Detection of leaks

NEXT GENERATION PIPE INSPECTION

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Detection of leaks: next-generation pipe inspection
Testing the FELL system under controlled field conditions

By

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Preface

This thesis is presented in partial fulfilment of the requirements for the degree of MSc. in Water Management and has been completed at the Delft University of Technology. This report covers a method of inspection that includes a mobile geo-electrical measurement system (FELL) which was designed to detect and locate leakages in sewer pipes and was previously tested under laboratory conditions. The objective of this research was to test the FELL system under controlled field conditions, which involved field experiments, analysis and interpretation of the data, and coordination between different companies. That's what caught my attention and persuaded me to tackle this topic. The research was challenging and, in hindsight, very ambitious, which meant I had to fine-tune my goals during the research period. However, I am proud of the result and have learned a lot throughout this complete project, which will definitely be helpful in my future career.

I was fortunate to have a lot of support from friends, family, and supervisors who managed to help me in more difficult times. That is why I would like to take this opportunity to express my heartfelt thanks to Jeroen Langeveld, who gave me the opportunity to work on this topic, arranged an internship at Vandervalk+degroot, and for the trust he had in me during the past months. In particular, I would like to thank the people who assisted me during the field experiments when I could not do this on my own, my family, who have always been providing a sympathetic ear, and my friends who could always cheer me up and help me when things got tough. I would also like to thank the other members of the graduation committee; Martin Nederlof for always thinking along when plans changed, Thom Bogaard for all the great and encouraging feedback when I needed it the most, and of course, for helping install the soil moisture sensors, and François Clemens for his critical view during the meetings and beyond. Finally, I would like to thank the people from the municipality of Breda for their cooperation and help during the moments when I measured at the test set-up; without them, I could not have carried out the fieldwork the way I wanted to carry it out.

Desiree Vermeulen
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Abstract

The wastewater system in the Netherlands is ageing, which increases the probability of failure of the systems as time progresses. A vital failure mechanism is leakages, which occur in leaky connections, joints, or at cracks and holes along the pipe. Eventually, leakages result in infiltration of groundwater into the sewer pipe or exfiltration of sewage into the groundwater system, depending on the location, condition, and system type of the sewer. When the sewer pipe is located below the groundwater table, infiltration of groundwater will occur, and when the sewer pipe is located above the groundwater table, exfiltration of wastewater will most likely occur. Both can have severe consequences for the sewer system, e.g. collapsing pipes, reduction of the groundwater quality, silting up the sewer, and high hydraulic influent load. To prevent these failures, maintenance of the urban drainage system is essential, also referred to as 'asset management'. It is crucial to find out whether there is a leak in the sewer pipe, where the infiltration or exfiltration occurs, and what the amount of leakage is.

There are different methods to detect leaks, such as camera inspection, pressure tests, and distributed temperature sensing. However, these different techniques each have their specific limitations. The Focussed Electro Leak Location (FELL) system, which is the main focus of this report, has been developed to detect and locate leakages by using electric voltage between an electrode in a sewer pipe and an electrode in the surrounding ground. The electrode in the sewer pipe, also called the probe, consists of three parts. The outer electrodes serve as a guard and also to send electric voltages, like the middle electrode, but they are mainly there to block the area behind it so the signal does not escape. This probe is pulled through the sewer. As soon as an increase in current is visible, this means that the resistance in the sewer pipe wall decreases, and there is a risk of leakage. There is some noise in the signal, but generally, when there is a leak, a more prominent peak in current is present. This peak can say something about the length of the leak, it could say something about the size of the leak, and perhaps it could say something about the leakage rate. There are doubts about whether the last is possible.

Explorative experiments with a PVC pipe above the surface, under ideal conditions, have shown that a clear signal can be obtained caused by leaking water using the FELL prototype 2.0 equipment at hand. The results show that the settings of the FELL prototype 2.0 have a major impact on signal size and noise. However, based on the performed field experiments with a concrete pipe below the surface, it can be concluded that also passing trains, moisture of the soil surrounding the grounding pin, and the position of the FELL prototype 2.0 in the sewer pipe have a strong influence on the resulting leak detection signal of the FELL prototype 2.0. The signal-to-noise ratio was ~1. Environmental factors influence the results in such a way, to an order of magnitude of even greater than 0.1 mA, that it is impossible to see where and whether there is a leakage in the concrete sewer pipe below the surface. To make the signal visible in practice, the FELL prototype 2.0 has to be redesigned, so that environmental influences have limited and known influences on the overall measurements. Also, the vertical movement of the FELL prototype 2.0 during the pulling of the system through the concrete sewer pipe has to be avoided as much as possible, as any change in the measuring geometry clearly affects the obtained signal. This research showed that the FELL prototype 2.0 should best be positioned precisely in the centre of the pipe. In short, the measurement principle theoretically sounds promising under ideal conditions, but the technical implementation of the FELL prototype 2.0 is very fragile, as shown in this study. Theoretically, it is possible to detect leakages, but in a practical sense, many improvements still need to be made to make the implementation robust. It can be confirmed that the performance of the FELL prototype 2.0 was not sufficient yet to tell if this device is able to detect, locate and quantify leaks under simulated field conditions. Both the design and practical condition first need to be optimised.

Acronyms

AC	Alternating current
CCTV	Closed-circuit television
DTS	Distributed Temperature Sensing
EC	Electrical Conductivity
FAT	Factory Acceptance Test
FELL	Focussed electrode leak location
FZU	Forschungszentrums Umwelt (in Karlsruhe)
Hz	Hertz
mA	Milliamperes
mS/cm	Millisiemens per centimetre
NEN-EN	Dutch and European standardization of guidelines
PVC	Polyvinyl chloride
SAT	Site Acceptance Test
TRL	Technology Readiness Level
VWC	Volumetric Water Content
WWTP	Wastewater treatment plant

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Introduction

The sewage system in urban areas is a valuable part of the urban infrastructure. It collects and transports urban wastewater of citizens and businesses, mostly underground. It also collects and disposes a large part of the rainwater. The functions of urban drainage systems are supporting public health and safety, flood control, waste transport, water collection, and reprocessing. The wastewater system consists of, among other things, pressure mains and gravity sewers (Langeveld & De Haan, 2015). According to the readers of the British 'Medical Journal', the construction of the sewage system has been the biggest contributor to improving public health (ONRI-werkgroep riolering & Stichting RIONED 2009; Ferriman 2007). Life expectancy has increased significantly due to the construction of the modern sewerage system. The sewage system may be invisible because it is underground, but it is worth its money in gold for our health.

The public sewer system in the Netherlands is already more than 150 000 kilometres long. Almost 100% of the buildings are connected, and about 43 000 houses (i.e. 0.5% of all houses) in the Netherlands do not have a sewer connection because they are too far from a sewer system (Stichting RIONED n.d.; Stichting RIONED 2009). The sewage system has an average lifespan of 60 years but varies between 30 and 100 years based on, among other things, the soil condition and the developments above ground (Oosterom & Hermans, 2013). Due to the often advanced age of the pipes, their management will require more and more attention in the years to come.

To determine the technical (physical) state of the system, inspections are required. Leakages are one of the failure mechanisms that can occur in a sewer pipe. When such defects are present, infiltration of groundwater or exfiltration of sewage can occur. The occurrence of these two events depends on the groundwater level and/or on the water level in the sewer pipes. Exfiltration causes pollution of the soil and groundwater due to, amongst others, pathogens and pharmaceuticals. This endangers the drinking water quality since groundwater can potentially be used as a drinking water supply (De Bénédittis & Bertrand-Krajewski, 2005). When the infiltration of groundwater occurs on a significant level, the efficiency of treatment plants declines because of the dilution of sewage and due to the reduction of hydraulic capacity (De Bénédittis & Bertrand-Krajewski, 2005). So, it increases the operation and capital costs and raises the fundamental degradation of the sewer system (Harris & Dobson, 2016). Next to this, there is a possibility that a leakage causes surrounding soil to ingress into the pipe. An accumulation of sand forms in the pipe, the soil density also shifts and underground cavities can arise around the pipe, which can again trigger sinkholes and may cause the sewer pipe to collapse (Stanić et al. 2013; Davies et al. 2001). In many cities in the west of the country, the amount of extraneous sewage is of the same magnitude as the net precipitation. In other words: the leaking mixed sewerage system leads to uncontrolled management of the groundwater level in these cities. Given climate change, which could also lead to more prolonged droughts, this uncontrolled management may not be a desirable situation. So, in the area of risk reduction, leakage inspection is becoming increasingly important to prevent failure mechanisms, reduce infiltration of unwanted water and keep public health at an adequate level (Korving et al., 2015).

According to Stichting RIONED (2016), the life expectancy of a sewer pipe under the road has increased to about 64 years, partly due to better repair techniques. Replacing sewers is expensive. The municipality must close off the street, break open the road and dig deep into the ground. In 2015, municipalities invested 650 million euros in the replacement and improvement of the sewers and installation of new sewers. In order to save money (as agreed in the Administrative Agreement on Water of 2011), in recent years, municipalities are taking a more critical look at which planned replacements are necessary and which can wait. To find out which are essential, trustworthy knowledge of the remaining service life is required. This service life is again related to the infiltration and exfiltration, in other words, the leakages. Leakages are an essential part of Asset Management. To manage the leakages, the following information is required:

1. Is there a leak?
2. Where is the leak?
3. What is the leakage rate?

Therefore different inspection methods, such as visual inspection (using CCTV), come into play. Partly based on the assessment of the inspection images, an estimation of the management measures can be made, such as repair, renovation, or replacement. About 80 per cent of the inspections are done using a video camera; in the other cases, ‘mirroring’ from manholes, photo inspection, or personal inspection is applied (Oosterom & Hermans, 2013). These methods have been the mainstay of pipeline condition assessment practice for decades. But methods like CCTV have multiple limitations. CCTV can only be used when the pipes are empty, so not during a big precipitation event. This is a substantial disadvantage of the method because the system identifies a damaged joint or leakage when water is flowing through. This happens typically after a big storm event, so it is not possible to detect infiltration when the groundwater level is below the sewer pipe. Exfiltration can also not be detected after a storm event as a result of the pressure increase in the pipe relative to the environment. The reliability of this method also depends on the awareness and ability of the operator, which makes CCTV a subjective technique (Dirksen et al. 2013; Harris & Tasello 2017). The reason why CCTV has limitations in performance is that there is a shortage of the ability to see the leakages inside the pipes. The lighting conditions of the achieved pictures are hard to quantify (Azizzadeh & Riahi, 2019). So far, no technique has been brought onto the market that can detect, locate and quantify leakages in a single procedure. When such a new technology is developed, TRLs (Technology Readiness Levels) are often used to indicate the stage of development. This model is used for many European and national subsidies to indicate for which phase of an innovation project a subsidy is intended. The TRLs, for a new technique in sewer inspection, are:

Level 1: Basic principles observed in sewer environment
Level 2: Technology concept formulated for sewers
Level 3: Experimental proof of concept
Level 4: Technology validated in lab or with available historic data
Level 5: Technology validated in sewer field environment
Level 6: System/subsystem model or prototype demonstration in a sewer environment
Level 7: System prototype demonstration during operational sewer maintenance
Level 8: System complete and qualified / calibrated
Level 9: Actual system proven in operational sewer environment

The first paragraph of this chapter illustrates the problem statement, including a description of the project's location and the research's relevance. In the following the scope of the study, which explains where the boundaries of this project lie and what is included in the study are discussed. Subsequently, the objectives and research questions are mentioned, and finally, the outline of the report is presented.

1.1 Problem statement

Since most of the sewer systems in the Netherlands were constructed in the early 20th Century (Pauwels et al. 2004; Stichting RIONED 2009), multiple pipes are getting older, and the probability that defects occur is increasing. Rather than replacing these pipes, their service life may be extended with repairs. Defects that can occur in ageing systems are infiltration and exfiltration (Stegeman et al., 2022). These defects should be detected in an early stage, which requires a suitable inspection method. Based on the inspection results, the decision of whether to fix the pipe via repair or to replace the whole pipe can be made. However, there is no accurate, validated, and practically applicable method yet to quantify and locate leakages. Some techniques can quantify, and some techniques can localize, but there is no technique that can do both accurately. A technique is required to know what is going on in a sewer pipe, where defects occur, and preferably also a technique that can say how serious the defect is.

To collect the data needed for asset management mentioned above, a technique is required that does the following: detect, locate and quantify. New inspection methods are indeed being explored to improve the qualification of leakages in pipelines. An inspection method developed in the 1990s in Germany is currently being developed/redesigned at the TU Delft. The technique is called Focussed electrode leak location (FELL). This technique can be used to detect and locate leakages. FELL applies an electric potential between a mobile electrode in an underground pipeline and a stationary electrode at the surface. The current is measured, and when a leak occurs, there will be an increase in current. Ongoing research in the context of the TISCA program (overarching research project) of Bram Stegeman has developed the FELL prototype 1.0. So far, this FELL prototype 1.0 has only been tested in the lab and meets level 4 of the TRLs. It has not yet been tested in actual practice on full-scale conditions, which is the main focus for levels 5 and 6 of the TRLs. Obviously, full-scale inspection is essential to investigate leak locations and the order of magnitude of the leaks. The FELL prototype 2.0 is used in this research. It is the same as the FELL prototype 1.0, used in the study of Bram Stegeman, only the size of the device is different, and with this FELL prototype 2.0 it is possible to perform measurements from the trailer in field conditions instead of the lab. In this thesis, the functioning of the FELL prototype 2.0 is investigated in a sewer environment and it is extensively tested and demonstrated at a test set-up site to resemble an operational environment, on the basis of TRLs.

1.2 Scope

This research will focus on field experiments and analysis and interpretation of the data, using a further developing available data analysis tool. The FELL prototype 2.0, which was already constructed, will be tested.

Largely, the field experiments are carried out in a test gravity sewer in Breda. This sewer pipe is made of concrete, with a diameter of 600 mm and is located underground. Also, tests on the site of ID-Tec are performed with a PVC pipe of 315 mm located above the surface.

The test set-up with the concrete sewer below the surface was used to detect and locate the constructed leakages under controlled conditions. At this location, it was possible to work safely and to repeat tests several times to determine the detection limit of the FELL prototype 2.0. In essence it is not different from a real sewer. Ideally, to meet TRL level 7, tests would have to be carried out at selected operational sewer pipelines of the municipality of Breda to measure the accuracy of quantifying the size and flow rate of leaks. The results of these tests would then be compared with the results of pressure tests of the same pipes. So, the FELL prototype 2.0 should be tested and demonstrated in a user environment to prove operation in an operational environment. However, the results showed that TRL level 7 tests were not appropriate yet, as will be discussed in this report.

The focus of this project is, therefore, mainly on test set-up B (controlled sewer test location of a concrete pipe below the surface) and test set-up A with a PVC pipe above the surface. Here, different sizes of leakages will be studied in different pipe materials, soil conditions, and pipe diameters using the FELL prototype 2.0. To determine the accuracy of the FELL prototype 2.0, the data from the experiments will be compared to two other techniques of inspection: CCTV and pressure tests. Eventually, the anomalies in the data and the order of magnitude will be analysed to optimise the interpretation of the data.

1.3 Objective and research questions

The objective of this study is to test the FELL prototype 2.0 system under controlled field conditions. As such, the study investigates the detection limit and locating leakages. The method is based on constructing leakages in a test set-up first, after which sizes and flow rates with real leakages should be assessed in parts of the sewer system of Breda. The results are compared to pressure tests and CCTV as a reference. This research aims to answer the main research question:

"What is the detection limit and accuracy of quantification of the FELL technique?"

To answer the main research question, the following sub-research questions, divided into two parts, are investigated to simplify the process of answering:

Part 1, detection limit at test set-up A and B:

1. Is the FELL prototype 2.0 able to detect leakages?
2. Is the FELL prototype 2.0 able to locate leakages?
3. Is the FELL prototype 2.0 able to quantify leakages?

Part 2, accuracy of quantification, at the selected operational sewer pipelines of the municipality of Breda:

4. How accurately can the FELL prototype 2.0 determine the location of the leakage?
5. How accurately can the FELL prototype 2.0 quantify the leakage rate?

To be able to answer part two of the sub-questions, it is first required to answer part one, which in the end gives the answer to the performance of the FELL prototype 2.0 system. Part 1 focusses on levels 5 and 6 of the TRLs, whereas part 2 continues on to level 7 of the TRLs. If it appears from part 1 of the investigation that levels 5 and 6 have not been reached sufficiently, the next step to level 7 (so part 2 of this study) is not applicable.

1.4 Report outline

This section presents a brief preliminary outline of the report. Chapter 1 provides the introduction with background information, problem, scope and objective of the study. Chapter 2 describes different techniques that are used to detect leakages in sewer pipes and gives an explanation of the FELL prototype 2.0 system, including a manual, design and data processing. Chapter 3 gives the methodology to achieve the research objective. It describes the performed fieldwork and shows all the details of the study sites which were previously chosen. Chapter 4 gives the results of the performance of the FELL prototype 2.0, soil moisture sensors, pressure tests and camera inspection, followed by a discussion in Chapter 5, including limitations that were found. Chapter 6 presents the final conclusion, and in Chapter 7, recommendations are given regarding follow-up research.

2

Literature study

This chapter first gives an overview of the available techniques for pipe inspection. Next, the FELL system technique is explained. The method is discussed in detail, among other things, the influencing factors. Also, the design of the device is represented. After that, an explanation is given about the FELL system itself, and the data that can be produced by the device is reviewed.

2.1 Techniques to detect leakages in pipes

To be able to tackle leakages, detection of the leak, quantification of the magnitude of the leak and locating the place where infiltration and/or exfiltration occurs is essential. The types of defects that can occur in a sewer pipe are defective connections, cracks (longitudinal and transverse), leaky joints, root ingrowth, obstacles, corrosion, pipe bursts and fragmentation, positional deviation, and mechanical wear (Wolf, 2003). As mentioned in Chapter 1.1, CCTV is primarily applied in the Netherlands as an inspection method to determine the condition of gravity sewers. It is a valuable technique because images of the leaks are received without having to dig up the pipeline. With a moving camera, it can be observed whether pipes and protective layers on the pipes are damaged, whether the joints are too wide, and if they are not centrally located concerning each other. Also can be seen under which slope the pipes lie. The use of a camera does require a more or less clean sewer, so that the camera cannot get stuck and observations are not obscured or made impossible by pollution. The images captured by the camera can be tracked on a monitor and are captured digitally. CCTV gives a first interpretation of the general condition of the pipe and its features, but the quality of the data on the location of the leakages and their quantity is not assured. Mostly, CCTV shows structural defects and the ingress of roots and joints (Moy et al., 2012). According to Moy et al. (2012), CCTV is not a reliable indicator of pipe leakages compared to an electro scan. The information gathered by the USEPA experiments the electro scan, or FELL, showed 2.1 times more defects than CCTV, and lots of leakages were missed by using CCTV. Due to dry weather conditions, it is difficult to identify leakages and quantify them (Gokhale & Graham, 2004). For gravity sewers, it is difficult to quantify infiltration and exfiltration. Only indirect indications can be observed, like cracks on the inside of the pipe wall. For pressure mains, it is also hard to find access points for inspections, which makes the technique costly and cumbersome. Table 1 and Table 2 give an impression of the techniques that are available for the assessment of infiltration in gravity sewers and exfiltration from gravity sewers and wastewater pressure mains.

Table 1: Methods for infiltration in gravity sewers (Langeveld, n.d.)

	Detecting	Quantifying	Locating
Conditions for infiltration	CCTV (above water line), Sonar (below water line), Laser (above water line), Pressure test (air or water), Smoke test, FELL, Gamma gamma probe, Impact echo	Pressure test (air or water)	CCTV (above water line), Sonar (below water line), Laser (above water line), FELL
Infiltration	CCTV, DTS (in pipe)	CCTV, DTS (in pipe) (both very rough estimate)	CCTV, DTS (in pipe)
Effect of infiltration	Dye testing, Manual survey (from ground level), QUEST-C, Modelling, Flow monitoring, Water quality monitoring, Ground penetrating radar	Dye testing, Manual survey (from ground level), QUEST-C, Modelling , Flow monitoring, Water quality monitoring	Ground penetrating radar, Infrared thermography

Table 2: Methods for exfiltration from gravity sewers and leakage from wastewater pressure mains (Langeveld, n.d.)

	Detecting	Quantifying	Locating
Conditions for exfiltration	CCTV (above water line), Laser (above water line), Pressure test (air or water), Smoke test, FELL, Acoustic methods (Listening stick, Sonar, Smartball, SAHARA, Leak noise correlation), Magnetic flux leakage , Gamma gamma probe, Impact echo	Pressure test (air or water)	CCTV (above water line), Laser (above water line), FELL, Acoustic methods (Sonar, Smartball, SAHARA, Leak noise correlation)
Exfiltration	DTS and TDR in pipe bedding (only for new pipes),		DTS and TDR in pipe bedding (only for new pipes)
Effect of exfiltration	Direct: QUEST, QUEST-C, Flow monitoring, Modelling, Balancing time series sewage and drinking water, indirect: Soil characterization, Groundwater sampling, Infrared thermography, Ground penetrating radar	Direct: QUEST, QUEST-C, Flow monitoring, Modelling, Balancing time series sewage and drinking water, indirect: Groundwater flow monitoring	Ground penetrating radar, Infrared thermography

Appendix A.1 provides a comprehensive explanation of the above-mentioned techniques. For most of the leak detection methods, human inspectors are needed, which makes the technique costly and time-consuming (Yu et al., 2021). The study of Yu et al. (2021) covers a review of acoustic and ultrasonic sensor technologies for sewer pipes. They mention: ‘Microphone sensing is well suited for being used in a partially filled sewer pipe to detect blockages, wall damage, and infiltration. Ultrasonic sensor arrays are well suited to measure the pipe wall thickness loss and to detect cracks, corrosion, and poor joints from within a pressurized clean water pipe. Distributed fibre optic sensors are well suited to detect leakage noise in a clean water pipe. These systems are capable of detecting multi-leaks with a low SNR and in the presence of high measurement uncertainty. However, these systems are relatively expensive to install.’

Pressure tests and tracer techniques, such as QUEST-C, are claimed to be the best in detecting and quantifying exfiltration so far (Rutsch et al., 2008). Information about the leakage rate is gathered while performing pressure tests. This research compares in the end the results of the pressure tests and the results of the FELL system for validation of whether the constructed hole is leaking water or not. It is, besides that, also to find a possible correlation, when both the pressure test and the FELL system are repeatedly proven to be good. Pressure tests are time-consuming, but they can give an accurate outcome about the leakage rate (Gokhale & Graham, 2004). During pressure tests, the pipe, or part of the pipe, is isolated, and the pressure inside the pipe is adjusted to a particular value which should be constant over a longer period. The difference in volume in the pipe is measured and exfiltration is established by observing this water volume in the pipe (Larrarte et el., 2021). Pressure tests can be performed to quantify the size of the leak by closing a section of the pipeline with valves, after which it is pressurized. Escaping flow or pressure drop is then monitored (Gastkemper & Buntsma, 2018). This technique is in fact well suited to quantify, for example, how leaky a leaking joint is, i.e. what the leakage rate is. For that reason, pressure testing is suitable to use as a reference in this research.

