6 mm.

Figures 24 and 25 present for the old and new pipe, respectively, the difference between uncorrected and theoretical profiles. As can be seen, the systematic differences are significant in both cases. For the old pipe, it is noticed that the maximum loss of wall thickness is larger in the uncorrected profile (18 mm) than in the corrected profile (14 mm). These figures only serve as an example. The 95% confidence interval in Figures 22, 23, 24 and 25 is based on the standard uncertainty in the \( x \) and \( y \) directions: 

\[ \sigma_{\text{loss of wall thickness}} = \sqrt{\sigma_x^2 + \sigma_y^2}, \]

assuming that the uncertainties in the \( x \) and \( y \) directions are mutually independent. It has to be mentioned that this is the lower limit for \( \sigma_{\text{loss of wall thickness}} \), when assuming a correlation of 1, the upper bound is defined as:

\[ \sigma_{\text{loss of wall thickness}} = \sigma_x + \sigma_y. \]

5. Discussion of the results

Using laser-profiling techniques it is possible to obtain information on the 3D geometry of a pipe. The obtainable uncertainty in the result is quantified and depends largely on the uncertainty of the laser distance measurements and the alignment of the reference coordinate system defined by three parallel lasers. Using relatively simple instruments, statistically significant differences between corrected and uncorrected profiles in the \( x \), \( y \) and \( z \) directions are obtained under laboratory circumstances. It has to be noted that the covered lengths in the experiments were relatively small, 17 and 55 cm for the new and old pipe, respectively. This results in relatively small values for shifts in the \( x \) and \( y \) directions. It is anticipated that, when longer stretches are measured, these shifts will be significantly higher, resulting in larger systematic differences between corrected and uncorrected profiles.

It has been shown that, using the corrections as described in this article, compensation for systematic errors due to orientation and position of the measuring platform is possible but at a price of an increased 95% confidence interval compared to uncorrected measure-
ments. In the simple set-up and the example shown, the corrections are not significant for the whole range of measurements performed. In the laboratory experiments, relatively simple and cheap instruments (as applied in practice) are used in order to investigate the practically feasible uncertainty. It is stressed that, when using high-end instrumentation, a far better accuracy is obtainable. The challenge, however, is to develop a measuring system that is applicable under practical circumstances and therefore has to be robust and economically feasible.

To this end, the main issues to work on are a more accurate distance measurement (see, e.g. Minoshima & Matsumoto, 2000) and the exact alignment of the three parallel lasers, or the implementation of another manner to measure the orientation and position of camFRONT.

As it has been shown, there are three main contributing sources of uncertainties, given in descending order: the misalignment of the lasers, the image quality of the two cameras and the distance measurement. In laboratory circumstances, the alignment of the lasers is feasible to within $2.5 \times 10^{-5}$ radials. For obtaining a system that is also applicable in practice, especially this issue seems to be quite a challenge and subject to further development. It is anticipated that for practical applications, the measurement of the orientation of the camera might be done using optical gyroscopes, although their main disadvantage is still their high costs.

Typically the price of optical gyroscopes is 10 times higher than the price of laser distance meters. In the measuring set-up as presented here, the achievable accuracy in the orientation of the measuring platform is in the order of magnitude of $7 \times 10^{-4}$ radials. Optical gyroscopes achieve an accuracy in angle measurement in the order of magnitude of $10^{-7}$ radials (see, e.g. Titterton & Weston, 2004). Applying such a device will result in an overall uncertainty (95% confidence interval) of $\pm 3$–4 mm, the accuracy given by Kirkham et al. (2000) while neglecting misalignment and positioning issues. Apart from realising a decrease in uncertainty, application of optical gyroscopes also allows for application in pipes that have bends; using the set-up as presented in this article the measuring device must be visible for stationary lasers.
Application of more accurate and sensitive video equipment is relatively simple to achieve given the rapid development of affordable video equipment. It is, however, questionable whether a more accurate camera is the key issue here, since the scatter in the light intensity on the sensor is also determined by the diffusion of the reflected laser light from the pipe wall, which cannot be totally controlled. Certainly, the sensor area and the dimensions of the pixels become more important when working with large sewer profiles. Possibly the application of laser light with a shorter wavelength (here a red laser with a wavelength range of 635–670 nm was applied) will result in an increase of accuracy since the divergence of a laser beam is less at shorter wavelengths (see, e.g. Wright, Greve, Fleischer, & Austin, 1992).

A disadvantage of the presented set-up is that, when sewers show significant curves, the three laser points may be projected outside the area of the reflection board. In such a case, the method will not work, unless the specific circumstances allow for the stationary lasers to be moved into the sewer. In such a case, a piece-wise approach is possible. For very big sewers, the dimensions of the set-up have to be adapted. For instance, the distance between the front camera and the laser profiler and the field of view of the front camera should be such that the laser projection on the pipe wall is completely visible. Furthermore, in order to achieve the accuracy sought for, the mutual distance between the three stationary lasers should be as large as possible.

Apart from obtaining the 3D inner geometry of a pipe using the proposed technique, it has been suggested by Duran et al. (2007) that using pattern recognition, defects such as cracks, surface damage, intrusion of house and gully pot connections can be detected. Using these techniques in combination with the technique presented in this article, it may become feasible to obtain an efficient method to collect data on the condition of pipes using just one apparatus.