2.2 FELL system technique

One of the geophysical methods is the FELL. This technique is already in use and exists for quite some time now, which means that practical experience of the method is already known. It is used to create a recovery system and it overcomes limitations of the technique of CCTV cameras (Condran & Hansen, 2019). According to Gokhale and Graham (2004), the FELL method is easy and quick. Money can be saved by applying the FELL before CCTV cameras. The FELL uses an electrical current between an electrode in the pipe and an electrode in the ground in the vicinity of the pipe. The technique used for the FELL is a measurement of the impedances in the electrical circuit (Stegeman et al., 2022). Impedance is the effective resistance of an electric circuit to alternating current, arising from the combined effects of ohmic resistance and reactance. The measuring basis is to see the contrast between the high specific electrical impedance of the pipe materials and the lower specific electrical impedance of the water (Wolf, 2003). An electrical voltage is applied between an electrode in the pipe and an electrode in the soil. A metal pole (hereinafter referred to as grounding pin) is used as an electrode in the soil and a probe is used as an electrode in the pipe, which completes the circuit. An electrical potential of 10 Volts rms with a frequency of 400 Hz (which can be set to different values up to 1000 Hz) between the electrode in the pipe and the electrode in the soil is used (ASTM, 2018). Sewage, which is present in the pipe while using this technique, is conductive. The conductivity of the pipe itself, for example, plastic or concrete, is lower. This diminishes the conduction of the electric current. The conductivity of the water means that the electric current can pass easily when leakages occur in the pipe. This represents a negative anomaly of the specific electrical impedance of the sewer pipe at the location of the leakage (Wolf, 2003). In general, the conductivity is calculated by dividing the length of the conductor by the area of the conductor times the uniform impedance of the conductor (Moy et al., 2012). Normally, when no leakages are present, the high electrical resistance of the pipe material blocks the electrical current between the probe and the grounding pin. When there is an anomaly present in the pipe, water is infiltrating or exfiltrating, so the electrical current will increase which means a reduction in impedance (Wilmut et al., 2005). The FELL is not only used to detect and determine leakages in underground pipelines but also used in subsea pipelines and geophysical applications like borehole logging (Stegeman et al., 2022; Ho et al., 2019). Below, Figure 1 shows an impression of what the FELL system looks like.

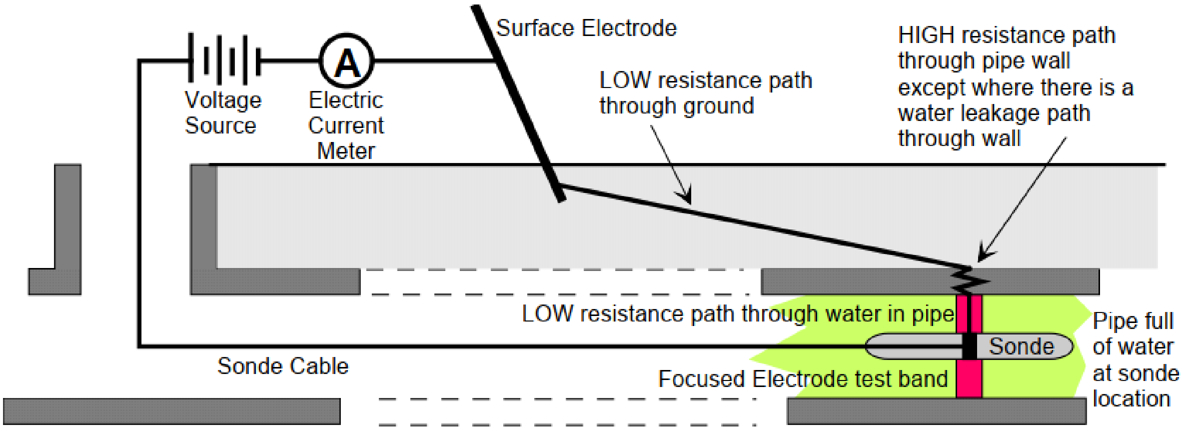


Figure 1: Simplified Electrical Circuit (Wilmut et al., 2005)

The increase in current is registered and coupled with the location of the probe. The probe is a three-electrode array, and the electrical field of the middle electrode is focused in a disc, which performs the measurement. The two electrodes on the outside of the central electrode are called the shield electrodes. This shield ensures that the electrical field of the central electrode is isolated from the outside impedances of the pipe (Wilmut et al., 2005; Stegeman et al., 2022). The cable carries electric power to the probe, transmits the data from the probe to the computer, and is used to pull the probe through the pipe from the downstream or upstream manhole. A shaft encoder pulley on the cable measures the position of the probe between the two manholes. The probe is supplied with a constant-voltage power. The voltage impressed on the three electrodes of the probe is an alternating current voltage at a frequency of 400 or 600 Hz. Higher conductivity through the water will be faced by lowering the voltage on the electrodes. To get a current flow focused from the middle electrode onto the perimeter of the pipe in a 1-in. disk, the potential of all electrodes is held at the same level by the power supply (Martel et al., 2011). So, an alternating current is generated between the two electrodes (the grounding pin and the probe in the sewer pipe), creating an electric field. The magnitude of this depends on the current strength and distance between the electrodes. The voltage between the current electrodes decreases due to the resistance of the soil and the resistance of the sewer pipe.

FELL system design

The design of the FELL prototype 2.0 is based on literature, and prototype 1.0 was used in the study of Stegeman et al. (2022). As mentioned, the probe has three cylindrical-shaped electrodes isolated by plastic compartments. The central electrode has a length of 6.5 cm and the outer electrodes have a length of 26.3 cm. With a casing around the electrodes, the total length of the FELL prototype 2.0 is 77.5 cm and the diameter is 250 mm. In the probe, a CTD-Diver can be installed which, in addition to pressure and temperature, also measures the conductivity of the water. The ceramic housing with a diameter of 23 mm fits into the end of the probe and is suitable for applications in brackish and saltwater or other aggressive environments. The CTD-Diver can store up to 48,000 measurements. Appendix A.3 gives a detailed overview of the design of the probe. Figures 2 and 3 show pictures of what the FELL prototype 2.0 looks like without the CTD-Diver.

Figure 2: Picture of the FELL prototype 2.0 probe without casing

In the paper of Stegeman et al. (2022) is demonstrated that the shape of the current-position diagram depends on the vertical distance between the probe bottom and the leakage in the pipe. So, while measuring in a big pipe diameter, it is useful to keep the probe in the middle of the pipe to make sure all the leakages can be measured at the same distance. To do so, different casings are constructed around the probe. Figure 3 shows the casing of the FELL prototype 2.0 used during this study. The diameter of the FELL prototype 2.0 with the casing is 250 mm as mentioned before, which makes it impossible to place the FELL prototype 2.0 completely in the middle of a 600 mm pipe diameter, for example.

Figure 3: The FELL prototype 2.0 probe with casing in a PVC pipe 400 mm diameter

Appendix A.2 shows a complete overview of pictures of the design of the FELL prototype 2.0, including the trailer by which the FELL prototype 2.0 is transported. The trailer is an external unit in which equipment is stored, a driver license BE is required. The trailer has two compartments, one in which the equipment such as PC and laptop is stored and one in which the water tank, pull system, and other 'dirty' equipment are present. The pull system consists of an absolute shaft encoder to maintain the position. The winch at the start and end is able to pull the probe automatically with a constant speed in both directions. Nozzle (+500 litre barrel) to bring the probe to start position. Hose reel of 100 meters ½" hose, associated with nozzle. The electronics in the trailer control the electrodes in the pipe filled with water with two power amplifiers to be able to supply sufficient current. The signal is generated in a generator, consisting of a DDS (Direct Digital Synthesizer) followed by an amplitude control. The generator's frequency and amplitude are adjustable by the user. The signal of the generator is applied to the power amplifier. One of the amplifiers has resistors in series, which measure with its output which causes a voltage drop that is proportional to the current flowing through the connected electrode. The electrodes in the pipe can be connected to one of the amplifiers, using one of the switches LS1A, LS1B, and LS1C. The current of the upper amplifier is measured with one of the six measuring resistors. The amplifiers of the two outer electrodes follow the signal of the measuring electrodes to achieve that the three electrodes have the same voltage. The voltage that arises across the measuring resistor is amplified 100x in order to keep the voltage across the resistor limited. The voltage from the current amplifier is amplified by a buffer amplifier and made suitable to pass through the 200-meter long cable. The system will measure the phase shift between the current through and the voltage on the electrode. The phase shift in the electronics is low enough not to influence the measurements. The software detects the phase shift between the current and voltage. The phase shift is used to determine the current through capacitances in the system. The probe is connected to this cable, which can be seen in both Figures 2 and 3. Measurements are taken from the measuring heads of the probe so that the losses over the cable are not of great significance. The signal is also inverted to be able to measure the signal and it's inverted simultaneously and in this way to limit disturbances. All settings and switches/relays are controlled by the Embedded processor, which receives commands from the PC at the other end of the cable using commands from the control PC via RS485. In this way, the operator can adjust the generator voltage and frequency, and choose the connections between the electrodes and amplifiers as well as the measuring resistance, to get useful values. With the electronics built into the probe, there is a risk of overheating because the ventilation may turn out to be too low. To avoid overheating, a temperature sensor is mounted on the cooling plate, which is read by the processor. This happens one time per second. If the temperature gets too high [about 60 degrees], the processor turns off the main power and stops heating. The heating is greatest at a high current, and it is therefore recommended to set the current not greater than necessary for a useful measurement by keeping the electrode voltage as low as possible (ID TEC, 2021).

Until the present day, the FELL has been used in several pieces of research to detect and locate defects. According to Tuccillo et al. (2011), Moy et al. (2012), Harris and Dobson (2016), and Harris and Tasello (2017), the FELL showed better results than other methods, like pressure tests and CCTV. To measure with the FELL, the probe is pulled through a water-filled sewer with leakages, which induce infiltration or exfiltration when the water level in the pipe and groundwater level are not aligned. Infiltration and exfiltration are discovered and situated by geo-electrical measurements. In the study of Stegeman et al. (2022), a model is made for this geo-electrical measurement system. For this research, laboratory experiments were performed to explore the effect and impact of the model components on the determined current and the validity of the theory. The model is implemented in a Matlab (2019b) script and is used to simulate the electrical current flowing through the network.

There are some factors that can influence the measurements, for example, the pipe materials, pipe bedding, composition of the water, and surrounding soil since they all have different specific electrical resistivities (Wolf, 2003). According to Wolf (2003), only pipe materials with high resistance can be used for measurements. The type of soil and bedding are determined by the mineralogical composition and water content. These factors differ per location and time of measuring. Leaky joints are, however, characterised by a higher current signal compared to leak-free joints and can be recognized by a joint-specific threshold value filter. It is not possible to distinguish between defective and intact, professionally executed house connections with the geo-electric probe used. Wolf (2003) noticed that the anomalies in the measured currents were dependent on the size of the leak, and all joints showed slightly increased signals too.

So, the variation in electrical current is dependent on the electrical resistance of the water filling defect, which can be explained by the formulas 2.1 to 2.4 given in the study of Moy et al. (2012):

$$\Delta I = V_o/R \qquad \text{Eq. 2.1}$$

V_o is the open circuit voltage of the electro scan system and is constant, ΔI is the change in current and R is the electrical resistance. The conductivity of the water in the pipe, σ_w, is calculated by:

$$\sigma_w = \frac{T}{A*R} \qquad \text{Eq. 2.2}$$

T is the thickness of the pipe wall and A is the area of the leakage. The area of the leakage can be calculated by:

$$A = \frac{\Delta I*T}{\sigma_w*V_o} \qquad \text{Eq. 2.3}$$

The sewage conductivity is 11 microSiemens/mm and the FELL gives V_o is 10 Volt and ΔI has a rise in leakage current in 10^{-4} Ampere. The final formula is:

$$A = 0.0909 * \ \Delta I * T \ [mm^2] \qquad \text{Eq. 2.4}$$

In the study by Moy et al. (2012), many assumptions were made. The study of Stegeman et al. (2022) showed that by using the FELL prototype 1.0 during experiments in the lab various elements impact the measured current. Large errors in the leakage area are obtained if it is assumed that the measured current is determined only by the resistances of the leakage. When not only the leakage in the pipe implies a change in current, the features of the leakage are expected to be substantially under- or overestimated. The question is whether this is the case under full-scale circumstances. The paper explains that quantifying leakages is applicable when the thickness of the wall and cross-sectional area are assumed to be homogenous. During the experiments of this paper, the influence of the admittances involving the thickness of the pipe is neglected, which play probably a role under full-scale conditions. Also, the admittances between the central and outer electrodes have not been studied. Stegeman et al. (2022) assumed that there is no current between these electrodes. The formula used in the experimental set-up of the study by Stegeman et al. (2022) to calculate the resistance is shown below 2.5 to 2.7. To determine these, the following electrical circuit is used.

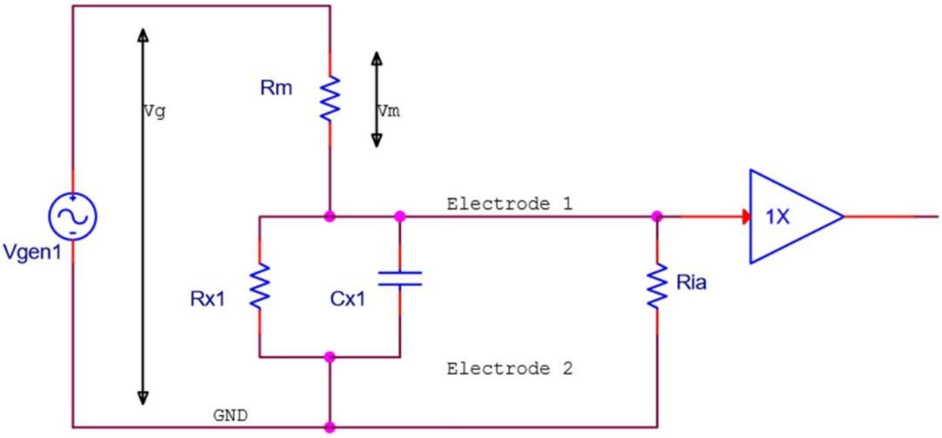


Figure 4: The electrical circuit with impedances in the experimental set-up (Stegeman et al., 2022)

V_g is the signal generator, V_m is the potential differences, R_x is the total resistance, R_{IA} is the resistance of the voltage follower, and R_M is the shunt resistor. These parameters are all measured. R_{X1} and C_{X1} are the unknown resistance and the capacitance of the impedance between the two electrodes. Using the impedance of this electrical circuit, the capacitance can be calculated.

$$C_{x1} = \frac{\sqrt{V_m^2 R_m^2 + 2V_m^2 R_m R_x + V_m^2 R_x^2 - V_g^2 R_m^2}}{R_m R_x \omega \sqrt{V_g^2 - V_m^2}} \quad \text{Eq. 2.5}$$

$$R_{x1} = \frac{R_x \cdot R_{IA}}{R_{IA} - R_x} \quad \text{Eq. 2.6}$$

$$R_x = -\left(\frac{R_m \cdot V_m^3 - R_m \cdot V_g^2 \cdot V_m + \kappa_3 + \tan^2(\phi_Z) \cdot R_m \cdot V_m^3 - \kappa_2 + \tan^2(\phi_Z) \cdot R_m \cdot V_g^2 \cdot V_m}{\kappa_1} \right) \quad \text{Eq. 2.7}$$

Where:

$$\kappa_1 = \tan^2(\phi_Z) \cdot V_m^3 - V_g^2 \cdot V_m + V_m^3$$

$$\kappa_2 = R_m \cdot V_g \cdot V_m^2 \cdot \sqrt{\tan^2(\phi_Z) + 1}$$

$$\kappa_3 = R_m \cdot V_g^3 \cdot \sqrt{\tan^2(\phi_Z) + 1}$$

2.3 Data processing

A computer application is available that will automatically carry out an analysis of the electrical current. The database is stored, and tables and graphs of the outcomes are given, the variation in current between the probe and the grounding pin is shown. From there, a relationship must be established between the increase in the flow, the leakage area, and the possible location. The equipment of the FELL prototype 1.0 is associated with the data acquisition system, a computer-controlled A-D Converter to guarantee synchronisation (Stegeman et al., 2022). According to Martel et al. (2011), it is not possible to define the source of the leakage (e.g., misaligned joints, pipe cracks, defective service connections) or position around the pipe perimeter of the leakage. By computer processing, it should be possible to determine the leakage size. What is not possible yet with the FELL prototype 1.0 used in this study by Stegeman et al. (2022) is the possibility to organize the results in different types of defects that occurred due to faulty joints, service connections, manhole connections, and structural defects such as pipe crack by computer processing. For now, the results just show spikes or raised levels of the measured electrical current. This spike implies the location of the leakage, defect, or feature of the pipe. The way the spike is formed indicates the type and severity of the leakage. The FELL-41 described by Gokhale and Graham (2004) show potential problems at different locations, including pipe changes. Wolf's study (2003) illustrates the raw data of measured electrical currents for four of the eight radially arranged sensor elements. Here, the current increases at the leakage location, as shown in Figure 5.

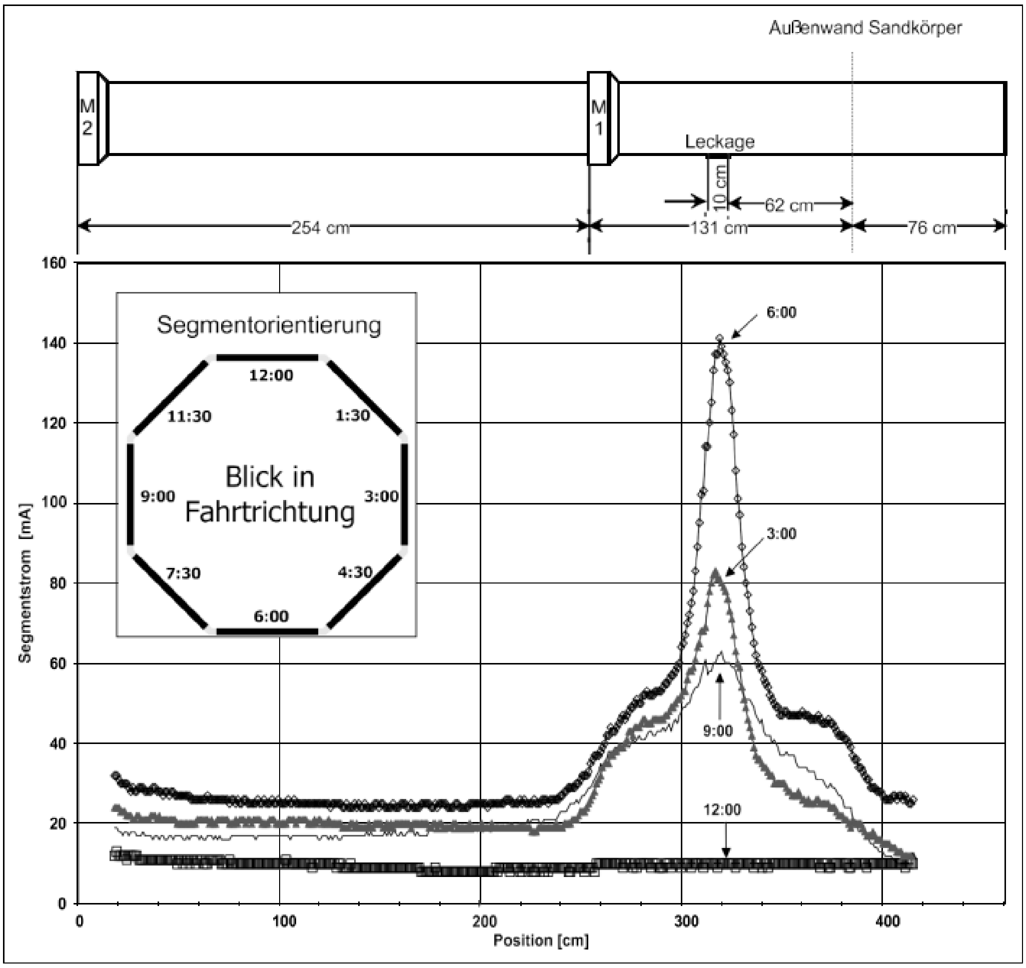


Figure 5: Position of the artificial leak in a section of the FZU test section and corresponding signals from the geoelectric probe (Wolf, 2003)

Harris and Tasello (2004) claim that "Anomalies that occur at regular intervals are usually due to joint defects. Anomalies that occur at joint intervals are considered to be associated with a joint defect. Other anomalies are usually due to faulty service connections and structural defects". In this study, the probe current level of the anomaly is related to the size of the leakage. It is stated that the shape and amplitude of the graph determine the type and severity of the leakage. The location and the length of the peak indicate the longitudinal location and length of the leak along the pipe. However, theoretically, material blocking the hole or leakage could also affect the monitoring. This makes it difficult to classify the anomalies.

Data processing of the results done by Stegeman et al. (2022) is done in Matlab ® (2019b) scripts. This script reads and processes the measuring data from different files. First, the recorded time series are split into sub-sections; a time window *k* with each holding *N* data points. The Matlab script consists of a function that defines the frequency, amplitude, and phase of the applied potential difference over the function generator in each time window. This script also contains a Fourier analysis that defines the amplitude and phase shift of the potential difference across the shunt resistor. The Fourier analysis obtains the amplitude and phase of alternating current (AC). Second, the current, resistance, and capacitance are defined by using the electrical circuit explained in section 2.2. The calculated amperage and phase are used to calculate the resistance and capacitance. Third, the Monte Carlo technique (uncertainty analyses) is applied, so the 95 per cent confidence interval for the output parameters is determined. Last, the outcomes are collected, and graphs are made for each time window, and the data can be exported. With these data processing steps, the following results are created:

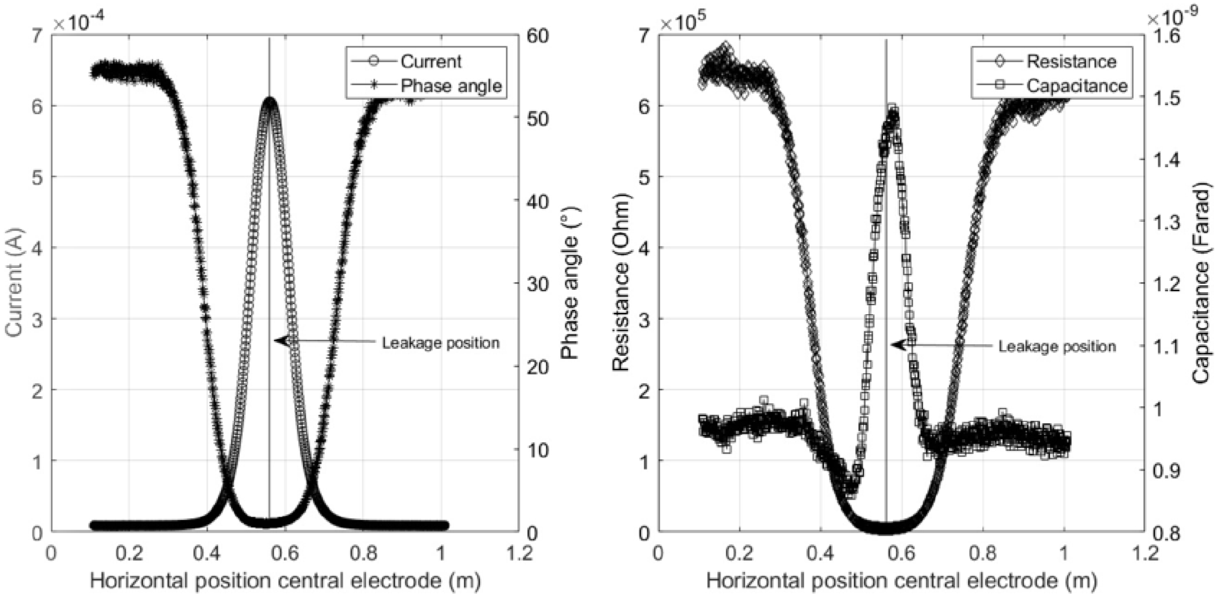


Figure 6: The current, phase angle, resistance, and capacitance measured at total. The probe moves in a horizontal direction and is fixed at a vertical position of 0.045 m above the leakage (Stegeman et al., 2022).

The figure on the left illustrates the current and phase angle between the electrode in the pipe, known as the probe, and the grounding pin. The figure on the right illustrates the resistance and capacitance. Capacitance is the ability of the system to store an electric charge. The resistance is the degree to which the pipe opposes the passage of an electric current. Ohm's law resistance is equal to the voltage divided by the current. The measured current and resistance are affected by the amount of space between grounding pin and leakage, and between probe and leakage. Another factor is the depth of this grounding pin. Leakage quantification with the FELL prototype 1.0 in sewer pipes is therefore challenging (Stegeman et al., 2022).

3

Methodology

This study is split up into two lines of research with two different research methods. The first part investigates the detection limit (what is the minimum size of the leak that the FELL prototype 2.0 can detect), and the second part will investigate the accuracy of the quantification of the leakages.

During the first part of the research, a certain amount of holes (artificial leakages) are made in a concrete sewer pipe below the surface at test set-up B to mimic leakages in real-world conditions and to measure the ability of the FELL prototype 2.0 to detect, locate and quantify leakages. At the start and the end of the study, tests at test set-up A are done with a PVC pipe above the surface to investigate the signal of a hole in a 315 mm PVC pipe under ideal conditions. Finally, the results of the FELL prototype 2.0 at test set-up B are referred to the findings of CCTV and joint tests.

During the second part, still to be performed, five selected sewer pipes in Breda will be investigated with the FELL prototype 2.0 to explore the accuracy of the measuring device. The results will be compared with CCTV cameras and pressure tests. These sewer pipes are fully used for the public sewer network. Before the start of every experiment, it is mandatory to free the pipe from obstacles and the surrounding of the probe should be completely filled with water. During the experiments, the groundwater level and quality will be monitored. Also, information about the soil is collected, if necessary: e.g. soil maps, groundwater levels, hand drillings, and maps with the underground infrastructure; e.g. water distribution pipelines and powerlines. When part one of the project shows that the FELL prototype 2.0 is not ready yet to detect, locate and quantify leakages, the second part becomes irrelevant.

In this chapter, the process of the experiments is explained. First, the general approach is discussed, followed by an insight into the locations of the experiments and aspects to take into account. Subsequently, the steps of the fieldwork are quoted, and a detailed implementation is discussed.

3.1 General approach

Before the final experiments for this study take place, an FAT, Factory Acceptance Test, must first be performed to verify that the FELL prototype 2.0 is set up correctly and will operate as expected before it ships to field conditions. After that, an SAT, Site Acceptance Test, is performed to validate if the FELL prototype 2.0 is operational in field conditions. The FAT is performed at test set-up A and the SAT is performed at test set-up B. When these tests show that everything works sufficiently to continue the experiments, the first part of this research can start.

Part one – test set up A and B

In a typical measurement session for the FAT at test set-up A, measurements with the FELL prototype 2.0 have been performed in a PVC pipe that was dug in the ground. This PVC pipe consists of a constructed hole at the bottom and in the middle of the pipe, with a diameter of approximately 5 mm. Multiple measurements were performed until the repeatability of the data output was stable enough. From that moment on, the FELL prototype 2.0 with trailer can then be moved to test set-up B to carry out follow-up measurements with a more giant concrete sewer pipe constructed below the surface. At the start, a camera inspection is performed in the concrete sewer of test set-up B to check the condition of the pipe. After that, zero measurements were performed in this sewer pipe that was completely filled with water. The FELL prototype 2.0 is pulled 40 times from the start- to the endpoint. The total amount of measurements done at test set-up B is adjustable, so if more or less measurements are needed, this is altered in the field at the moment itself. The grounding pin was inserted into the ground at a depth of 24 cm during all the measurements. The pin is moved in between the measurements to analyse if this has an influence on the results. After that, a pressure test is carried out to check whether the pipe is leak-tight which has to be confirmed in case the results of the FELL prototype 2.0 deviate from expectations. If the results of the FELL prototype 2.0 matches with the results of the pressure test and camera inspection it is time to check what happens when leakages are present. For these experiments, it is necessary to drill some holes at the bottom of the concrete sewer pipe. The concrete sewer pipe at test set-up B has a diameter of 600 mm. In order to be able to drill the holes from inside the pipe, it is essential to make the pipe dry temporarily. After drilling the holes, the pipe was re-filled with water. Before starting the experiments, calibration of the FELL prototype 2.0 was needed to establish its properties. The distance registration must be properly calibrated. It is necessary to calibrate the conductivity meters as well, and this is done before the start of the experiments. Calibration of the FELL prototype 2.0 is simply done by moving the FELL prototype 2.0 back and forth to verify whether the same distance is registered during the movement. After all the experiments are carried out, the holes are neatly closed again at the end of the research, and a control test at the PVC pipe above the surface is performed to verify that the FELL prototype 2.0 still works as at the start of the study.

Different conditions were analysed at test set-up B:

1. Pipe without holes (zero measurement)
    - Pipe of concrete (Ø 600 mm) of length 35 meters in total
    - Pipe of concrete (Ø 600 mm) with measuring length of 24.3 meters
    - Above groundwater level
    - Different locations of the grounding pin
2. Pipe with a constructed hole at clock position 7 at 66 cm distance
    - Hole sizes 4 and 5 mm at same position
    - Pipe of concrete (Ø 600 mm) of length 35 meters in total
    - Pipe of concrete (Ø 600 mm) with measuring length of 24.3 meters
    - Above groundwater level
3. Pipe with a constructed hole at clock position 6 at 156 cm distance
    - Hole sizes 4,5,6,8,10,12,14,16 and 20 mm at same position
    - Pipe of concrete (Ø 600 mm) of length 35 meters in total
    - Pipe of concrete (Ø 600 mm) with measuring length of 24.3 meters
    - Above groundwater level

The pipe should be emptied every time a new hole size is constructed and must be re-filled to do the measurements. Every hole size is repeated at least eight times to verify if the results show the same graphs under the same conditions. When more measurements are considered necessary, the amount is altered at the moment itself. While measuring the same condition eight times, the grounding pin is placed at different locations to check whether this influences the results. The measurements of each hole size are eventually done with the same position of the grounding pin. Removing the grounding pin in the beginning is only done to verify whether this influences the accuracy of the measurement results. This means that at the end, about 40 graphs for the zero measurements and about 72 graphs of different hole sizes and a few graphs of different positions of the grounding pin are available from the above set of tests. This is not an exact number of graphs as these are adjusted appropriately if more or fewer measurements are needed. To analyse the entire perimeter of the pipe, the pipe must be completely filled with water at the position of the probe. The probe is pulled through the pipe with a velocity of approximately 0.06 m/s. For a step-by-step plan on how to work with the FELL prototype 2.0 and the computer system, a protocol has been added in Appendix B.1. Finally, a pressure test is performed as a reference to check the leakage rate for hole size of 5 mm and the joints in the concrete test sewer pipe. Appendix B.2 shows an overview of how pressure tests are carried out and what the used joint tester looks like at test set-up B.

Part two (which is only partly performed in this MSc thesis project)
First, a selection of sewer pipes was made based on groundwater levels, pipe material, pipe diameter, connection type, location, inspections data (images), drawings with manholes and possibilities to close off these manholes, and dates when relining is taking place. While selecting the pipes of the sewer system of Breda, it is important to make sure whether it is possible to do pressure testing as well. For the experiments at the selected sewer pipes of Breda, besides the pressure test, it is also required to have camera images available in advance. With the results of CCTV, the FELL prototype 2.0 technique can be assessed to obtain a better impression on what kind of leakages may occur in the sewer pipe. When performing the experiments in the public sewer network, the FELL prototype 2.0 is placed in the pipe via the upstream manhole, and the pipe is completely filled with water so that the entire perimeter is covered with water. The start location of the experiment is in the centre of the manhole; the central electrode should be placed in the centre of the manhole and is pulled towards the other centre of the downstream manhole. The probe current of the section with distances is recorded and presented on the laptop in real-time. Before the experiment starts, it is first necessary to close off the road and confirm there is a safe place to work. Also, the manholes need to be closed off, which means a particular part of the sewer network cannot be used for a certain period of time, which again needs to be submitted to the municipality to ensure the connected houses do not suffer from the experiments. After the FELL prototype 2.0 measurements are done, a pressure test should be carried out to provide a reference for the FELL prototype 2.0 results on leakage rates. A step-by-step plan of pressure testing can be found in Appendix B.2.

3.2 Study site

The city of Breda has different types of sewers. A distinction is made between pressure mains, dry weather drainage system, combined sewer systems, separated sewer systems, and improved separated systems. There is a combined sewer system, especially in the centre and a large part of the rest of the city. This means that both wastewater and rainwater end up in the same sewer and go to the wastewater treatment plant (WWTP). In some areas in the north and south of the city, there is a separated sewer system. The wastewater ends up in a different sewer than the rainwater sewer. In improved separated sewers, rainwater and wastewater both run to a pumping station. From the pumping station, a small part of the rainwater goes to the WWTP: the water from smaller rainfall and the start of larger rainfall. This part also contains wastewater from incorrect connections. The rest of the (often cleaner) rainwater runs over to a pond or ditch (Kuiphuis et al. 2017). The experiments for this study will be performed in the sewer system and not in a rainwater pipe since these pipes have more ecological impact. This study focuses on the municipality of Breda, where there is mainly sandy soil. When sewer pipes are constructed in a soil of sand, they can mostly last longer. Yet the pipes will be damaged sometime, and they will therefore become leaky at some point in time. Breda spends approximately 13 million euros per year on the maintenance of the underground system, which has a length of roughly 1300 kilometres. Changing the sewerage system is expensive.

Replacement of a pipe will not be done immediately to limit the costs. The municipality is doing this, among other things, by relining the existing sewerage system. This means that the inside is reinforced with a kind of plastic layer so that the pipe can last for a while longer and no digging is needed. A kind of new pipe is introduced into the existing pipe, which ensures that the pipe can last for some time again (Berglind et al., 2012). Most of the existing sewage system dates from the 1950s and 1960s. Assuming an average lifespan of sixty to eighty years, this means a replacement peak in the next five to ten years, which again means that lots of leakages exist in the pipes at the moment. To better assess whether a sewer needs to be replaced, an inspection of the condition of the sewer system is required. With inspection results, it is possible to weigh up whether or not to replace or improve a sewer (Schapendonk 2019; Gemeente Breda 2019). If TRL levels 5 and 6 have been fully completed, there is the possibility to investigate the already damaged sewer pipe, which is the aim of TRL level 7. This study selected the already damaged sewer pipes where it is known by inspection that these pipes are leaking. Selection criteria, such as location, pipe diameter, and the number of valves that have to be used to do the experiments, are composed. From there, a decision about the pipes to be used in this research has been made, which is shown in Appendix C.1. Before conducting and preparing the experiments in the selected sewer pipes, first experiments were done at the test set-up A and B to focus on TRL levels 5 and 6.

3.2.1 Test set-up A: PVC pipe above the surface

The test set-up to perform the FAT is located at Poeldijk. It is a self-made set-up where a PVC pipe is dug into the ground. The PVC pipe consists of a constructed hole with a size of 5 mm located in the middle of the pipe at the bottom. The diameter of the pipe itself is 315 mm, and the length is estimated at 2 meters. The PVC pipe is located next to a ditch, as illustrated in Figure 7.

Figure 7: Test set-up A: PVC pipe above the surface

Trucks regularly pass by next to the set-up. The wetness of the soil differs each day, depending on the weather. The measurement set-up also differs per day since the pipe is not placed back precisely at the exact location and the grounding pin is also inserted in the ground at different places. The PVC pipe itself is taped and sealed at both ends so that the pipe can be filled with water. Before the start of the measurements at this location, the soil is first thoroughly wetted by means of a garden hose.

3.2.2 Test set-up B: concrete pipe below the surface

The test set-up is located at the Slingerweg in Breda and consists of a pumping station (1.5 x 1.5 x 3.3 meters), a free-fall sewer (Ø 600 mm) of approximately 50 meters in total, including a discharge pit and a flow measuring pit (both 1.5 x 1.5 x 0.8 meters) and an overflow pit (3.0 x 3.0 x 3.0 meters). Figure 8 shows an overview of the situation of test set-up B, with the pumping station, overflow, and pressure main.

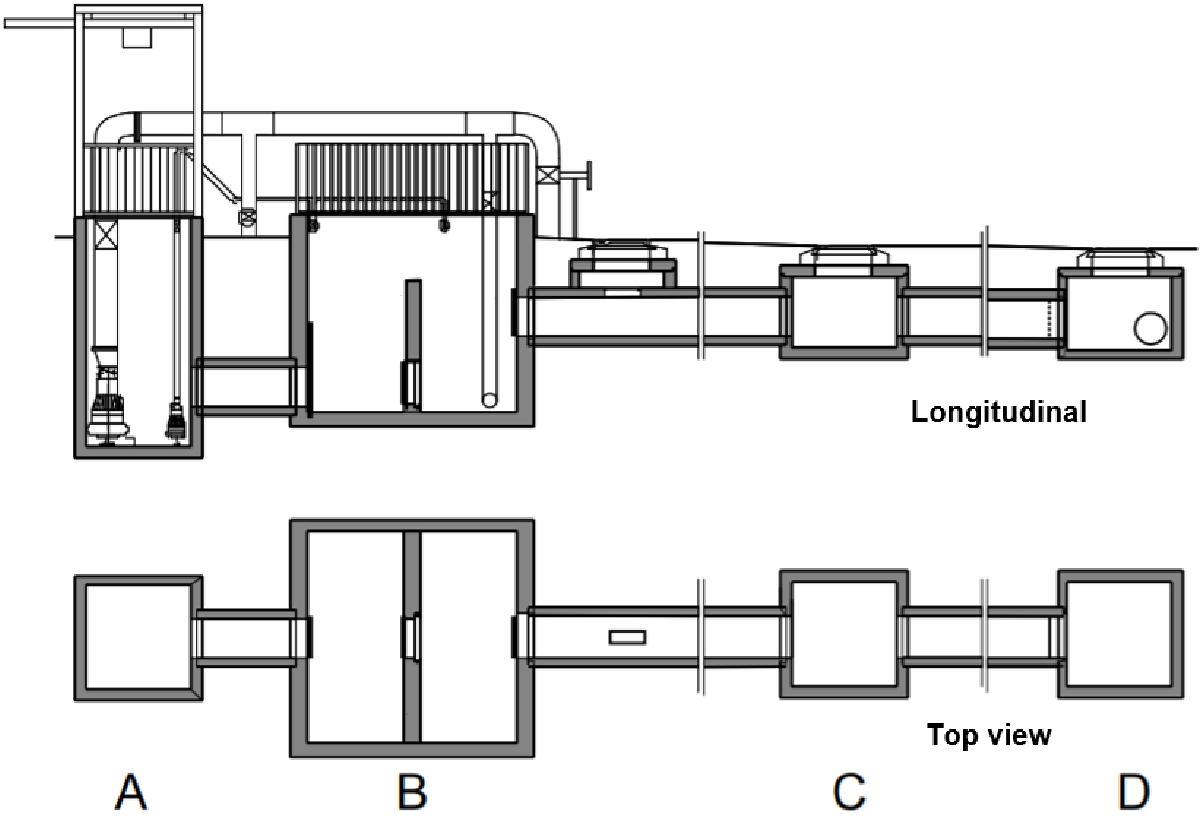


Figure 8: Longitudinal section and top view of the test set-up B (STOWA & Stichting RIONED, 2009)

From the pumping station (A), sewage can be pumped via two pumps and a pressure main into the overflow (B) or discharge pit (D). The pumps have a frequency converter so that the capacity can be adjusted. The water flows into the overflow via the gravity sewer and a flow measuring pit (C). The water then flows from the overflow back to the pumping station. In the pumping station (A), two pumps circulate the water: pump 1 is an ITT Flygt submersible pump, type 3085; and pump 2 is an ITT Flygt submersible pump, type AB NP3153 LT. Pump 1 can pump water to the overflow via a pressure main (Ø 100 mm). Pump 2 can pump water to the discharge and overflow pit through a pressure main (Ø 315 mm). The pressure main has a factory-calibrated electromagnetic flow meter from Krohne. From the overflow (B), the water flows into the pumping station via a concrete pipe (Ø 600 mm) consisting of two parts. The measuring pit connects the two parts. From the discharge pit, the sewer rises slightly to the measuring pit, with a slop of 0.5‰. This part of the sewer is 15 meters long. Due to the slope, there is a difference in level of 7.95 mm between the lower pipe level of the discharge pit and the lower pipe level of the flow measurement pit. Between the flow measurement chamber and the overflow, the sewer slopes down slightly, with a slope of -0.3 ‰ and over a length of 35 meters. This results in a level difference of 10 mm between the invert pipe level of the flow measurement chamber and the invert pipe level of the overflow (STOWA & Stichting RIONED, 2009). The gravity sewer, with a diameter of 600 mm and a length of 35 meters, will be used to carry out experiments for this study. Next to this sewer pipe, close to the pumping station, a PVC pipe with a diameter of 315 mm is present. From a core sample profile near the location of the sewer pipe, it is known that the surrounding soil consists of mostly sand (Ondergrondgegevens | DINOloket, 2012). The groundwater level near the concrete pipe differs per season and it depends on the location, permeability of the soil, weather conditions, and other factors. Generally, the groundwater level is, on average, around 2 or 3 meters at this location in Breda. The sewer pipe is at a depth of approximately 1.2 meters, which means that the sewer pipe is located above the groundwater level. The measurements with the FELL prototype 2.0 will be done in an upward direction, as is illustrated in Appendix B.5.

3.2.3 Selected operational sewer pipelines of the municipality Breda

In total, there is approximately 1100 km of sewer pipes and approximately 200 km of pressure sewerage and pressure pipes in Breda. Approx. 20% of this area consists of wastewater pipes (230 km), approximately 25% of rainwater pipes (285 km), and approximately 50% of mixed sewers (520 km). The remaining percentage of approximately 5% consists of infiltration sewers (23 km) and drainage pipes (22 km). There are still about 1.5 km of asbestos cement sewers (Gemeente Breda, 2019). The pipes that are selected for this research are all made out of concrete, and camera images from a current inspection are available. In this way, it is known what kind of leakages are present in the sewer pipe. While making the selection, the following criteria were taken into account; pipe diameter, pipe material, type of leakage (infiltration severity), convenient location, as few valves as possible that must be used for good measurements, possibility to perform pressure tests, groundwater level, year of construction from which can be determined what type of connection is present in the pipeline and drawings of wells and possibilities to shut off. All selected sewer pipes are most likely below groundwater level since camera inspection is mainly done below groundwater level; otherwise, no infiltration can be seen in the images and videos. This is in contrast to the test set-up sewer pipe, where the pipe is above groundwater level. The selection of 8 pipelines was made by using Kikker, a program that is used by the municipality of Breda to overview all the pipelines in Breda. Appendix C.1 gives an overview of all the selected pipes with a street view of the locations and a logbook of all the aspects or defects, detected in the pipes. During this study, the selected sewer pipes shown in Appendix C.1 were not inspected; this is for further research as soon as more is known about how accurate measurements can be performed from an operational point of view. First, TRL levels 5 and 6, demonstrating the FELL prototype 2.0 in a test environment, have to be completed before the switch can be made to TRL 7, where the FELL prototype 2.0 is demonstrated in a practical and realistic environment.

3.3 Fieldwork

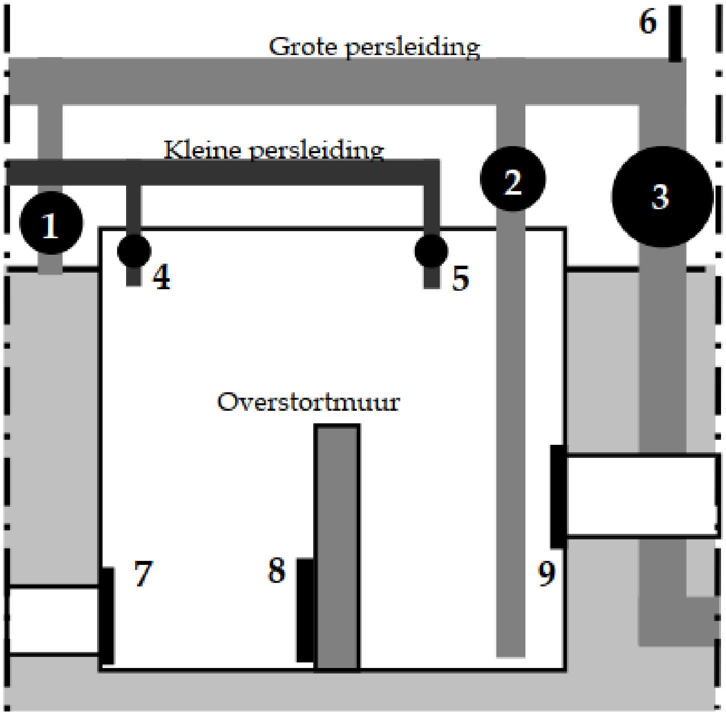
Before the experiments start, information about the soil and location is collected in both parts of the research. Calibration of the equipment is essential, as well at the test set-up as the selected operational sewer pipes. By doing so, the accuracy of the pressure transducer of the probe is confirmed. Calibration is done by setting the atmospheric pressure (Martel et al., 2011). Also, the conductivity meters (CTD-Divers) should be calibrated in advance. The CTD-Diver goes in front of the probe. The small sensor is an (air)pressure sensor, so compensating for the pressure from the underwater sensors is possible. In this way, the water level can be calculated. Calibration of the conductivity meters can be done by immersing the sensor for one minute or in different reference liquids (values around 1440). After that, measurements and reference values should be compared to determine the calibration function. The CTD-Diver

measures the conductivity of the liquid. Based on measured conductivity and temperature, the CTD-Diver can calculate the specific conductivity at 25°C. You can choose to register the conductivity or the specific conductivity. This is a setting in the Diver that must be selected prior to a start. The value of the selected setting is saved (logged). As a rule of thumb, it can be stated that the conductivity varies by 2% at 1 °C temperature change. This means that a calibration fluid of 5 mS/cm (at 25 °C), at 15 °C only has a conductivity of about 4 mS/cm.
In the practical application of the FELL prototype 2.0, it is necessary to fill the sewer as completely as possible using packer systems and flushing vehicles, and to position the corresponding hauling ropes and deflection pulleys. At the test set-up sewer pipe, it is possible to fill the pipe with water by turning on the pumping station. Shut-off and safety measures at the manholes are unavoidable. The sewer cleaning truck should be set up at the downstream manhole and the hose should be pulled from the upstream manhole. The measurement itself, on the other hand, can be carried out comparatively quickly within a few minutes (Wolf, 2003). When the soil is sandy and dry, water should be poured on the ground around the grounding pin to improve the connection. Also, adding some salt and detergent to the water around the grounding pin is helpful to make sure the current flow is reliable (ASTM, 2018). Appendix B.1 shows a step-by-step plan of how to measure with the FELL prototype 2.0. When the experiments are done and the data is collected the pipes will be repaired or relined, which gives an opportunity to inspect the pipe and check the defects that are displayed as results. For both parts of the research, the test set-up and the selected sewer pipes, different methods are applied, as described in the following sections.