6. Conclusions
The interior geometry of sewer pipes and the hydraulic roughness are sewer properties that drive sewer rehabilita-
tion to a large extent. Laser profiling has been shown to potentially be a technique that allows to measure the interior geometry accurately enough to be able to quantify the interior geometry and to quantify the hydraulic roughness for heavily deteriorated pipes, provided that the position and alignment of the camera and laser are adequately accounted for. Laser profiler results that are not corrected are subject to unknown, and potentially very large, errors, which systematically overestimate wall losses.

The accuracy of the experimental set-up is mainly determined by the uncertainty of the distance measurement and the alignment of the three lasers used to quantify the position and orientation of the camera and the laser sheet. Applying more accurate laser distance-measuring techniques easily solves the former; the latter is, certainly in practical circumstances, a challenge. Improving the alignment of these lasers, or introducing another method for measuring the orientation of the mobile platform allows for an accuracy level leading to an anticipated 95% confidence interval of about 4–5 mm in profiles up to 600 mm in dimension, yielding significant differences between corrected and uncorrected profiles.

Once the 3D geometry is obtained, this can serve as an input for FEM analysis on the structural strength and stability (see e.g. de Borst, Crisfield, Remmers, & Verhoosel, 2012). Certainly, the external profile and material properties have to be known for this, in most cases, however, the former can be obtained either from documentation of the manufacturer, whereas the material properties can be determined from analysis of drill cores. Future developments will focus on the following:

- Alternative methods, e.g. optical gyroscopes, for determining the orientation.
- More accurate laser distance meters.
- Construction of a low-cost device that can operate in practical applications.
- Effects on the overall uncertainty using lasers with smaller wavelengths.
- Optimisation of the post-processing software.

Figure 20. Relative contribution of the individual source of error to the overall measuring error in $x$, $y$ and $z$ positions for the old pipe with $\sigma_{\text{misalignment}} = 2.5 \times 10^{-5}$ radials.
Figure 21. Relative contribution of the individual source of error to the overall measuring error in x, y and z positions for the old pipe with $\sigma_{\text{misalignment}} = 8.3 \times 10^{-6}$ radials.

Table 3. Maximum deviation between corrected and uncorrected profiles and the maximum standard deviation for the new pipe.

<table>
<thead>
<tr>
<th>Maximum deviation (in mm)</th>
<th>Maximum $\sigma$ for the corrected profile with $\sigma_{\text{misalignment}} = 2.5 \times 10^{-5}$ radials (in mm)</th>
<th>Maximum $\sigma$ for the corrected profile with $\sigma_{\text{misalignment}} = 8.3 \times 10^{-6}$ radials (in mm)</th>
<th>$\sigma$ for the uncorrected profile (in mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>4.9 (0.78)</td>
<td>3.2 (0.94)</td>
<td>1.8</td>
</tr>
<tr>
<td>Y</td>
<td>7.7 (0.70)</td>
<td>5.7 (0.88)</td>
<td>1.8</td>
</tr>
<tr>
<td>Z</td>
<td>10.0 (0.97)*</td>
<td>3.2 (0.99)*</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Notes: Results marked with an asterisk show a significant difference between corrected and uncorrected results for which a one-sided $t$-test with acceptance level $p = 0.95$ was used. The figures between brackets show the $t$-test significance level.

Table 4. Maximum deviation between corrected and uncorrected profiles and the maximum standard deviation for the old pipe.

<table>
<thead>
<tr>
<th>Maximum deviation (mm)</th>
<th>Maximum $\sigma$ for the corrected profile (mm) with $\sigma_{\text{misalignment}} = 2.5 \times 10^{-5}$ radials</th>
<th>Maximum $\sigma$ for the corrected profile (mm) with $\sigma_{\text{misalignment}} = 8.3 \times 10^{-6}$ radials</th>
<th>$\sigma$ for the uncorrected profile (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>15.9 ($p = 0.96$)*</td>
<td>3.7 ($p = 1.00$)*</td>
<td>1.8</td>
</tr>
<tr>
<td>Y</td>
<td>12.8 ($p = 0.96$)*</td>
<td>3.2 ($p = 1.00$)*</td>
<td>1.8</td>
</tr>
<tr>
<td>Z</td>
<td>1.2 ($p = 0.60$)</td>
<td>2.3 ($p = 0.66$)</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Notes: Results marked with an asterisk show a significant difference between corrected and uncorrected results for which a one-sided $t$-test with acceptance level $p = 0.95$ was used. The figures between brackets show the $t$-test significance level.
Figure 22. Difference between corrected measured and theoretical profiles for the new pipe.

Figure 23. Difference between corrected measured and theoretical profiles for the old pipe.
Figure 24. Difference between theoretical and uncorrected profiles for the new pipe.

Figure 25. Difference between uncorrected and theoretical profiles for the old pipe.
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Notes
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5. The scaling factor is the ratio between the measure of an object and the size of its projection through the lens on the optical sensor in the camera.
6. Laser number 1 defines the origin of the reference coordinate systems $S'$ and $S''$.
7. The prefix (7) indicates the vector is shifted.
8. The new pipe was produced in accordance with the Dutch Standard NEN 7126.

References