3.3.1 Test set-up B

Before the experiments can start, safety regulations must be observed. Before starting the measurements, all switches in the green cabinet/box must be off. Also, the open wells (flow measuring pit and discharge pit) need to be cordoned off by using road barriers. This prevents people from falling into the well or trucks from driving into the well. Subsequently, the presence of people needs to be checked. The pumping station, overflow, flow measurement pit, and discharge pit need to be checked in sequence to confirm that there are no people in the parts of the installation. Next to this, pollution control is required. No dirt (such as twigs, bottles, and cans), loose parts, materials, or tools should be present in the installation or water. These may clog up the pumps and cause deviations in the measurement results. Removing the dirt is necessary prior to the measurements. In the overflow, there are various shut-off valves and valves that control the flows; these need to be checked whether the correct valves are open. Next to that, an installation of soil moisture sensors has previously been installed. These sensors can monitor the VWC, temperature and EC. The installation is done by digging a hole in the ground close to the sewer pipe. The first sensor (T1200079016) is placed 1.24 meters underneath the ground, with the pins pointing to the west (towards the pumping pit), 50 centimetres from the outside pipe and 15 centimetres from the side of the pit. The second sensor (T1200079021) is placed 1.33 meters below the ground and pins pointing vertical to the south (down into the ground), this sensor has the same location as the first sensor, but it is placed a few centimetres below the first. The third sensor (T1200079084) is placed 30 centimetres below ground, a little bit further from the sewer pipe with the pins pointing towards the pumping pit. After inserting the sensors into the soil, the sensors are plugged into the data logger. After that, data logger software is applied to change settings to the sensors, and the trench or hole is backfilled where the sensors were installed. The materials that are needed to perform the experiments at the test set-up are given in Appendix B.6.

After observing the safety conditions and material check, the measuring equipment must be installed. An overview of the order to do so is found in Appendix B.1. The first measurement is the zero measurement. When the pipe is not filled with water yet, it is required to fill the system, so the pumps and sensors need to be turned on. First, switch on the main switches in the pump sump, then switch on the frequency converter (in the green box). The flow situation should be adjusted, and the whole pipe should be fully filled with water. This can take several hours. Figure 9 illustrates which valves are present in the system.



1 Afsluiter grote persleiding voor lozing op vrijverval riool.
2 Afsluiter grote persleiding naar overstortput.
3 Afsluiter grote persleiding naar lozingsput.
4 Afsluiter kleine persleiding naar overstortput.
5 Afsluiter kleine persleiding naar overstortput.
6 Ontluchtingskraan grote persleiding.
7 Schuif naar pompput.
8 Schuif in overstortmuur.
9 Schuif uiteinde rioolbuis.

Figure 9: Locations of valves and gates

To drain the system, valves 2 and 3 should be closed and valve 1 should be opened. All sliders in the overflow pit must be opened. To flow water through the gravity sewer, valves 1 and 2 should be closed and valve 3 should be opened. All sliders must be opened too. When a completely filled pipe flow is created, slide 8 of the passage in the overflow wall is closed. When the sewer pipe is not filled, camera inspection can take place before the zero measurements to check the condition of the pipe. Appendix B.4 gives an impression of the camera truck which is used for video inspections. The inspector registers the condition of the pipes in accordance with NEN-EN 13508-2. The inspection company vandervalk+degroot provides the results in a report in exchange format GWSW.RibX with (digital) images. When compiling the report, the observations class is establishes on the basis of the 'Rioned classificatie methodiek van visuele inspecties: Classificeren van toestand aspecten van leidingen en putten' in accordance with NEN-EN 13508-2, version January 16, 2020 (Verkerk, 2019). When the sewer pipe is filled with water, the FELL prototype 2.0 is pulled through the pipe. While doing so, the grounding pin is placed above the middle of the pipe. Also, the pin is placed once on the right side of the 35 meters long sewer pipe. The grounding pin is at a fixed position during the run but differs in the first experiment, to check the influence of this position. The depth of this grounding pin is 24 cm and at a distance of 14.6 meters from the starting point. This is illustrated in Appendix B.5. To increase the signal-to-noise ratio, the change in current after increasing the conductivity of the water can also be quantified. Increasing the conductivity can be done by adding a container of saltwater into the sewer pipe to see what happens, also some saltwater solution around the grounding pin to see if it makes a difference. By doing this, the operator can become familiar with handling the FELL prototype 2.0 device and check whether the location of the grounding pin and conductivity have a lot of influence on the results. After reproducing the zero measurements multiple times, the pressure test can be performed for the joints; this method is explained in Appendix B.2. Then, the sewer pipe needs to be emptied to drill a hole from the inside of the pipe at a distance of 66 cm (at the height of 12,5 cm) and 156 cm (bottom, so 0 m). This is done from the manhole at the end of the pipe. An impression of the situation while drilling the holes is shown in Appendix B.5. The first hole will be of the size of 4 and 5 mm, at clock position 8, 12.5 cm from the bottom. The second hole is placed 156 cm from the starting point of the pipe, exact at the bottom, at clock position 6. After creating the holes, the pipe must be again filled with water, after which the FELL prototype 2.0 takes three successive measurements to see whether the outcomes are the same while replacing the grounding pin as mentioned at the zero measurements. Then a fixed position of the grounding pin is used while doing 8 measurements again for hole size 4. After that, the second hole is constructed with a diameter of 4 mm, and the first hole is made to a size of 5 mm. From there on, the second hole is made bigger after taking the measurements, and the first hole stays at a diameter of 5 mm. When the data from these measurements have been received, a leak test (pressure tests) is performed to check the current leakage rate in the pipe. The process of draining the pipe, drilling the holes, refilling the pipe, and taking eight measurements with the FELL prototype 2.0, is done for all hole sizes at clock position 6. After all measurements at these clock positions are done, pressure tests are performed for joints and hole size 5 mm. After that, the hole will be repaired. In total, 72 graphs are produced, with results of different hole sizes at different clock positions on the pipe. Next to this, also 40 graphs are produced of the zero measurements. These results are compared with the pressure tests and camera inspection.

Individual joints of the pipeline are tested, along with a constructed hole. Therefore national safety regulations are studied. First of all, the pipe must be cleaned prior to the inspection. The liquid tightness of a part of the concrete sewer pipe is determined. Air inclusions are prevented by venting that part of the pipe as much as possible during filling. The individual joint is filled with water, and a specific pressure is applied, after which conditioning is required. Generally, 30 minutes is enough, but pressure tests can take more time when it is used for concrete pipelines than is the case for PVC pipelines due to the porosity of the material. While measuring the pressure drop, an accuracy of 10% should be taken into account. The minimum pressure is 10 kPa at the invert of the pipe and a maximum of 50 kPa. To determine the amount of water that must be added or is lost, the variation of the volume of water during the test is measured (NEN-EN 1610:2015). At the start of the measuring time, a pressure sensor is suspended in the water of the facility, where the value is read and registered. After the measurement time has elapsed, the value is read and re-recorded, and it is determined whether there is any water loss. Account must be taken of the fact that if the current groundwater level is higher than the highest part of the pipeline or pipeline to be tested, then the overpressure must be at least 1-meter water column above the current groundwater level. During the measurement, the water level is kept at the reference height, during which it is measured how much water is added or whether there is water loss (SIKB 2018; CEN/TC 2013).

During the experiments, a logbook is used to keep track of which pipes and which factors play a role in order to create an overview of the total situation. This logbook layout is given in Appendix B.3, where information can be stored on calibration information for the measuring device. Prior to the experiments at the test set-up, a selection was made of pipes where the investigation could take place to enable quantification. The selection of sewer pipes is mentioned in Appendix C.1. It is crucial to visit the selected location with a supervisor in advance to view the situation. Before the FELL prototype 2.0 measurements are performed at these locations, the selected sewer pipes are cleaned, and a camera inspection is performed to make sure the inspection videos of the pipes are up to date. This is done the same way as mentioned in section 3.3.1. However, during the experiments of part 1 (i.e. test set-up A and B), the decision is made not to execute part 2 of the study. The FELL prototype 2.0 is assigned to a TRL rating based on project progress. In this study, simulations were run in environments that are as close to realistic as possible, which is TRL 5. TRL 6 will be reached when the FELL prototype 2.0 is a fully functional prototype, which is not yet the case. So, TRL 7, demonstrating the working prototype in a practical and realistic environment, could not be accomplished since TRL 6 is not entirely reached.

4

Results

The following section presents the results of this study. Firstly, the outcomes of the measurements at test set-up A are discussed. These first calibration measurements were performed in a PVC pipe, with a diameter size of 315 mm, above the surface. They were conducted to assess whether the FELL prototype 2.0 works as efficiently as before defects occurred and to determine if the device can be used at test set-up B. Furthermore, the results of test set-up B act as a reference to check whether constructed holes can be detected in a concrete pipe below the surface. Secondly, a camera inspection at test set-up B is shown. Here, an illustration and description of the 600 mm concrete sewer pipe below the surface is given. Thirdly, the soil moisture sensor information at test set-up B is demonstrated. Fourthly, zero measurements of the concrete sewer pipe below the surface are shown. Subsequently, measurements after constructing holes in the concrete sewer pipe are indicated. Finally, the results of the second calibration of the FELL prototype 2.0 at test set-up A are given to compare the results at the start to the end of the research. In this way, it can be ruled out whether the unexpected results of the measurements at test set-up B are due to environmental changes or due to internal problems of the device.

4.1 Measurements at test set-up A

This section demonstrates the outcomes of the measurements that are done at test set-up A to exclude internal influencing factors of the FELL prototype 2.0 device itself. Here, among other things, figures are shown where the FELL prototype 2.0 did or did not have a casing, where the grounding pin was or was not wet enough, and where the grounding pin was positioned at two different depths in the ground during the measurement.

To normalise the data, the initial values of the current outcomes of different measurements have been joined, so that the measurements always start at the same current. It must be taken into account that the results of the FELL prototype 2.0 do generally not indicate this automatically since the starting value is different for every measurement. The x-axis is expressed in the proxy distance (proximate scale) because all measurements at test set-up A are done by hand rather than with the reel that converts voltages into meters. As a result, the original outcomes are not plotted in distance but in time. To make it more clear, the figures that are plotted are those showing when the FELL prototype 2.0 passes the hole 5 seconds before and 5 seconds after. The distance travelled by the FELL prototype 2.0 during these 10 seconds is approximately 50 mm. Appendix D.3 presents the steps performed to normalise the data output of the model used in this study. Here, it is illustrated how all x-values and y-values are brought to the same starting point to be able to validate the total data output. The y-axis is denoted by the unit [mA], which ultimately makes it better to read. All y-axis limits are subsequently set, so that the signals, offsets, and noise are visible during all measurements.

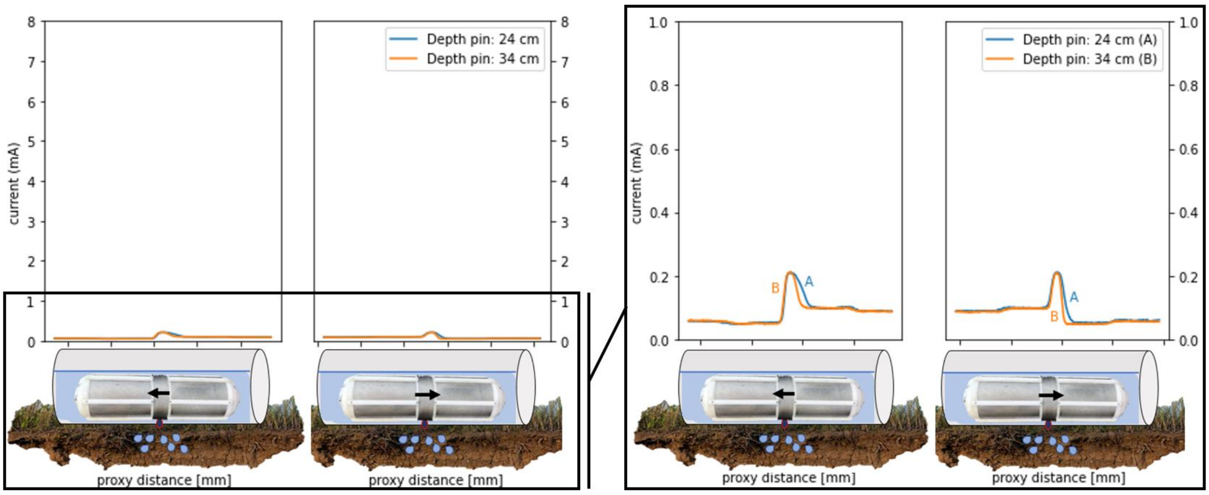


Figure 10: Moving FELL prototype 2.0 in PVC pipe (R-L & L-R) passing the same hole with different grounding pin depths (setting: 600 Hz 10 Ohm 3 V)

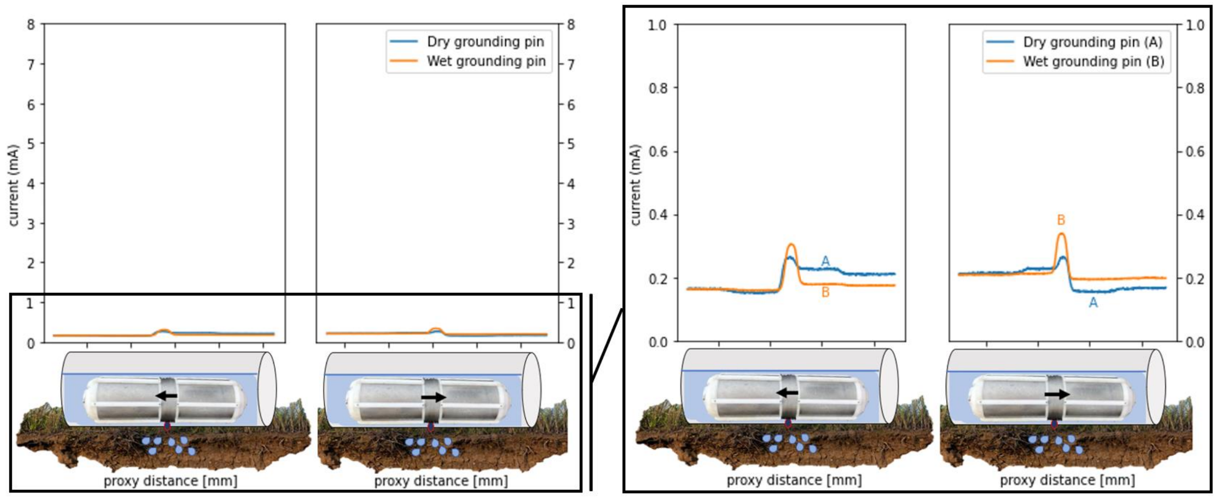


Figure 11: Moving FELL prototype 2.0 in PVC pipe (R-L & L-R) passing the same hole with different wetness around the pin (setting: 600 Hz 10 Ohm 3 V)

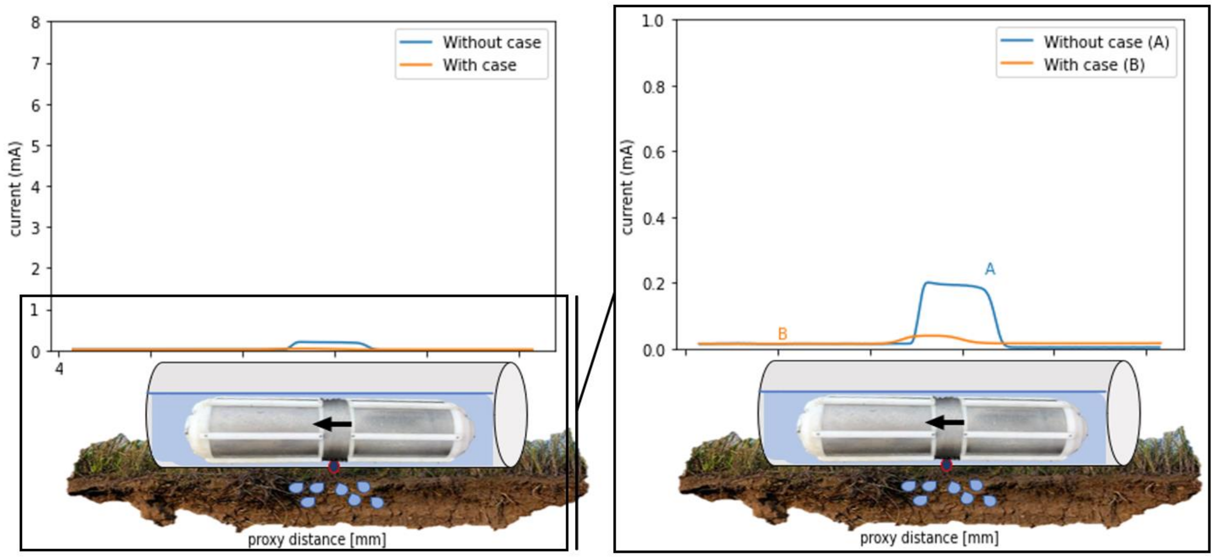


Figure 12: Moving FELL prototype 2.0 in PVC pipe (R-L) passing the hole one time with and without casing (setting: 400 Hz 10 Ohm 3 V)

The measurements from Figures 10 to 12 are done in a PVC pipe with a constructed hole located in the middle and bottom of the pipe. The size of the constructed hole is roughly 5 mm. Figure 10 and 11 represent the data output of the FELL prototype 2.0 while moving the probe by hand from left to right and from right to left during one measurement. The same hole is measured twice during one measurement. Figure 12 shows a measurement where the FELL prototype 2.0 is moved only once from right to left, so it passes the hole once instead of twice. In addition, it must be kept in mind that during all measurements at test set-up A, the vertical distance of the probe to the pipe wall is almost zero.

Peaks of the order of less than 0.2 mA can be found in all measurements that have been performed at test set-up A. Under ideal conditions, the signal for leakage of a hole that is 5 mm in size in a PVC pipe, is less than 0.2 mA. Figure 12 shows an even smaller signal, approximately 0.05 mA, with a casing around the FELL prototype 2.0. This measurement was done on a different day, and the grounding pin was located further away from the leakage, as illustrated in Appendix A.2. The location of the grounding pin alone creates a difference in signal of 0.1 mA. Furthermore, on a scale of 0 to 1 mA, a peak is clearly visible at the location of the hole. The width of the peak should not be considered in this case, as the FELL prototype 2.0 did not move across the hole at exactly the same speed during each measurement. During these experiments, the electrical resistance is measured. If there is a slight change in the water composition, the temperatures, the thickness of the pipe wall, soil composition or other parameters, it influences the outcome of the measurement. That is why the lines in the figures do not completely run continuously before and after the signal (i.e. location of the leakage). Figure 10 shows a blue line (A), where the grounding pin is inserted at a depth of 24 cm, and the orange line (B) gives the signal at a depth of 34 cm. Figure 11 illustrates again a blue (A) and an orange line (B), which compares the soil's moisture around the grounding pin. For the orange line (B), some tap water was put on the soil around the grounding pin, and the blue line (A) shows a measurement where the soil around the grounding pin was dry. The wetness of the soil around the grounding pin greatly influences the signal and the noise. A wet grounding pin gives a signal of 0.2 mA, and a dry grounding pin shows a signal of 0.1 mA, which is a factor two in difference. The noise when the soil is dry is 0.01 mA, and when the soil is wet, this is 0.002 mA, which is a factor of 5 in difference. These results clearly show that the soil conditions around the grounding pin are important influence factors for the data output of the FELL prototype 2.0. The two measurements were carried out in quick succession and therefore indicate that such a small change already has a large impact on the measured current. Table 3 and Table 4 summarise the measured current while performing measurements in a PVC pipe above the surface, which can also be seen in Figures 10 to 12.

Table 3: The order of magnitude of a leakage in a PVC pipe, with and without casing of the probe (test set-up A)

400 Hz - 10 Ohm Different position pin	**Without casing**	**With casing**
Signal/peak	10^{-1} mA	10^{-2} mA
Noise	$10^{-4} - 10^{-3}$ mA	10^{-4} mA

Table 4: The order of magnitude of a leakage in a PVC pipe, with various grounding pin settings (test set-up A)

600 Hz - 10 Ohm	**24 cm**	**34 cm**	**Dry soil pin**	**Wet soil pin**
Signal/peak	10^{-1} mA	10^{-1} mA	10^{-1} mA	10^{-1} mA
Noise	10^{-3} mA	10^{-3} mA	10^{-2} mA	10^{-3} mA

The measurements illustrated in Table 3 had different settings, locations of the grounding pin, and soil conditions compared those illustrated in Table 4. What is known is that the casing and the soil conditions do impact the data output in order of 10 mA in difference and that almost all the signals at the start of the study are less than 10^{-1} mA.

4.2 Camera inspection at test set-up B

During the camera inspection, several camera images were created along with a video to give an overview of the whole pipe. Figure 13 shows a picture of the sewer pipe at test set-up B. According to this inspection, the total length of the sewer pipe is 36,1 meters, and the total length of the pipe of the measurements with the FELL prototype 2.0 is about 24 meters. Appendix C.2 gives a table with all the observations and distances with clock positions, including more pictures of the concrete sewer pipe at test set-up B.

Figure 13: An impression of the sewer pipe at test set-up B, view from starting node

4.3 Soil moisture sensors at test set-up B

This section shows the data output of the soil moisture sensors installed at test set-up B. The sensors monitor the volumetric water content, the temperature in soil and electrical conductivity. They determine VWC using capacitance/frequency-domain technology. They use a thermistor in the centre needle to measure temperature and a stainless-steel electrode array to measure electrical conductivity. The sensors were placed close to the pipe. Port 1 is the sensor placed in the upper layer, about 30 cm under the surface, which is approximately the depth of the grounding pin. Port 2 is inserted at a depth of 133 cm under the surface and port 3 is located 124 cm under the surface level. Figure 14 shows the output of these sensors at different locations during the whole project period at 12 pm. This figure shows a difference in both water content and EC. The EC is the ability of a substance to conduct electricity and can be used to infer the amount of ions that are present in the solution. It is measured in the same way as the FELL prototype 2.0 does, by applying an alternating electrical current to two electrodes and measuring the resistance (conductance) by the cell constant (the ratio of the distance between the electrodes to their area). The results are highly dependent on the weather conditions at a specific time of the day. Port 3 differs the most over the study period, which is the sensor that is placed in the upper layer of the ground. This is also the part of the soil where the grounding pin was inserted during the measurements with the FELL prototype 2.0.

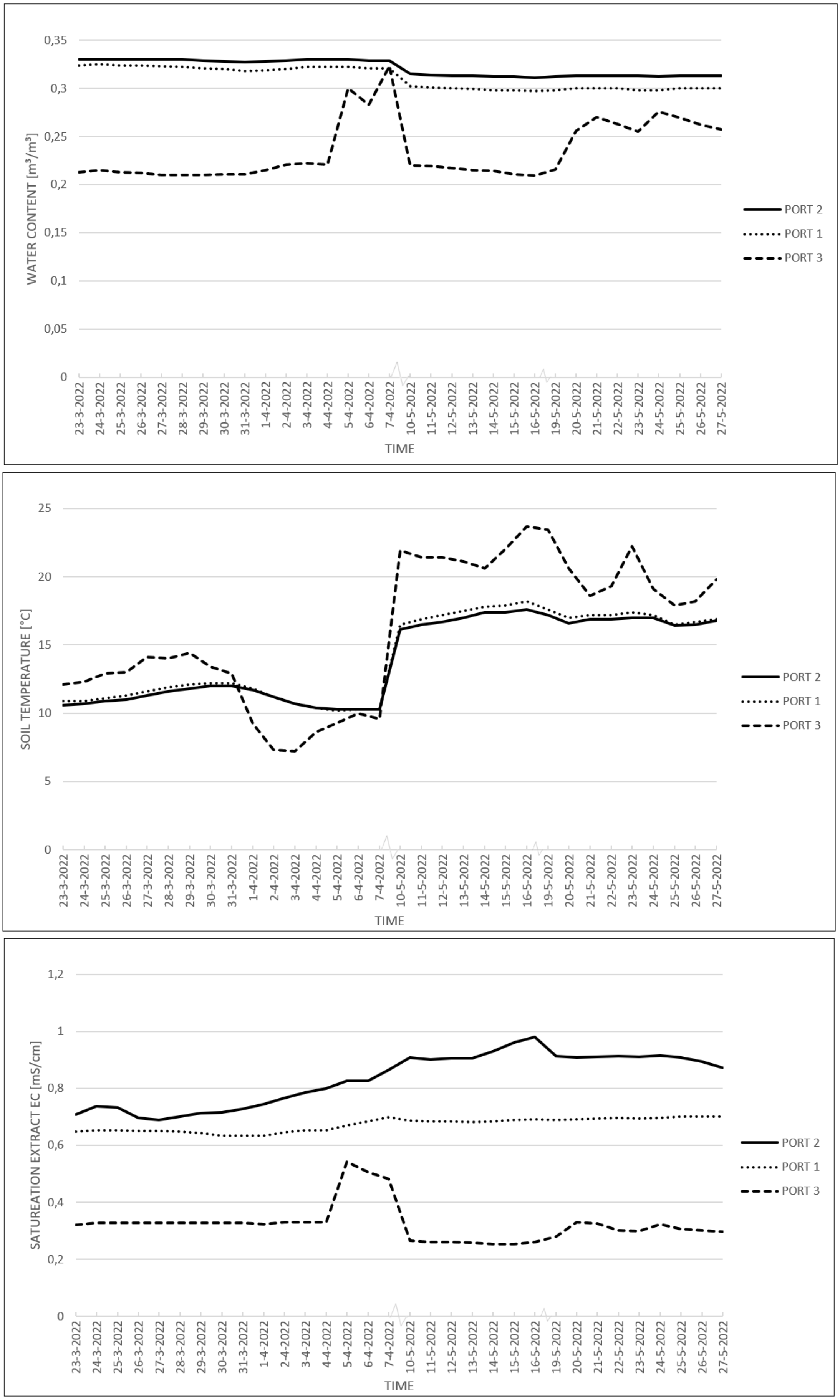


Figure 14: Soil moisture sensor data output over the complete study period at 12 pm

Appendix D.2 shows figures of the data output of the soil moisture sensors for two measuring days. Here, it is clear that the soil moisture content does not differ much over one day but differs enormously over the entire study period of measurements. The difference in soil conditions between the months of April and May must be emphasised.

The above-mentioned sensors supply a 70 MHz oscillating wave to the sensor needles, which charge according to the dielectric of the material. The charge time is proportional to substrate dielectric and substrate VWC. The charge times are measured, and a raw value based on the substrate dielectric permittivity is the output. The raw value is then converted to VWC by a calibration equation specific to the substrate. Besides, the soil temperature and the EC are measured. According to the graphs, the water content is almost the same shape as the EC during the study period, especially at port 3. The soil temperature measured by all sensors rose during the study period. The EC of port 3 decreases, and the water content of port 1 and 2 remain fairly constant during the measurement period. From the 5^{th} to the 7^{th} of April, the soil temperature measured by all sensors is almost the same (±10°C). This differs significantly for all other measurement days. The water content measured by the sensor located in the top layer of the soil is also much higher than on all other measuring days.

4.4 Zero measurements at test set-up B

This section demonstrates the outcomes of the measurements that are performed at test set-up B. Here, the figures are shown of the zero measurements, with the possible influencing factors. The data is normalised to make the graphs easier to comprehend, which is also explained in previous section 4.1. The script used for this normalisation is given in Appendix D.3. It shows how all x- and y-values are horizontally and vertically placed on the same starting point, and then y-limits are set to be able to compare the data output. The figures in this section show measurements over the time when the FELL prototype 2.0 is stationary and over the distance of the entire pipe (±24 meters) when the FELL prototype 2.0 is moving.

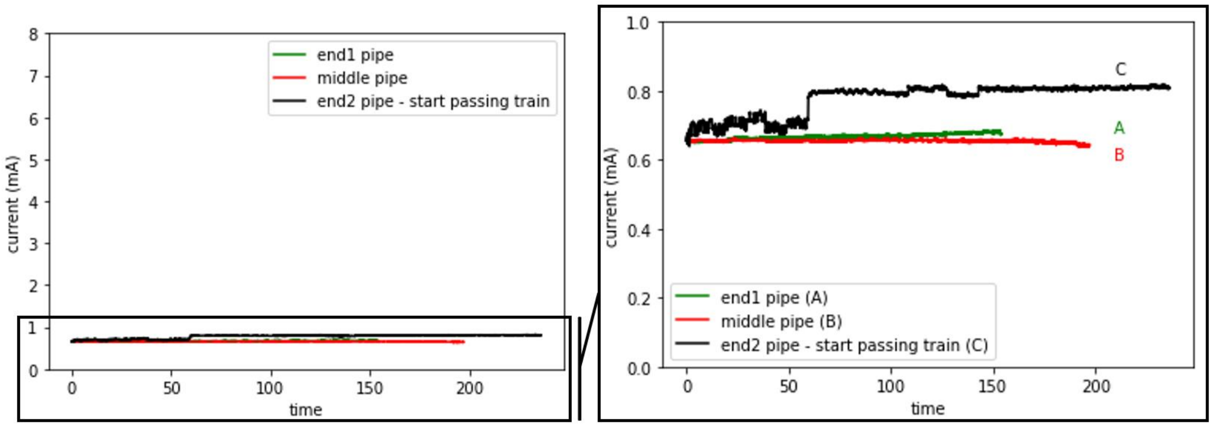


Figure 15: Same settings (400 Hz 10 Ohm 3 V) while the FELL prototype 2.0 is not moving in the sewer pipe

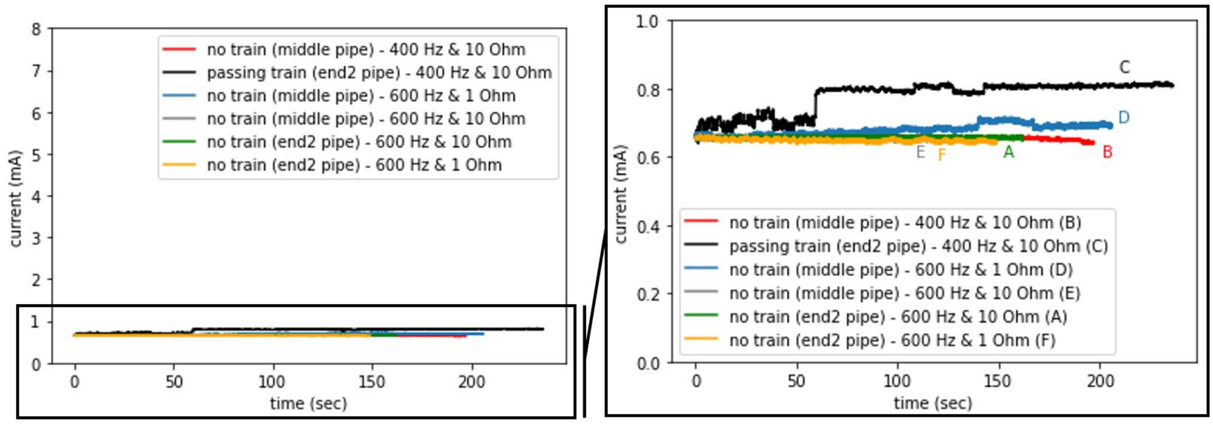


Figure 16: Different settings while the FELL prototype 2.0 is not moving in the sewer pipe

Figures 15 and 16 show the results of the FELL prototype 2.0 while the probe remains still in the sewer pipe at different locations. Figure 15 shows the results during the same settings (400 Hz – 10 Ohm – 3 V). The green line (A) indicates a stationary measurement at the start of the concrete sewer pipe [approximately 1 meter], and the red line (B) implies a stationary measurement at the middle of the concrete sewer pipe [approximately 11 meters]. The black line (C) shows the outcome when at the start of the stationary measurement a train was passing by close to the concrete sewer pipe of test set-up B. This gives a current increase of almost 0.2 mA. For this measurement, the probe was located approximately 23 meters from the starting point, so at the other end of the sewer pipe. The same settings are used in Figure 12 and Figure 15; however, the notable increase displayed in Figure 15 is twice as high as the signal in Figure 12 (when the FELL prototype 2.0 is measuring with its casing). In general, when the probe is stationary, the line is still fairly constant even after the train passes (Figure 15). Only the line does not return to its initial value after the resistance amplitude of almost 0.2 mA, which should be the case. It is also clear that the FELL prototype 2.0 displays more noise once it is used in practice, even if the FELL prototype 2.0 is stationary in the pipe. This noise becomes even greater while the train is passing. The noise that occurs during the passing of the train, appears in the order of a magnitude of almost 0.1 mA. This is in the same order as the leakage in the PVC pipe under ideal conditions with settings of 400 Hz, 10 Ohm, and 3 V. This is an indication that environmental influence may play a role in influencing the outcome of the FELL prototype 2.0. Figure 16 shows constant lines, with noise in order of magnitude of 0.05 mA, for all different settings when the FELL prototype 2.0 is stationary in the concrete sewer pipe at different locations. Table 5 gives an overview of the order of magnitudes of stationary measurements when a train is passing by, as illustrated in Figure 15.

Table 5: The order of magnitude of stationary zero measurements

400 Hz - 10 Ohm Without movement	**Train**	**No train**
Offset	10^{-1} mA	/
Noise	10^{-1} mA	10^{-2} mA

Table 6 provides an overview of the order of magnitudes of zero measurements with and without controlled movement of the probe. This table shows the same results as Figure 17.

Table 6: The order of magnitude of zero measurements with (un)controlled movement

600 Hz - 10 Ohm Concrete pipe ±23m	**Structure (unknown)**	**No structure (high WC)**	**No structure (low WC)**
Signal/peak	/	10^{-2} mA	/
Noise	10^{-4} mA	10^{-3} mA	10^{-2} mA

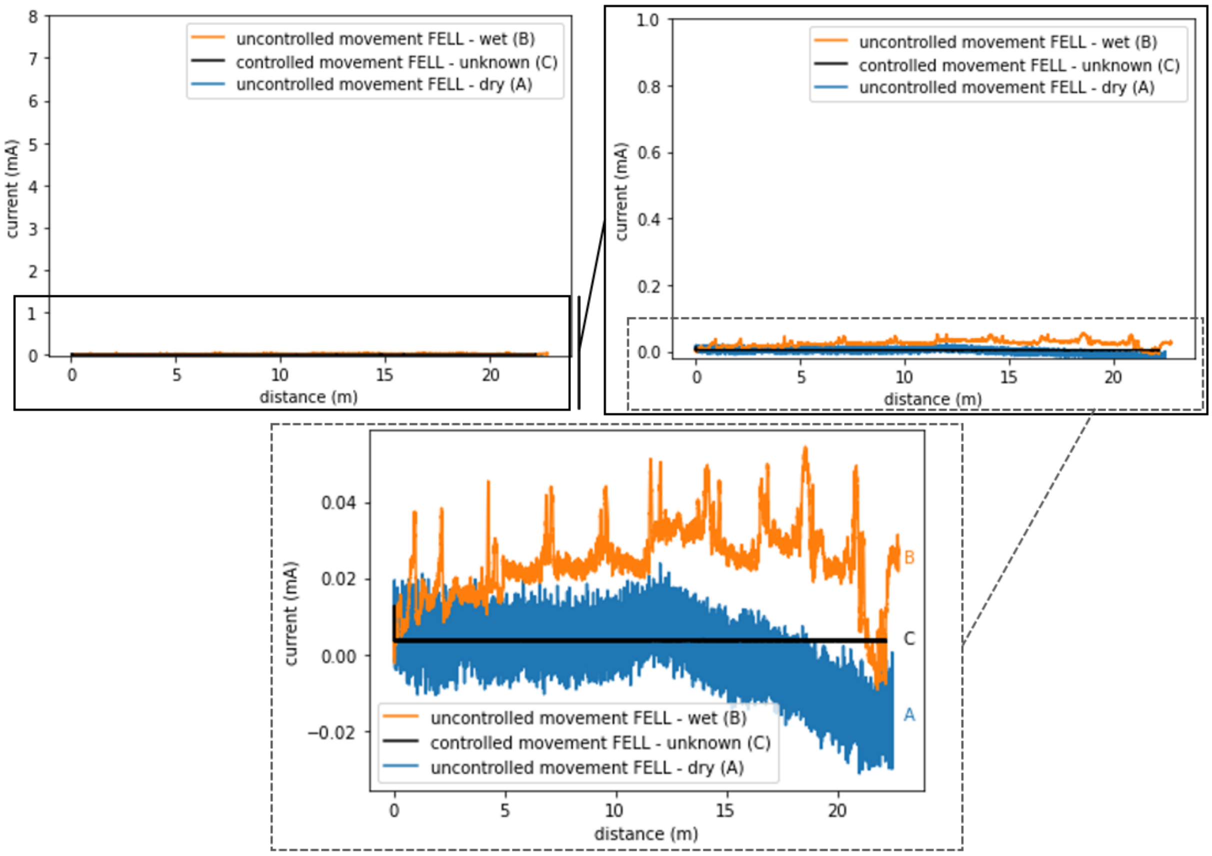


Figure 17: Zero measurements with and without vertical movement (setting: 600 Hz 10 Ohm 3 V)

In Figure 17, the black line (C) demonstrates the ideal conditions of no vertical movement of the FELL prototype 2.0 in the sewer pipe, so a controlled movement. For this measurement, a structure around the probe was placed so that the FELL prototype 2.0 could be pulled accurately through the centre of the sewer pipe. An minimal noise, in order of magnitude of 0.001 mA, was created. The aforementioned noise is 10 times as small as the measurement of the orange line (B) [when the soil moisture conditions were more ideal] and 20 times as small as the measurement of the blue line (A) [when the soil moisture conditions were less ideal]. Unfortunately, it is not known what the soil conditions were at the time of measuring with the controlled movement, as the soil moisture sensors had not been placed yet.

Additionally, it should be noted that the measurement of the orange line (B) has a higher water content in the top layer of the soil, so the EC in this layer is greater too, and the temperatures of the layers of the soil are closer together. The reduction of the noise during that day of measuring may be due to soil moisture conditions, especially when comparing it to the measurement of the blue line (A) when the soil was drier. Hence, the question arises whether this extreme reduction of noise is due to the structure around the probe during the measurements, the soil moisture conditions or the distance to the pipe wall (i.e. the way of moving the probe through the sewer pipe). Notably, there are too many changing factors during the measurements; therefore one component cannot be excluded from another. A possible reason why the measurement of the controlled movement (C) does not show signals and the measurement of uncontrolled movement (B) shows signals/peaks, is the contact between the probe and the joints. During the measurements of the controlled movement (C), there was a structure around the probe, which ensured that the probe was positioned [approximately 175 mm] further away from the wall of the sewer pipe. As a result, there is no contact between the pipe wall and the probe. The orange line (B) shows a measurement that the probe was positioned closer to the sewer pipe wall and it was pulled through the pipe without the structure.

Another explanation could be that the structure around the probe in general had a negative influence on measuring the current.

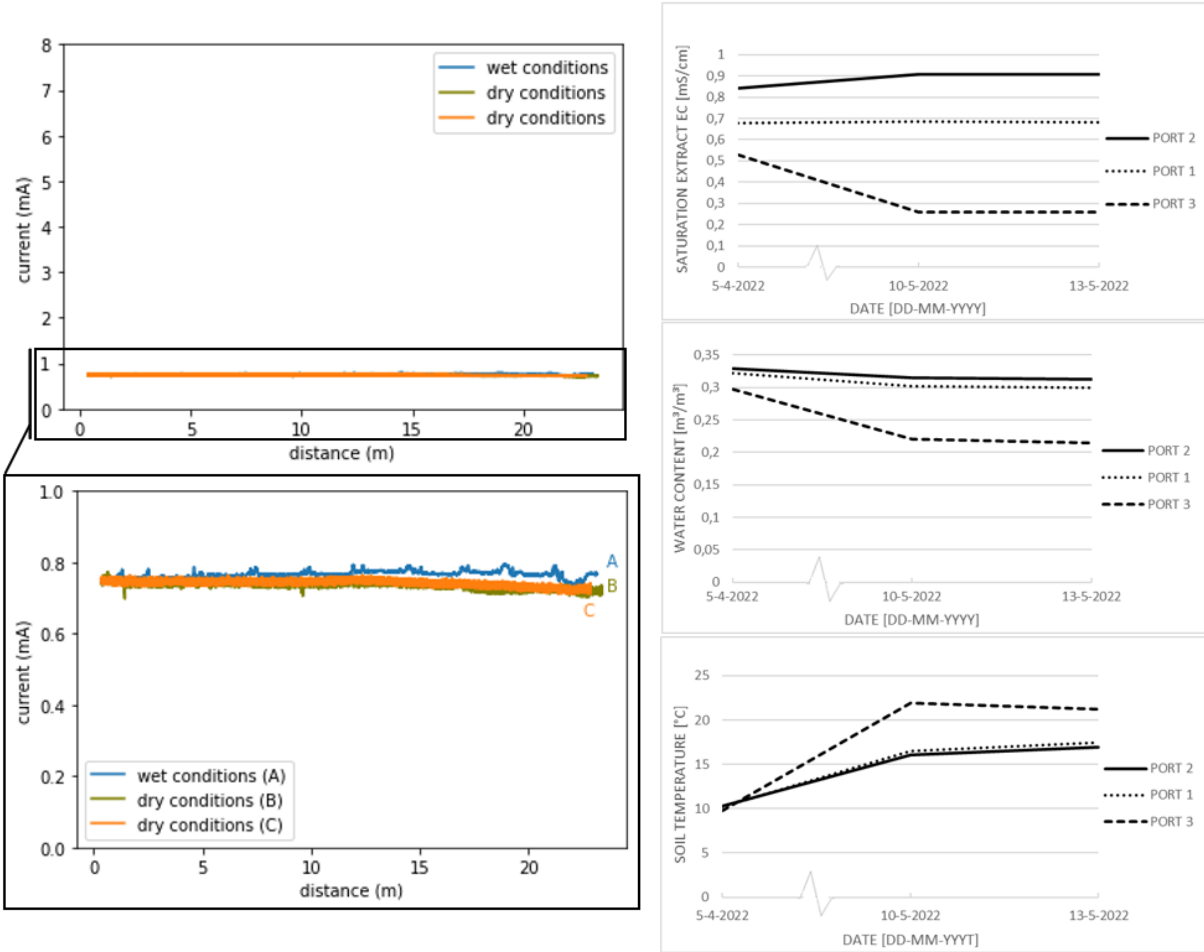


Figure 18: Zero measurements over the total length on different days, with various soil moisture sensor data

Figure 18 indicates three zero measurements performed on different days with the same settings (600 Hz – 10 Ohm – 3 V). The right side of the figure displays information on the soil moisture sensors on the day of measuring. Port 3 is most influenced by weather conditions, which means that it will be affected by different daily soil temperatures and varying water content, which leads to a different saturation extraction. There is a considerable difference between the soil moisture content of the measurements, which is also reflected in the bandwidth of the lines in the graph. The bandwidth of the measurements under dry conditions is less than 0.1 mA by default and the bandwidth of the line of the measurement under wet condition is 0.01 mA and appears to show a pattern. Therefore, measurements with less WC, higher temperature, and less EC in the upper layer of the soil (so the soil around the grounding pin) have an average level surrounded by some white noise. The measurement under a wet conditions gives a smaller white noise with peaks in an order of magnitude of significantly less than 0.1 mA. An explanation of these differences in the bandwidth of the lines is that when the soil is wetter, the bandwidth is smaller, and when the soil is drier, the bandwidth is larger and therefore no longer a signal of leakage is visible. An explanation of the peaks of the measurement under wet conditions can be that these are joints because the joints are located in close proximity to the peaks. Another explanation can be that the probe bounces on these joints, causing a disturbance or peak. This is another indication that errors in the sewer pipe give a signal in the order of 0.05 mA, which is the same as the bandwidth of the measurements in dry conditions. Table 7 demonstrates the order of magnitude of the signals and noise of above-mentioned conditions.

Table 7: The order of magnitude of zero measurements with different top soil conditions

600 Hz - 10 Ohm Concrete pipe ±23m	**Higher EC & WC (top soil)**	**Lower EC & WC (top soil)**
Signal/peak	10^{-2} mA	/
Noise	10^{-4} mA	10^{-2} mA

Table 8 gives the results of the order of magnitude of zero measurements with different settings and almost the same soil moisture content. The same information is illustrated in Figure 19, where it is expressed in the form of a graph with noticeable differences in offsets.

Table 8: The order of magnitude of zero measurements with different settings

Concrete pipe ±23m	**600 Hz - 10 Ohm**	**600 Hz - 1 Ohm**	**400 Hz - 1 Ohm**	**400 Hz - 1 Ohm**
Offset	/	1 mA	/	10^{-2} mA
Noise	10^{-2} mA	10^{-2} mA	10^{-2} mA	10^{-2} mA

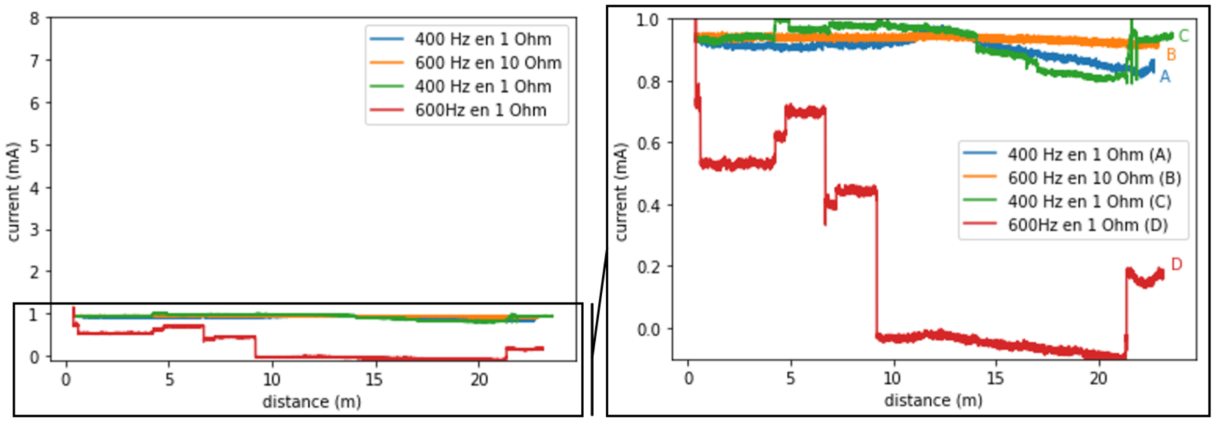


Figure 19: Zero measurements over the total length of the pipe with different settings under dry conditions

Figure 19 shows the same zero measurements with various resistances and frequencies. It seems that resistance of 10 Ohms gives the most stable result. A resistance change mainly ensures the stabilization of the internal measurements of the electronic device (so the capacity of the system), which in the end implies to a more stable current. When the resistance increases, the amount of energy flowing through the entire system decreases, because of the potential difference. When a potential difference is generated, an electric field is formed which in the end creates an electric current. The resistance is then defined as the ratio of the potential difference over the current. There is a possibility that the amount of current is too high and with this certain frequency, causing the offsets in the data output. This may possibly occur during the measurements done with the settings 600 Hz, 1 Ohm and 3 V. The measurements are performed with an AC to prevent a charge build-up at the electrode/medium interface. Perhaps, with these settings and the high resistivity of the soil, the dissipation of the electrical current running through the system results in a high voltage on the grounding system, which again results in a failure of reliable operation of over-current device. It seems that with 1 Ohm, a ten times higher deflection in current and very large jumps occur, after which the line stabilizes again. You would expect the line to come back to the same initial current, which is not the case. It jumps and comes back to new values, which is incomprehensible for now.

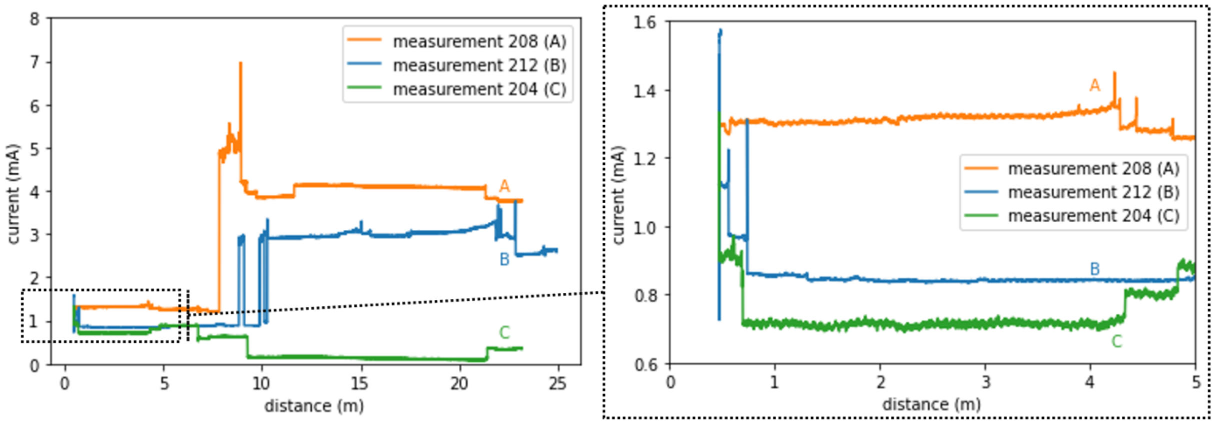


Figure 20: Zero measurements on the same day and conditions over the total length of the pipe and first 5 m (setting: 600 Hz 1 Ohm 3 V)

In consultation, it was decided to continue working with a resistance of 1 Ohm and a frequency of 600 Hz. All follow-up measurements with constructed holes were therefore carried out with this setting. There was a decrease in soil moisture during the project period leading to an increase in soil resistivity, so more voltage was needed through the electric field. It seemed that with 1 Ohm there was more signal, because more current is sent through the system and an error occurred while measuring with 10 Ohm. Subsequently, all measurements were done on this set, but the outliers are many times larger than the signal observed under ideal conditions. Since electronics are built into the probe, there is a risk of overheating as the ventilation may turn out to be too low. If the temperature is too high, the processor turns off the main power and stops heating. This heating is greatest at a high current, which can explain the unexpected data output. Figure 20 shows these outliers of the zero measurements on the same day with the same conditions and settings. The order of magnitude of error is 10^{-4} under ideal circumstances with a PVC pipe above the surface, and when applying the FELL prototype 2.0 in real practice in a concrete sewer pipe below the surface all errors are in order of magnitude of 10^{-2}. By all means, there is uncertainty but these outcomes are too far apart. It is tried to keep a repeatability condition of measurement, but the measurements are not close to each other and not close to the true or reference value. As defended in Clemens et al. (2021), the measurements are imprecise, not true and inaccurate.

The data validation was done manually. The obtained raw data were studied and assessed whether the obtained data are suitable. It should therefore be taken into account that the criteria for accepting/rejecting data points are subjective and lead to a non-reproducible assessment (Clemens et al., 2021). This also applies to the subsequent results, which explore leakages in the concrete pipeline.

4.5 Measurements at test set-up B with leakages

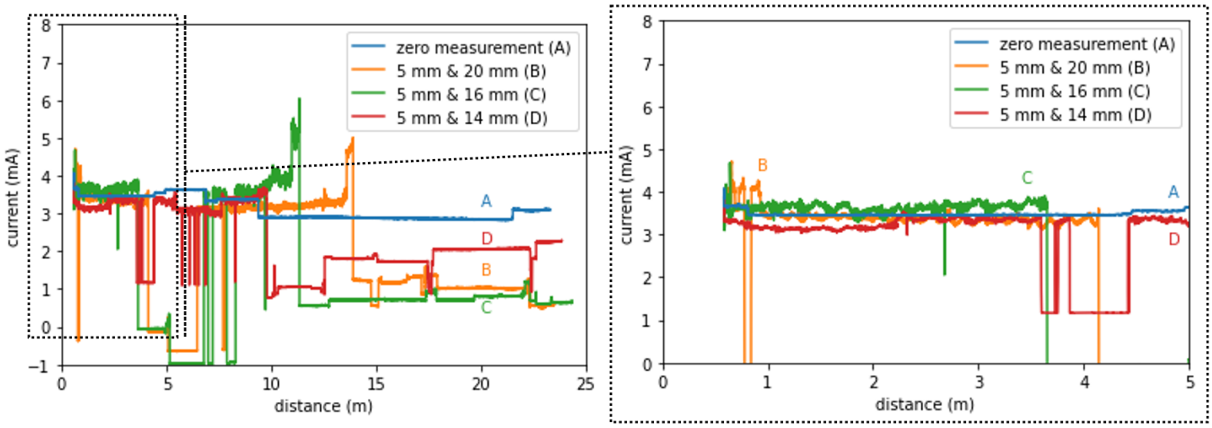


Figure 21: Measurements with hole sizes 0, 14, 16 and 20 mm over the total length and over the first 5 m of the sewer pipe where the holes are located (setting: 600 Hz 1 Ohm 3 V)

Figure 21 shows the measurements performed while leakages are present in hole sizes 14,16 and 20 mm. Appendix D.1 shows the rest of the results, with a zoom-in on the first 5 meters of the concrete sewer pipe where the hole sizes of 4, 5, 6, 8, 10, 12, 14, 16 and 20 mm were located. The data output of the FELL prototype 2.0 is normalised and validated, as mentioned before, to modify the data in such a way that it is clear in what order of magnitude the noise and signal occur. However, there is no signal, there is some initiation noise, but unexplained. There is no trend, and too many random errors occur, which makes these results not analysable. Both at full range and zoomed in on the first 5 meters, the deflection is of the order of magnitude 1 mA, while the signal of the leakage (proven at test set-up A at the start of the project) is of the order of 0.1 mA or less. So, in practice, the results are on the scale of 1 mA, and the signal of the leakage in the PVC pipe above the surface at test set-up A is on a smaller scale of 0.1 mA, meaning that the conditions have to be 'perfect' to find this signal smaller than 0.1 mA. In all measurements that have been performed, there are peaks of the order of 1 mA, and there are offsets of greater than 2 mA. Zoomed into the first 5 meters, there are initiation problems in the order of 2 mA. The measurement noise, even on the stable parts, is greater than 0.1 mA, this part is not even containing a signal. Table 9 illustrates an overview of the results of all the measurements with leakages in the concrete sewer pipe below the surface.

Table 9: The order of magnitude of measurements with leakages

Pin to probe position 1-14 m	**600 Hz - 1 Ohm (leakages)**	
Offset	> 1	mA
Noise	10^{-1}	mA

At last, also a pressure test is performed for different parts of the concrete sewer pipe. Testing the water tightness of the pipes in accordance with the test methods (by means of air and/or water) as indicated in the standard NEN-EN 1610 + NEN 3218 is sporadically applied in the Netherlands. If this test method is used, the water tightness of the entire sewer pipe, possibly including the wells, is tested as a rule. Local testing of connections (or parts of the walls) is usually only performed in sewers accessible to man. For the diameter of the test set-up sewer pipe no standard equipment was available. A prototype joint tester was built to carry out the tests at test set-up B. To determine exact leakage losses, this prototype has been tested several times for repeatability before it was applied in this study as a reference method. In order to be able to make reliable statements about the leakage rate of the hole in the concrete sewer pipe, this method should have been repeated and verified much more often. For now, it can at least be said that the 5 mm hole was actually present and leaking water because significantly more water was lost at the hole than at the other parts of the sewer pipe. It became clear that the leakage rate at the location of the holes was many times greater than at the joint or a part without a leak or joint in the pipe. This proves that there is actually a hole that leaks water at the specific locations mentioned above.

4.6 Control test at test set-up A

The control test in the PVC pipe above the surface indicates as verification whether there is a difference in the performance of the FELL prototype 2.0 for the start and the end of the study. Figures 22 to 25 show the performance of the FELL prototype 2.0 after all the measurements at test set-up B were completed. The set-up is identical to the first measurements with different pin depths at test set-up A, so the same location of the PVC pipe and grounding pin has been used. Different frequencies and resistances were set to verify if this influences the outcomes on a specific day, repeating the same measurement over and over again.

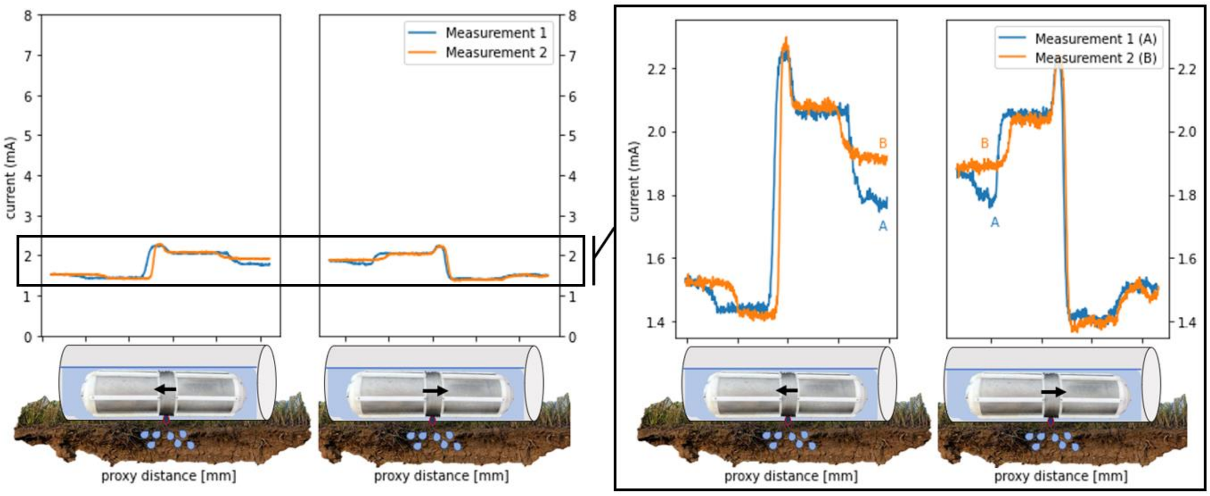


Figure 22: Control test - moving FELL prototype 2.0 in PVC pipe (R-L & L-R) passing the same hole (setting: 600 Hz 10 Ohm 3 V)

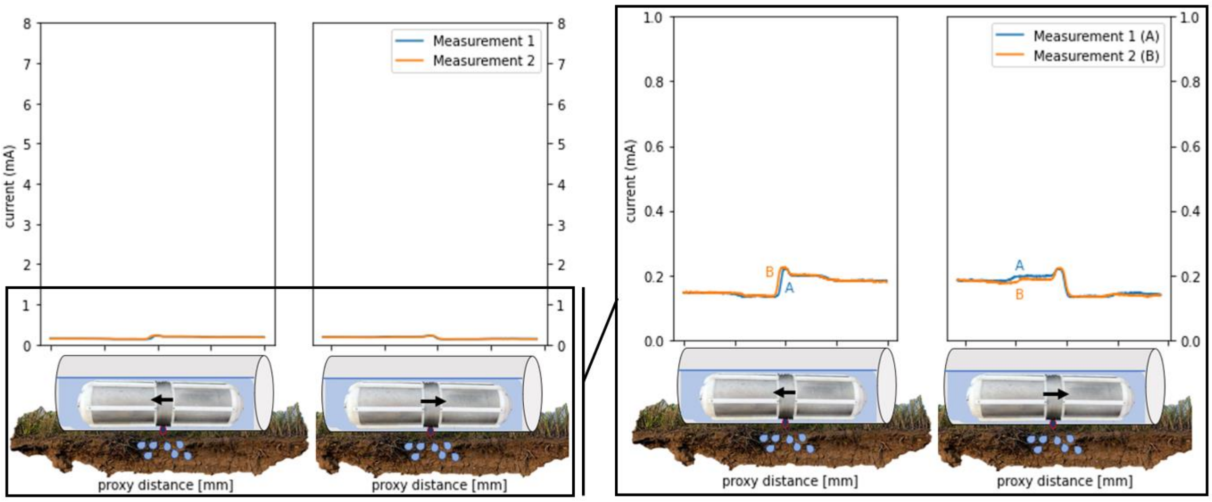


Figure 23: Control test - moving FELL prototype 2.0 in PVC pipe (R-L & L-R) passing the same hole (setting: 600 Hz 1 Ohm 3 V)

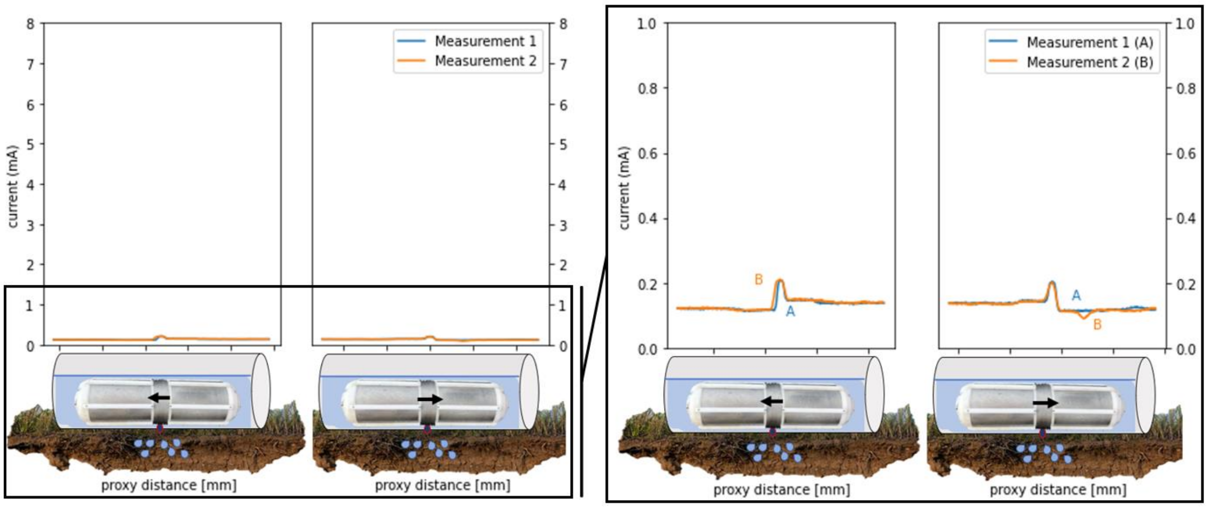


Figure 24: Control test - moving FELL prototype 2.0 in PVC pipe (R-L & L-R) passing the same hole (setting: 400 Hz 1 Ohm 3 V)

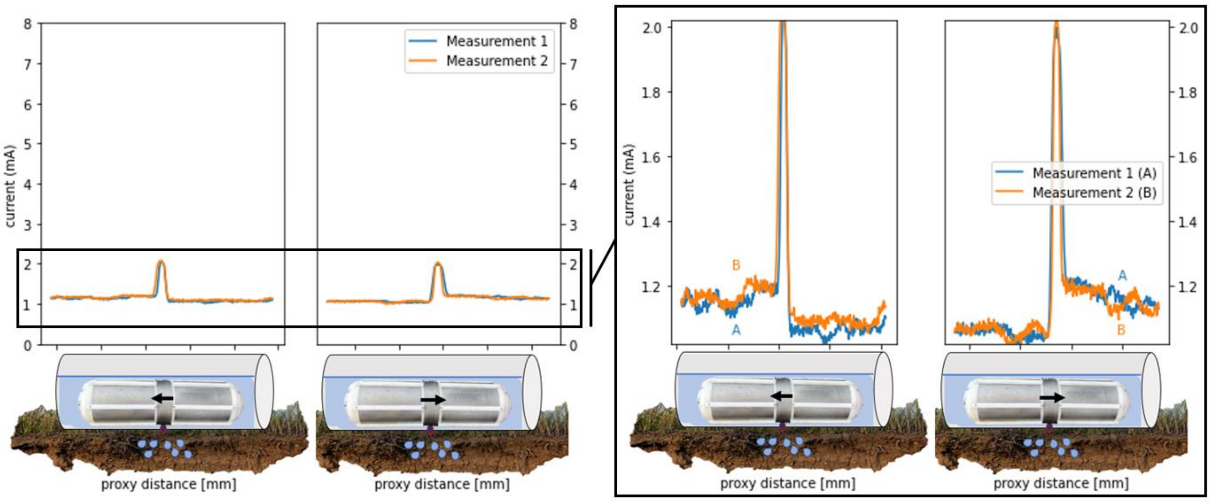


Figure 25: Control test - moving FELL prototype 2.0 in PVC pipe (R-L & L-R) passing the same hole (setting: 400 Hz 10 Ohm 3 V)

From these graphs it is clear that there is an enormous difference in the order of magnitude of the signal as soon as the setting of the FELL prototype 2.0 changes. The entire set-up remains unchanged during the measurements, but the graph shows a great difference in peak/signal. In addition, there is a difference in signal with the measurement of Figure 10, where the set-up and setting of the FELL prototype 2.0 remain the same as the measurement of Figure 22. Figure 26 shows these two measurements with the same settings and set-up; the only difference is that one measurement was taken at the start of the study and the other at the end of the study. The variation could be due to a difference in soil conditions or an internal error in the device itself. What is clear is that the FELL prototype 2.0 was able to detect a hole in a PVC pipe above the surface throughout the research period.

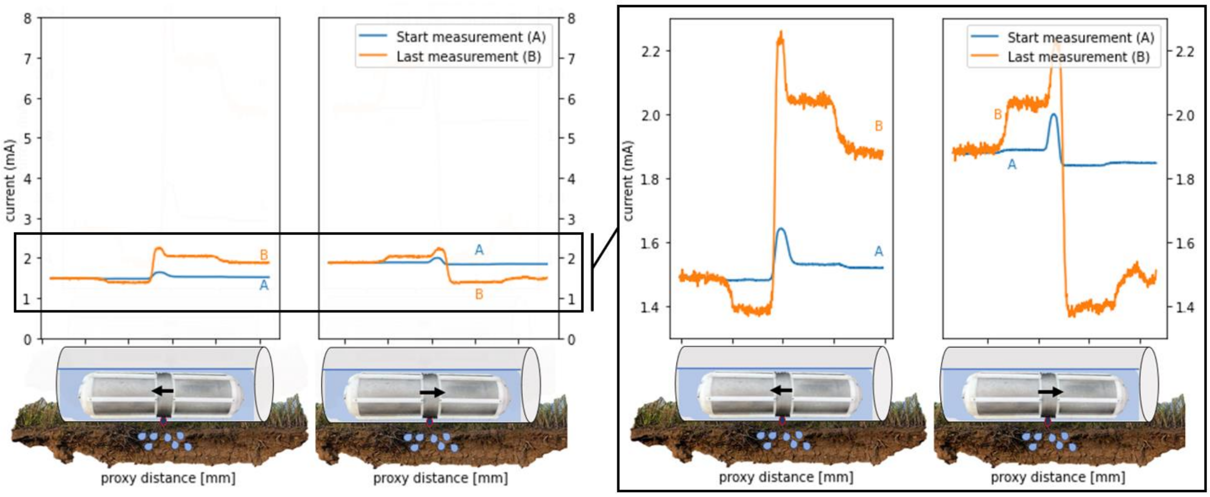


Figure 26: Start and last measurement - moving FELL prototype 2.0 in PVC pipe (R-L & L-R) passing the same hole (setting: 600 Hz 10 Ohm 3 V)

Figure 26 illustrates the difference between the first and the last measurement of the research period with the same settings of the FELL prototype 2.0. Despite the fact that the signal is not exactly the same, this figure illustrates that both at the end and the beginning of the study period, the FELL prototype 2.0 was able to detect a hole in a PVC pipe above the surface. The difference between the start and end measurement is that the soil conditions are different and that the casing is shifted in relation to the probe. The signal and the amount of noise has increased at the end of all the measurements using the same settings of the FELL prototype 2.0. Probably due to the difference in ground conditions, an internal problem in the FELL prototype 2.0 electronics or due to the intensive use of the probe in test set-up A, where the probe collided with the wall of the concrete pipe. Table 10 shows an overview of the order of magnitudes for different settings during the final measurements at test set-up A.

Table 10: The order of magnitude of the control tests with different settings in a PVC pipe above the surface

PVC pipe above the ground	**600 Hz - 10 Ohm**	**600 Hz - 1 Ohm**	**400 Hz - 1 Ohm**	**400 Hz - 10 Ohm**
Signal/peak	1 mA	10^{-1} mA	10^{-1} mA	1 mA
Noise	10^{-2} mA	10^{-3} mA	10^{-3} mA	10^{-1} mA

The FELL prototype 2.0 is a device that provides non-reproducible measurements, where the interpretation of the result depends on too many parameters. An optimal set-up cannot be established because it depends on the circumstances and they are not precisely known. It is, therefore, truly essential to first research the repeatability of the data output of the device at different settings. In order to quickly and reliably detect leaks with the FELL prototype 2.0, it is not feasible to run the experiment numerous times before the correct settings have been found. The data output of the FELL prototype 2.0 consist of too many random measurement errors. The bottom line is that the application of the FELL prototype 2.0 has not yet reached the level of maturity that would allow an objective judgement of its usefulness (Clemens et al., 2021).

5

Discussion

The results indicate that the magnitude of the signal of a leakage, under ideal circumstances, differs enormously from the order of magnitude of the noise and influencing factors in field conditions. An overview of this order of magnitude is given in the tables below.

Table 11: Overview of the range of the order of magnitude in field conditions (test set-up B)

	Field condition concrete sewer pipe below the ground								
	Influencing factors								
	400 Hz 10 Ohm		*600 Hz 10 Ohm*				*600 Hz 1 Ohm*		
	Stationary: no train	**Stationary: train**	**Stationary: no train**	**High EC and WC top soil**	**Low EC and WC top soil**	**Controlled movement**	**Stationary: no train**	**No leakages**	**Leakages**
Outliers/offsets	/ mA	10^{-1} mA	10^{-3} mA	/ mA	/ mA	/ mA	/ mA	>1 mA	>1 mA
Noise/bandwidth	10^{-2} mA	10^{-1} mA	10^{-1} mA	$10^{-4}-10^{-3}$ mA	10^{-2} mA	10^{-4} mA	10^{-2} mA	10^{-2} mA	10^{-1} mA

Table 12: Overview of the range of the order of magnitude of a leakage under ideal conditions (test set-up A)

	Ideal condition PVC pipe above the ground with hole size ±5 mm				
	Start project		End project		
	400 Hz 10 Ohm	*600 Hz 10 Ohm*	*400 Hz 10 Ohm*	*600 Hz 10 Ohm*	*600 Hz 1 Ohm*
Signal/peak	10^{-2} mA	10^{-1} mA	1 mA	1 mA	10^{-1} mA
Noise/bandwidth	10^{-4} mA	10^{-3} mA	10^{-1} mA	10^{-2} mA	10^{-3} mA

From tables 11 and 12, it can be clearly seen that the order of magnitude varies widely. The measurement result of the leakage in a PVC pipe above the surface is a very small signal at the start of the project. Stegeman et al. (2022) demonstrated that a smaller vertical distance to the leak results in an increased current between the central electrode and the grounding pin and a sharper peak in a current-position diagram. This means that as soon as the FELL prototype 2.0 does not move close enough over the hole, even a smaller peak (i.e. signal) might occur, which then disappears under the noise because the noise has a greater range than the 'ideal signal' itself at the start of the project. There were ideal conditions at the start of the project. The signal was less than 10^{-1} mA, between 0.02 mA and 0.15 mA, when the probe was pulled in a controlled manner and using the settings 400&600 Hz and 10 Ohm. Meanwhile, the noise in field conditions was already in the same order of mA's. It is noteworthy that settings make much difference in the output. The results determined at the end of the project show that as the resistance decreases, the signal and noise decrease too. This can be seen in Table 12, where it is visible that at the end of the project, an order of magnitude difference arises between the measurements using 1 Ohm and 10 Ohm. In principle, a specific signal should be measured no matter what settings are used. There is a difference in impedance that exhibits a current difference, where settings can somewhat impact this. However, zero measurements in the PVC pipe above the surface at the end of the project demonstrate a substantial difference once the settings vary.

The wetness of the soil at the grounding pin influences the signal and the noise. The wet soil around the grounding pin gives a signal of 0.2 mA, and the dry soil around the grounding pin shows a signal of 0.1 mA, which is a factor of two in difference. When the soil is dry, the noise is 0.01 mA, and when it is wet, it is 0.002 mA. This is a factor 5 in difference. These measurements were carried out in quick succession and therefore indicate that even a minuscule change occurring over a short period of time has a significant impact on the measured current. So, these results show that the soil conditions around the grounding pin are an essential factor influencing the data output of the FELL prototype 2.0. Also, the concrete pipe below the surface gives a result of 40-50 times larger than that of a hole measured with the FELL prototype 2.0 in a PVC pipe above the surface. To be able to perform measurements in practice and detect leakages, more factors (such as influential components/parameters) should be under control.

The noise generated by a stationary measurement is in the same order as the signal measured at a 5 mm hole in a PVC pipe above the surface. It seems like a passing train has an impact on the measurements because it is in the same order of magnitude as the leakage under ideal conditions. It produces both shocks of 0.1 mA and a jump of 0.2 mA, after which the line runs relatively constant again. However, this line does not return to its original starting value. The measuring method suffers a lot from measuring noise. This noise does not change when different settings are used in the concrete sewer pipe while the probe remains still. At test set-up B, it seems that a difference in resistances and frequencies does not alter the outcome of the FELL prototype 2.0 much when the probe is stationary and placed at a specific location in the concrete sewer pipe below the surface. The end measurements performed in the PVC pipe above the surface, on the other hand, differ greatly in the data output signal and noise once other settings of the device are applied, and the probe is moved back and forth.

The moisture content of the soil does influence the outcome either. The bandwidth of the measurements taken when the soil was drier, is less than 0.1 mA, and the bandwidth of the measurements taken when the soil was wetter seems to have a pattern. The soil moisture of the upper layer of soil is the location where the grounding pin is inserted. As soon as this soil moisture decreases, the noise increases, which means that a signal of 0.1 mA (from the start measuring results at test set-up A) could never be found when the noise of the zero measurements in field conditions (also test set-up B) is in this same order. The measurement where the top soil was wet and the upper layer of the soil, the soil around the pipe, and the water inside the sewer pipe were of the same temperature (±10 °C) show a more detailed outcome. Here, the EC of the soil from the pipeline to the grounding pin is closer together. The white noise is therefore less, and peaks in the order of significantly less than 0.1 mA occur. A possible explanation is that when the measurements are taken, the soil is drier and the temperature of the top layer of the soil (at a depth of the grounding pin) is much higher than the temperature of the soil around the sewer pipe and water inside the sewer pipe. Therefore, the EC of the soil varies from one location to the other, and no longer a clear signal is shown in the data output of the FELL prototype 2.0. There is a narrower bandwidth in the trend line, and some peaks where the joints are located are shown by the measurements taken with a wetted soil. This is another indication that inaccuracies in the pipe give a signal in the order of 10^{-2} mA. So, in perfect conditions, signals can be plotted, which are in an order of 10^{-1} mA, but only when the soil is wet, the FELL prototype 2.0 is pulled at a constant distance between probe and pipe wall (i.e. a controlled movement) and when the settings are used that best suit the ground conditions.

The data validation during field measurements is essential to guarantee consistency and to allow for optimum interpretation of the data. Clemens et al. (2021) described: ‘High-quality data increases the trustworthiness of the derived information enabling informed decisions, but obtaining high-quality data is not an easy task’. The data validation in this study is done manually, so the criteria for accepting and eliminating data are subjective and lead to a non-reproducible analysis. Besides, the results show lots of random errors. These occur due to sensor flaws and defects, their use under unknown conditions, noise in parameters, the actions of the operator, and variable environmental conditions affecting the measurements without being controlled. Even when it is tried to keep a repeatability condition of measurement in this study, the measurements are not close to each other and not close to the true or reference value. Hence, the measurements are imprecise, not stable and inaccurate (Clemens et al., 2021).

5.1 Limitations

To start, all the previous experiments with the FELL prototype 1.0 in the lab were performed in a PVC pipe. Therefore, in this study, it was not taken into account that a difference in result will occur as soon as the material and thickness of the pipe changes. In practice, of course, this affects the data output of the measurements. Dry concrete with nothing but the usual concrete compositions is a reasonably good insulator, as is the case for PVC. The moment the water content in concrete increases, its conductivity increases substantially as well. This is quite different for a PVC pipe, because here no water is stored in the wall of the pipe, and that makes the baseline resistance much more stable. During the study period, the temperature in the layer around the sewer pipe rose. The aforementioned makes the concrete warmer (similar to the water in the pipe), which also results in lower resistance because of the improved conductivity. This can lead to a less straight line in results with the FELL prototype 2.0, which creates more noise. The measurement where peaks occurred at test set-up B are located at the position of the joints. The temperature of the concrete wall was low compared to the other days of measurements were taken on, so there was resistance and, therefore, better data output. With PVC, this may have had no influence because the pipe wall had a high resistance regardless of the temperature.

The pipe's size, shape and temperature can seriously affect its conductivity, i.e. resistance. To know the order of magnitude of a leakage in a concrete pipe, a different set-up should have been devised prior to this research. Also, at set-up B, the soil consists mainly of sand. This is in contrast to the soil type at test set-up A, which consists mainly of clay. At this location where the PVC pipe is placed, there is a ditch, which ensures that the surrounding soil is more wet than the soil in Breda. Resistances of drier fine-grained soils are generally much higher than those of wet coarse-grained soils. The difference in specific resistance between the soil in a dry and a saturated state can be several orders of magnitude. This is not included in the results, even though it does influence the conductivity and resistivity. In addition, the soil consists of several layers with different temperatures, which also affects the strength of the signal from the probe inside the sewer pipe to the grounding pin. This is because the conductivity of the soil also varies greatly from location to location in the soil itself. The measurement taken under wet conditions is supposedly more accurate because less noise occurs in the data output. During this measurement, there was little temperature difference between the soil layers and the water in the sewer pipe. This could also be an explanation for the decrease in noise in the data output. The measurements when the soil was drier have a high-temperature change in soil layers, in addition to the fact that the moisture content was less. These two factors may therefore play a role in the accuracy of the data output and can be observed in the EC of the soil moisture sensors.

On top of all this, there are bound to be changes in conductivity at the location of the leakage due to water flowing in or out of the leakage. This can influence the electrical resistance of the leakage. If water leaks into slightly dry soil, this can cause a gradual increase in current. Furthermore, there can be percolation where continuous water channels are formed, potentially causing discontinuities in the current. This process cannot be measured with the experimental set-up A, with a PVC pipe above the surface. By using the soil moisture sensors placed next to the concrete sewer pipe at test set-up B, it would have been possible to see how much the soil was saturated at the location of the leak if they were placed at the exact right location next to the leak. In this way, it would be possible to investigate if the amount of saturation or water flow has any influence. More water will flow through the hole when the hole has just been made, and the soil around it is not yet saturated. As soon as it is more saturated after making several holes, there will probably be less water flow. This could not be investigated in this study because the soil moisture sensors could not be placed exactly next to the location of the holes.

Furthermore, the grounding pin at test set-up B is located at a different place than at test set-up A, where the PVC pipe was placed above the surface instead of below the surface. At test set-up B, a greater distance is covered where the probe is always at a varying distance from the grounding pin. If the probe is close to the grounding pin it is within 1 metre and if the probe is furthest away from the grounding pin is it approximately 14 metres horizontally. When measuring with the PVC pipe above the surface, there is minimal distance between the probe and the grounding pin. This remains under 1 metre approximately. Another difference in the set-up is the fact that in the concrete sewer pipe below the surface a steel cable is connected to the FELL prototype 2.0, and at test set-up A, this was not the case. These factors could not be included in this study. In general, metallic gates, rails, pipes, or other materials or devices that conduct or transmit electricity, which may stimulate impulsive potentials and provide shirt-circuit paths for the current, can have an effect on resistivity measurements.

In this analysis, a signal in the order of less than 10^{-1} mA has to be detected because, according to the starting tests, in a PVC pipe above the surface, this was the range of the signal. It may be possible that completely different signals appear within a concrete pipe with different soil types, different distances to the grounding pin, different EC through the soil layers and different temperatures of the water inside the pipe and surrounding the soil layers. TRL level 4 was achieved by Stegeman et al. (2022) during lab experiments. So, this study continued at TRL levels 5, 6 and 7, consecutively. In the course of this study, it became clear that level 5 was not yet feasible since the above-mentioned factors had not been sufficiently examined. Before TRL level 6 can be reached, there must be complete clarity about the data output in different conditions and it must be possible to explain the influencing components such as pipe material, soil type, moisture content, grounding pin distance and settings of the FELL prototype 2.0 itself. TRL level 6, where the FELL prototype 2.0 is demonstrated in a relevant test environment (also test set-up B), provides insight into the operation of all components together. But before this level is reached and other environmental factors come into play, such as nearby railways and other traffic, there must first be clarity about the components when a concrete pipe is placed above sandy soil. Ideally, to meet TRL level 7, tests would be carried out on selected operational sewer pipes of the City of Breda to measure the accuracy of quantifying the size and flow of leaks. The results of these tests should then be compared with the results of pressure tests in the same pipes. However, the results showed that TRL level 7 tests were not yet opportune to measure in operational sewer pipes at different locations. It is therefore important for this study to look at the improvements within these TRL levels to ensure that they can be achieved in follow-up research.

To start with, for TRL level 5, it is still unexplained why the results of the FELL prototype 2.0 always start at a different initial current value. In this study, all initial values are set equal, but in reality, each measurement starts at a different current. It is unclear why, but for this study, the data output was adjusted manually to make the results more consistent. In order to proceed to TRL level 6, this issue must first be resolved.

At this moment, the data obtained by the model used in this study is not immediately usable. When recalibration of the initial position is not performed prior to every measurement, the output data plotted against the distance is shifting. The conversion to the correct distance is not working properly. This could be due to the fact that the voltage has to run through a coiled reel; in the model used in this study, the voltages are then converted into meters. However, there were occasional kinks in the cable during the measurements, and the cable no longer rolls perfectly around the reel. This causes the starting point of the x-axis (i.e. distance) to shift each time, while the measurement remains the same. It should therefore be included in the protocol used for FELL prototype 2.0 to recalibrate the initial position prior to each individual measurement, so that each measurement starts at 0 meters. In this study, the output was adjusted manually after each measurement to ensure that the starting distances matched with each other.

A possible influence on the results of the FELL prototype 2.0 is the bad connection of the casing around the probe. At the end of all the measurements, the casing was not completely wrapped around the probe, i.e. by bumping against the sewer pipe wall while pulling the probe from one side to the other. This can cause more significant noise with larger amplitudes. From the results of the measurements with the PVC pipe above the surface, it is shown that performing with and without a casing around the probe had an enormous influence. While zooming into the noise with cover is 0.0002 mA, and the noise without cover is 0.002. There is a difference of factor 10 at test set-up A, where a PVC pipe was located above the surface. This could explain why there is more noise generated as soon as more measurements were performed in a concrete sewer pipe below the surface. In addition, it had been observed that water flows into this casing of the FELL prototype 2.0 as more measurements are performed (this was noticeable due to the weight of the probe). The inflowing water was not demineralized water but ‘dirty’, which can also affect the data output.

When looking at TRL level 6, it is clear that there are influencing factors present while measuring in the concrete test sewer pipe. To my knowledge, these factors are the passing trains, the distance of the grounding pin to the constructed hole, the content of the surrounding soil, the vertical distance of the FELL prototype 2.0 to the pipe wall, the FELL program settings and the casing of the FELL prototype 2.0. In order to explain the extent to which these factors play a role, we must first return to TRL level 5.

What is clear for now is that the noise in the field conditions is in the same order of magnitude as a signal from a constructed hole in a PVC pipe at the start of the project, making it impossible to see the leakage at first glance. The FELL prototype 2.0 is extremely sensitive to its environment, which in the end affects the amount of current measured by the FELL prototype 2.0 and is the reason for not finding a current increase at the location of the leak. The environment and the system generate major resistance differences, which makes the signal analysis very complex. For now, this is the main reason why TRL level 5 cannot be completed.

When the above-mentioned variable factors are dealt with, it is time to go deeper into TRL level 7, which is mainly about improving the practical use of the FELL prototype 2.0. Among other things, the FELL prototype 2.0 broke down several times during the study, which made the FELL prototype 2.0 operationally uncomfortable. Adjustments of the FELL prototype 2.0 were made throughout the study, such as the CTD-Diver installation, new O-rings, an installation of a pressure sensor, a non-return valve in and outside the FELL prototype 2.0, limitation on the pulley, improvement of the cable connection at the probe, a new fuse in the A-D converter, and a reserve printed circuit board. The FELL prototype 2.0 is not yet operational because the internal leakage of the FELL prototype 2.0 is still not fixed. The temporal solution of constructing a pressure sensor in the FELL prototype 2.0 was invented during the project, but the FELL prototype 2.0 itself is still not watertight. Another operational aspect that makes working with the FELL prototype 2.0 uncomfortable is the weight and design of the FELL prototype 2.0. Preparations for the measurements cannot yet be done by one person because it requires too much manpower. The FELL prototype 2.0 is not lightweight and, therefore, challenging to move and lift. It is also not yet possible to pull the FELL prototype 2.0 through the centre of the pipe without the FELL prototype 2.0 floating through the pipe. It would be helpful if the trailer of the FELL prototype 2.0 would be designed in such a way that anyone with a B license could drive it so that the person taking the measurements can also move the FELL prototype 2.0 from location to location. During this study, I was very dependent on other people, which really decelerated the overall project.

What the results do show is that it is possible to detect a leak in a PVC pipe above the surface using the FELL method. However, as discussed before, too many environmental factors and operational aspects influence the output of the FELL prototype 2.0. This first must be filtered out before further measurements can be done in field conditions. Detecting holes in this situation is only possible with an extremely good baseline measurement at a location where there are absolutely no holes under ideal conditions. For now, too much has to change about the conditions and the design of the FELL prototype 2.0 to get the signal of the leakage visible. The sensitivity of the measuring device is still more than an order of magnitude away from the required outcome. As a result, the FELL prototype 2.0 currently has no added value yet compared to other measuring devices in the sewer inspection world. All of the above factors cannot be ruled out in the time frame of this study, but are important for assessing the quality of the FELL prototype 2.0. In short, there are too many variable parameters in the experiments in this study to achieve TRL 7. A return to TRL level 5 is required before looking at the overall picture of the FELL prototype 2.0 as a functioning device in the inspection industry.

6

Conclusion

This research aimed to identify the detection limit and accuracy of quantification of the FELL technique. The functioning of the FELL prototype 2.0 was tested in a relevant environment by means of a PVC pipe above the surface in order to reach TRL level 5. Based on data analysis, including data validation, it can be concluded that the FELL prototype 2.0 is able to detect and locate leakages in order of magnitude of $<10^{-1}$ mA under ideal conditions at the start of the project. At the end of the project, the FELL prototype 2.0 is (up to the present time) able to detect and locate a leakage in a PVC pipe above the surface. The order of magnitude of the signal and the noise differs per used resistance and frequency (i.e. setting of the FELL prototype 2.0). Subsequently, the FELL prototype 2.0 in TRL level 6 was demonstrated in an environment that resembles an operational environment, such as test set-up B, where a concrete sewer pipe was located below the surface. Here, errors caused by environmental and operational factors indicate an order of magnitude of $>10^{-1}$ mA. The signal of leakage under ideal conditions at the start of the project is, therefore, smaller than all other noise in practice. Everything must be tuned in such a way that it is possible to measure within a certainty in an order of 10^{-1} mA. This includes, among other things, the noise and offsets of the passing train, the soil moisture, the vertical movement of the FELL prototype 2.0 inside the pipe during measurement and the location of the grounding pin. By minimizing these influences, a lot of noise is already removed from the output. Owing to the many unchangeable influence factors in this study, no clear signal of the constructed hole sizes can be seen in the output of the data of the concrete pipe at test set-up B. There is some initiation noise, but the rest is unexplained. The output of the measurements with the PVC pipe above the surface at test set-up A, on the other hand, shows that a signal can be visible in more ideal conditions. But, as already mentioned, this signal is many times smaller in order of magnitude, depending on the used setting per soil condition. Therefore it is necessary to go back to TRL level 5 to ensure that certain influencing parameters can be excluded.

This could be done by launching a new test pattern. The new test set-up must ensure that a good baseline measurement is possible and preferably it should have a long concrete pipe placed in the soil, above the surface like the PVC pipe at test set-up A. Another option is to construct the concrete pipe in a closed container with water or different soil types and water content. In this case, it is sufficient to take the same diameter and wall thickness of the pipe as at test set-up B, so that it is easier to relate to each other. It is shown that the settings and the operational side of the FELL prototype 2.0 have to be in a certain way that the output is in a range of 10^{-1} mA stably. Only then may it be possible to see the leakages in the sewer pipe below the surface since a signal of a hole appears to be on the order of less than 0.1 mA at the start of the project. The jumps/offsets have to be solved first because, apparently with certain disturbances, the amount of current measured changes and does not return to its initial value. Moreover, the noise that arises in the practical situation at test set-up B has a magnitude that is too high. To lower this noise, an ideal condition must be created in which the moisture content of the soil is sufficient enough, or extra components should be individually studied and added to the existing model.

Before the FELL prototype 2.0 is able to detect, locate and possibly quantify leakages in practice, as achieved for TRL level 7, the device must undergo several improvements, and the environmental factors must be examined in detail. For example, the FELL prototype 2.0 must be pulled in a stable way through the sewer pipe with also well-conducting soil in all layers, so a high soil water content. The measuring principle works in theory, as proven in the PVC pipe above the surface. However, it is still too fragile in practice to answer part two of the investigation (examine the accuracy of the FELL prototype 2.0). The repeatability of the device is not yet acceptable due to random errors that are present, which makes the measurement imprecise, unstable and inaccurate. The current test set-up B, as described in this research, gives too much (measuring) noise. Only by excluding environmental factors, a definitive answer can be given whether leakages are detected and located in this specific field condition. Quantification of the leaks for this method seems very unlikely for now, because the signal and noise are too dependent on the ground conditions and the settings of the device. The FELL prototype 2.0 is an unusable device; it gives non-reproducible measurements, where the interpretation of the result depends on too many parameters.

7

Recommendations

What should be clear is that more follow-up research needs to be done before an overarching conclusion can be drawn about the functioning of the FELL prototype 2.0. Theoretically, the measuring principle of the FELL prototype 2.0 has been proven to work. In practice, the FELL prototype 2.0 turned out to not yet function sufficiently to switch from TRL level 5 to TRL level 6. It is therefore certain that, before the FELL prototype 2.0 can actually be used in an operational environment (i.e. TRL level 7), numerous improvements need to be implemented.

For now, it is not clear whether the signals of the constructed holes in the field situation at test set-up B are 'hidden' in the output data of the FELL prototype 2.0. The first step to completing TRL level 5, is to determine the order of magnitude of a constructed hole in a concrete pipe. My advice is to set up a new test setup. The principle of this set-up will be the same as test set-up A, but instead of measuring in a PVC pipe, a concrete pipe should be used. At test set-up A the PVC pipe was dug a bit in the ground to make sure the changes in impedances in the electrical circuit were measured. The leakage in the pipe is resulting in in- or exfiltration, which leads to a decrease in impedance, so the current at that location increases. The order of magnitude of the signal of different sizes of holes can be examined by using this set-up with a concrete pipe. In the new set-up, it would be valuable to know more about the soil, by making a 3D image of what is going on underground. In this study, no reproducible results were possible with the current set-ups; whether this is due to the measurement method or to the specific measuring device/sensor is another issue. Reproducible results should be looked for and then further researched. Alternatively, one can measure in a concrete pipe in a closed container filled with either water or different known soil types. For example, measuring in a closed container investigates the order of the signal present under ideal conditions. In this way, it would be sufficient to adjust the soil moisture content in such a way that different conditions can be checked. It can be concluded to what extent the material and thickness of the pipe influence the order of magnitude of the signal. Additionally, at this set-up different hole sizes can be constructed to study the signal present under ideal conditions. Besides, it is unknown how far the FELL prototype 2.0 will still pick up a signal if the distance from the grounding pin to the probe increases. When the set-up is large enough and it is known in what order of magnitude a signal of leakage occurs in the concrete pipe, it is possible to perform measurements with different distances from the grounding pin to the leakage in order to estimate the adverse effect of this component. Because too many variables were involved in the current study, it was complex to fully explore one component at the time. To meet TRL level 5, it is needed to explore the different influencing factors and to see how to remove the noise and offsets that arise as soon as the environment, settings of the FELL prototype 2.0 or operational aspects change. Examples are the presence of the steel cable, the internal leakage, soil conditions and the manner of pulling the FELL prototype 2.0. This is mandatory to do before TRL level 6 starts, where we go back to test set-up B to carry out further measurements under the ground with multiple other varying parameters, like the presence of other cables and pipes under the ground, variation of soil types and water movement in the soil and leak.

For now, the output of the FELL prototype 2.0 is not optimal yet. This is because the distance is not plotted correctly if there is no recalibration of the initial position at the start of the well before each individual measurement. This means that the initial value of the x-axis shifts every time a new measurement is performed. This has to do with the fact that the cable does not coil properly around the reel. In a way, at this point in the model, the output voltages are not properly converted into meters, making the data difficult to compare. It would be appropriate to automatically process this in the model instead of adjusting it afterwards for each measurement. This ultimately also ensures that the leakage can be located in a more accurate way. This should all be done automatically for future use of the FELL prototype 2.0 when TRL level 6 has been met. If the noise has decreased and the environmental factor no longer matters to a certain extent, the amount of water in the sewer pipe can also be looked at. It is interesting to know if the joints can be measured under ideal conditions. Moreover, if there is a variation in signal of the joints when the pipe is completely filled or not and what signal occurs at different water levels in the sewer pipe.

When it is time to switch to TRL level 7, attention should be paid to the operational aspects of the FELL prototype 2.0 and how the FELL prototype 2.0 can be used in an efficient way in practice. For now, the FELL prototype 2.0 is still far from usable in future practise because there are flaws that cause uncomfortable measuring with the device. The internal leak in the FELL prototype 2.0 has to be fixed, and the overall design has to be modified to make it easier to use. It would be helpful to construct some kind of handles on the FELL prototype 2.0, so that it can be placed in the sewer in an ergonomic way. The weight of the FELL prototype 2.0 is also a downside. There is a leak present in the casing of the FELL prototype 2.0; this could not be completely fixed and causes the sewage to flow into the casing, resulting in an even heavier FELL prototype 2.0. Besides, this will affect the output of the FELL prototype 2.0, and it would be interesting to see the difference in the order of magnitude of the signal whether there is water present in the casing of the FELL prototype 2.0 or not. There is a new, as they say, waterproof casing available at the company that constructed the FELL prototype 2.0, with a diameter of almost 600 mm. This was developed to ensure that the FELL prototype 2.0 would measure as close to the wall as possible. In this way, the FELL prototype 2.0 can also remain in the centre of the sewer pipe. This concept and idea are theoretically useful and interesting, but in practice, it will be very difficult to apply. Due to the enormous size of the casing of the FELL prototype 2.0, it is hardly possible to hold and lift it. In addition, in practice, the wall of a sewer pipe will not always be smooth. There will be occasional protruding and/or sagging connections or root ingrowth. These conditions can then cause the device to get stuck in the sewer pipe. In this case, measurements can only be done in sewer pipes where these kinds of conditions are not present, so where the pipe is completely straight from the inside. These ideal conditions are uncommon in the inspection speciality, which means this is a drawback of the design of the FELL prototype 2.0. It would be good to further investigate a better design of the FELL prototype 2.0, where the FELL prototype 2.0 cannot quickly get stuck in the sewer pipe but can still measure close to the pipe wall in a stable manner.

Possible ways to improve the operational aspects of the FELL prototype 2.0 are, for instance, placing wheels around the FELL prototype 2.0 to ensure that manually pulling of the FELL prototype 2.0 from one side to the other side of the sewer can be done in a smoother way. The ideal would be to make this automatic as well, for example by means of a pulley, so that no force has to be exerted at all. The structure that was made and used prior to the FELL prototype 2.0 was a good temporary solution, but in practice, it turned out less operational because it kept getting stuck. The FELL prototype 2.0 was pulled by means of the cable in an incorrect way because the trailer was located at a higher position than the pipe itself. As a result, the pulling system does not work efficiently and the FELL prototype 2.0 got stuck. This issue can be solved by placing a pulley in the pit at the height of the centre of the sewer pipe. Also, in combination with the wheeled structure (or some other way to make the FELL prototype 2.0 slide more easily through the pipe) is used to pull the FELL prototype 2.0 towards the trailer.

The FELL prototype 2.0 will stay in the centre of the sewer pipe and can't get stuck. The winding of the cable around the reel must also be improved since this way of use caused kinks in the cable. This would have probably influenced the output of the data as well. The trailer itself can also use an update. The arrangement of stuff is not efficient enough. At the moment, everything had to be lifted and moved physically, with manpower. It would be more pleasant if a system was constructed so that the FELL prototype 2.0 could be loaded from the trailer into the sewer. To get inspired, take a look at the construction of the trailer and loading system of the camera during camera inspection in the sewer pipe (illustrated in Appendix B.4). The place where the user checks his data and results can also be improved. There is no chair in this cubicle, which makes it hard to evaluate the data in an ergonomic way. When you are measuring all day long, this will cause complaints in the long term. There is also no cleaning system in the trailer, which is necessary in practice as soon as the FELL prototype 2.0 has gone through sewage. For now, measuring without this cleaning system was workable since the water wasn't of terribly bad quality because it wasn't an official sewer. As soon as the device is applied to other sewer pipes that are in use, a cleaning system is mandatory. The latter few improvements are of course, the very last step to meet all TRL levels to market the product, but it is still valuable to mention them in this report. An impression of the improved operators' room and pull system of the FELL prototype 2.0 is illustrated in Figure 27.

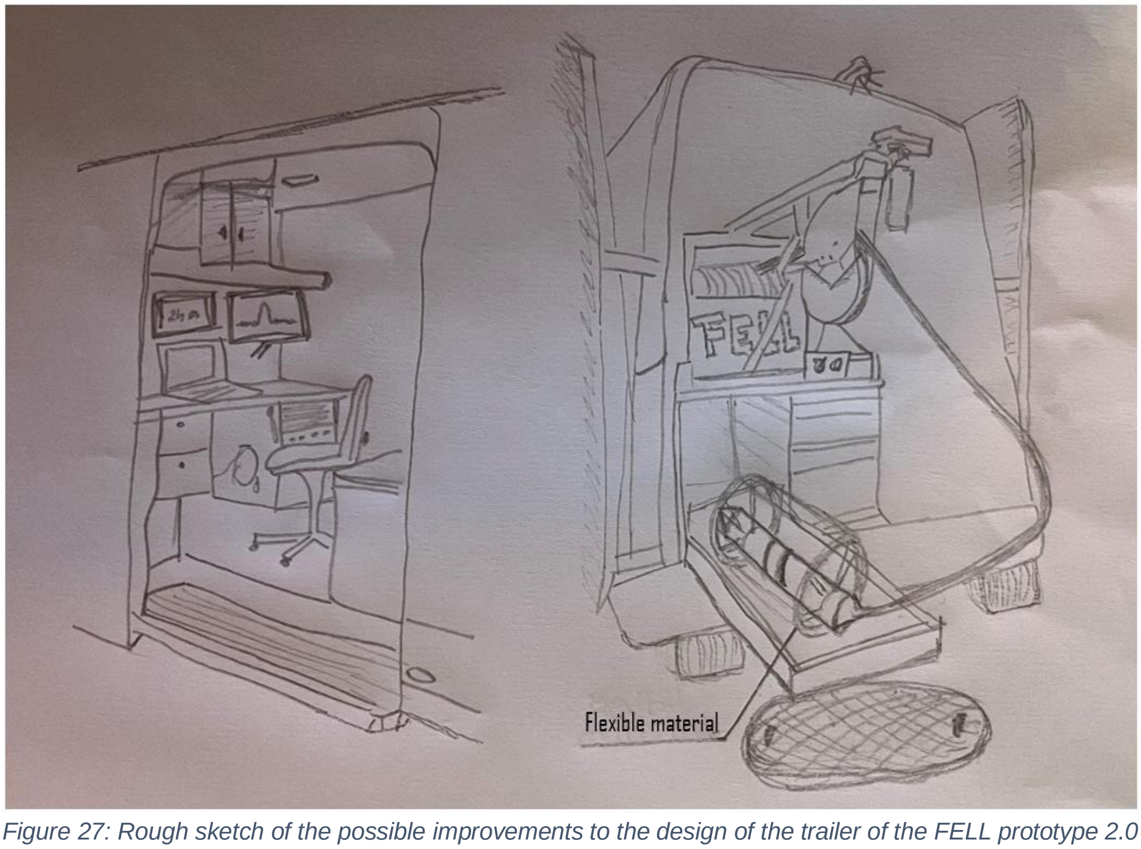


Figure 27: Rough sketch of the possible improvements to the design of the trailer of the FELL prototype 2.0

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A

Appendix A

A.1 Overview of available methods for assessment of infiltration in gravity sewers and exfiltration from gravity sewers and wastewater pressure mains (Langeveld, n.d.)

Listening stick

The easiest method to use is the listening stick. This stick has an earpiece and is used to listen to the sound generated by leaks on e.g. pipe fittings (e.g. (Glisic, 2014)).

Smoke testing

A relatively old, but simple method is the smoke test. Within this method smoke is injected into the sewer at a manhole. If there is a crack or a leak above the waterline the smoke is likely to show up at the surface, see Figure 28.

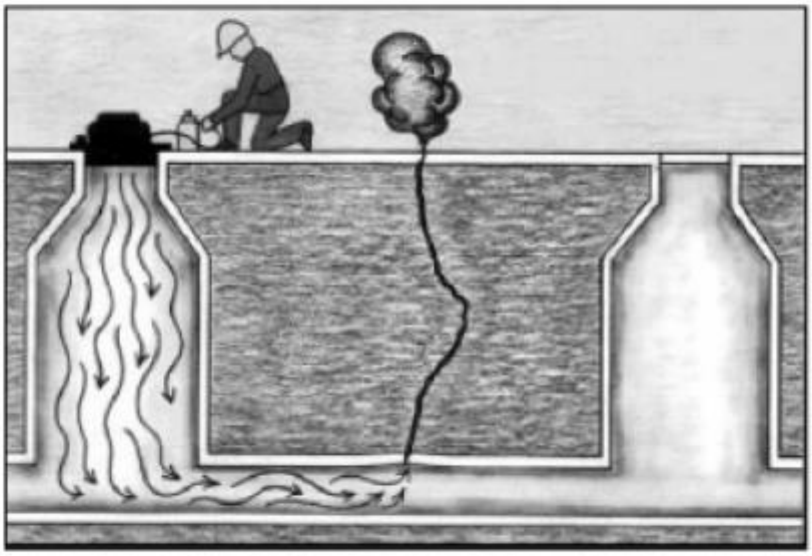


Figure 28: Principle smoke test (Gokhale & Graham, 2004)

Dye testing

Another simple method is the dye test; a dye (e.g. Rhodamine) is injected to the sewer and the dilution of the dye is measured (Gokhale & Graham, 2004).

Flow monitoring

The most simple flow monitoring method is manual survey; during night-time manholes are inspected on the presence of a significant flow (Gokhale & Graham, 2004). Alternatively, this flow could also be measured with two or more discharge meters to estimate the difference. These are however prone to unreliable results under specific circumstances (Smits et al., 2008). Discharge measurements could however also be applied at a larger (e.g. network) scale to set up a water balance. To this end, discharge measurements from pumping stations could be compared to drinking water consumption (e.g. (Korving et al., 2012)).

Pressure test
At a pressure test a (part) of the pipeline is isolated and the internal pressure is set at a specific height. This pressure has to be remained constant for a certain period (e.g. 30 minutes). In this period the variation of the volume of water during the test is measured (NEN-EN 1610:2015). An alternative, a prototype named the double packer, consists of two inflatable discs to seal a pipe section of 80 cm. Freshwater is subsequently added to the interspace. Exfiltration is determined by monitoring the water volume in the interspace (Wolf, 2006).

Tracer methods
In the recent EU Project APUSS (Bertrand-Krajewski et al., 2005) the QUEST (Rieckermann et al., 2005) and the QUEST-C (QUantification of Exfiltration from Sewers using artificial Tracers with Continuous –dosing) methods (Rieckermann et al., 2007) have been developed. In these methods artificial tracers are added to the wastewater flow to quantify exfiltration (i.e. tracer mass loss) in a sewer reach. The APUSS project has also developed various methods to quantify infiltration; one of these methods is the stable isotope method (Kracht et al., 2003). This method compares the isotopic compositions of the foul sewage and the infiltrating water.

Sampling and modelling
Sampling can also be used to trace leakage. Soil samples near the pipeline are collected to be analysed for parameters related to deterioration; e.g. contaminants or moisture content (Liu & Kleiner, 2013). Samples of wastewater and groundwater are analysed for drug remains to calibrate a groundwater flow model to estimate exfiltration (Fenz et al., 2005). More recent research (Guérineau et al., 2014) combined surface water quality modelling with analysis of surface water and sediment samples for E. Coli and wastewater micropollutants to estimate the amount of sewer exfiltration to a surface water canal.

Distributed Temperature Sensing
Distributed Temperature Sensing (DTS) can be used to detect and locate Infiltration (Hoes et al. 2009; Panasiuk et al. 2017; Schilperoort et al. 2013). In this method an in-sewer fiber optic cable is installed to conduct high-frequency temperature measurements. This detects and locates temperature anomalies due to exchange of groundwater with wastewater. To detect and locate exfiltration and leakage from a pressure main, a fiber optic cable could be placed in the pipeline bed to monitor the temperature differences (Nikles et al., 2004).

Time domain reflectometry
Alternatively, time domain reflectometry (TDR) as described by Cataldo et al (2014) could be applied to detect and locate leakage. In this method a sudden voltage increase propagates along a probe or sensing element (e.g. two-wire transmission line) which could be installed at the pipe bedding. The variations of the electrical impedance (which is influenced by leakage) that are encountered along the way are monitored and schematized in a reflectogram.

Infrared thermography
Infrared thermography is a technique that can also be used to detect leaks and voids in the surrounding soil from the ground level (e.g. (Wirahadikusumah et al., 1998)). This method detects temperature differences that occur as a result of the exchange between the pipeline and the surrounding soil. Lepot et al. (2017) demonstrated that infiltration through a crack can be detected using inline infrared thermography.

Smartball
The Smartball is an acoustic concept, it is a ball equipped with acoustic sensors, an accelerometer and a temperature and pressure sensor. The ball is inserted at an upstream part of the pipe system and flows downstream. The location of the ball and possible leaks are determined by analysing the emitted acoustic signal which is collected at ground station (Liu & Kleiner, 2013).

SAHARA
Another acoustic concept is the SAHARA system. In this system a sensor is mounted on an umbilical cable which is inserted at an upstream point of the pipe. The sensor, a hydrophone, is equipped with a small parachute which unfolds in the pipeline to let the sensor flow downstream (see figure 29). The hydrophone can detect the sound which is generated by the leak. Subsequently, the location of the leak is recorded with a receiver at ground level (Rizzo, 2010).

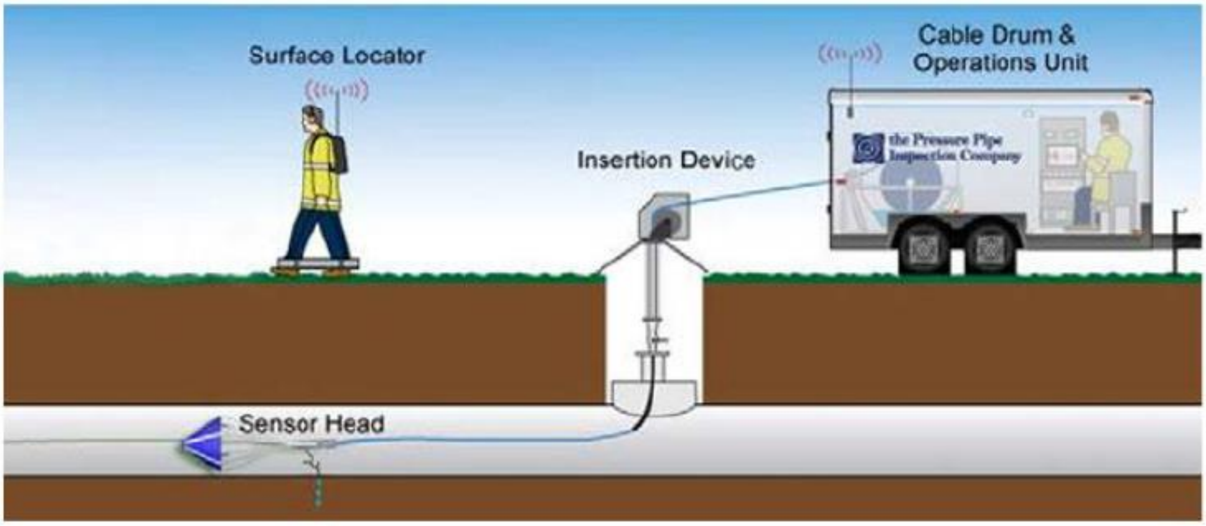


Figure 29: Principle SAHARA system

Leak noise correlation
Leak noise correlators can also be used to detect and locate leakage. Hydrophones up and downstream of a possible leak can be used to listen to noise generated by the leak. Subsequently, the leak position is identified by the delay between the leak noise reaching each monitoring point (Davis et al. 2013; Hao et al. 2012).

Magnetic flux leakage
Alternatively, electromagnetic methods are often used in pressured systems. The Magnetic Flux Leakage method uses large magnets to create a magnetic field around the pipe wall (only ferrous pipes). Defects are detected by measuring changes in the pipe's magnetic permeability (Rizzo, 2010). A magnetic flux leakage unit is usually mounted on a pig (pipeline inspection gauges). These 'intelligent' pigs (see figure 30) are mainly used in e.g. oil pipelines, but currently there is an increasing interest in application in wastewater pressure mains (Driessen, 2016).

Figure 30: Example intelligent PIG (Driessen 2016)

Ground penetrating radar

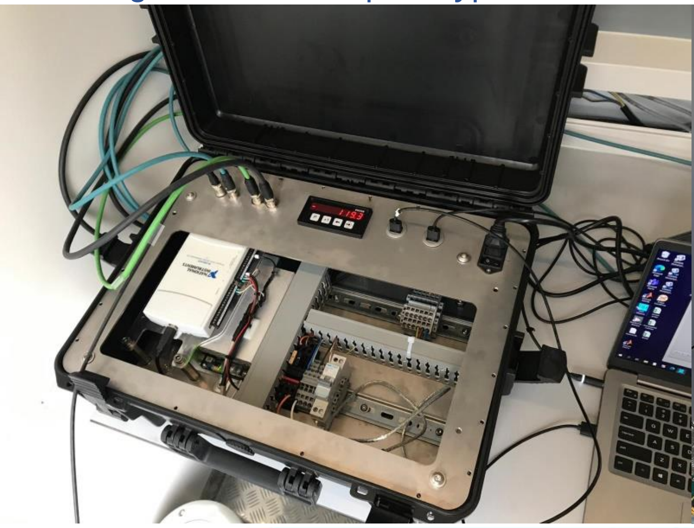
The ground penetrating radar (GPR) is also an electromagnetic method. The GPR uses electromagnetic radiation in the microwave band. With a transmitter microwaves are sent through materials of different dielectric constants to detect reflected signals from the subsurface. To this end, GPR can detect voids in and changes in soil saturation. Traditionally GPR is used from the ground surface towards the soil, but in-pipe GPR systems also exist (Hao et al. 2012; Liu & Kleiner 2013).

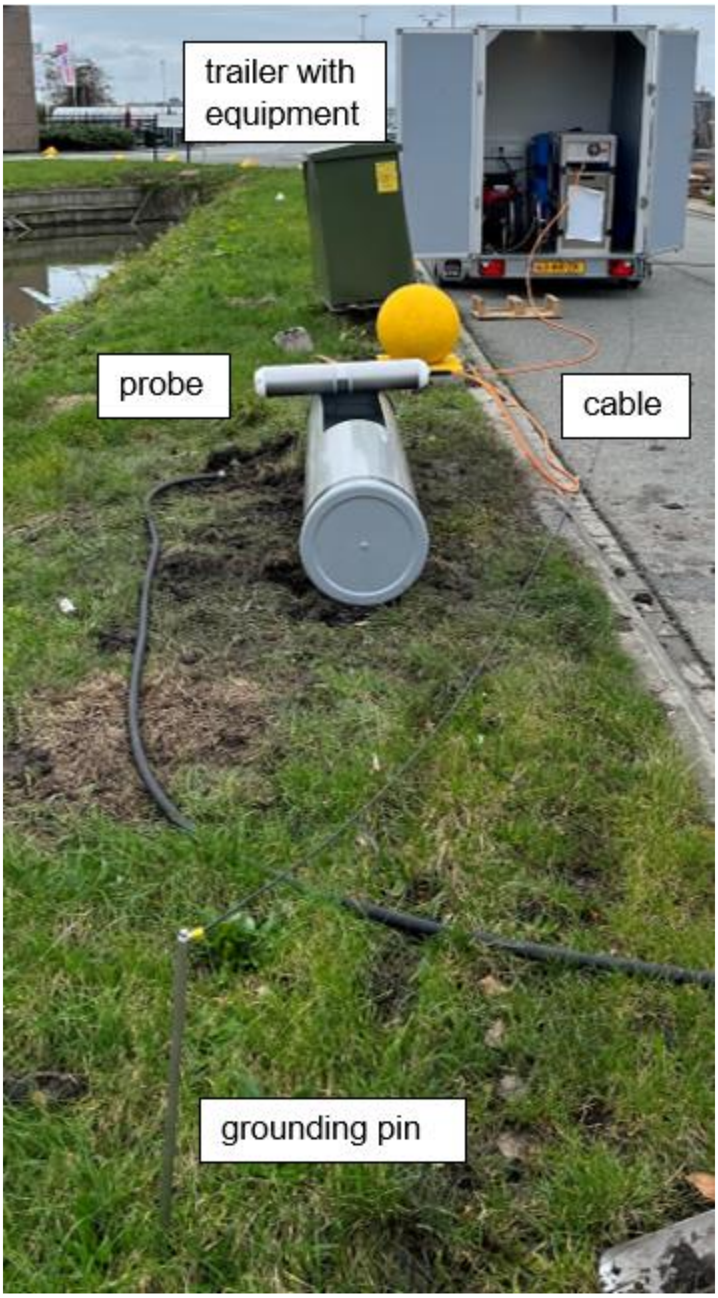
Multi-sensor systems

Multi-sensor systems have also been developed over the years. In the PIRAT system (Kirkham, Kearney & Rogers, 1996) CCTV is combined with sonar and laser profiling on a robot. Sonar is also an acoustic technique and can be used to identify sediments and cracks below the water line. For inspection of e.g. cracks above the waterline laser profiling can be used (Selvakumar et al., 2014). In this technique a ring of light is projected on the sewer wall. A digital camera is used to capture the images of these projections (Clemens et al., 2015).

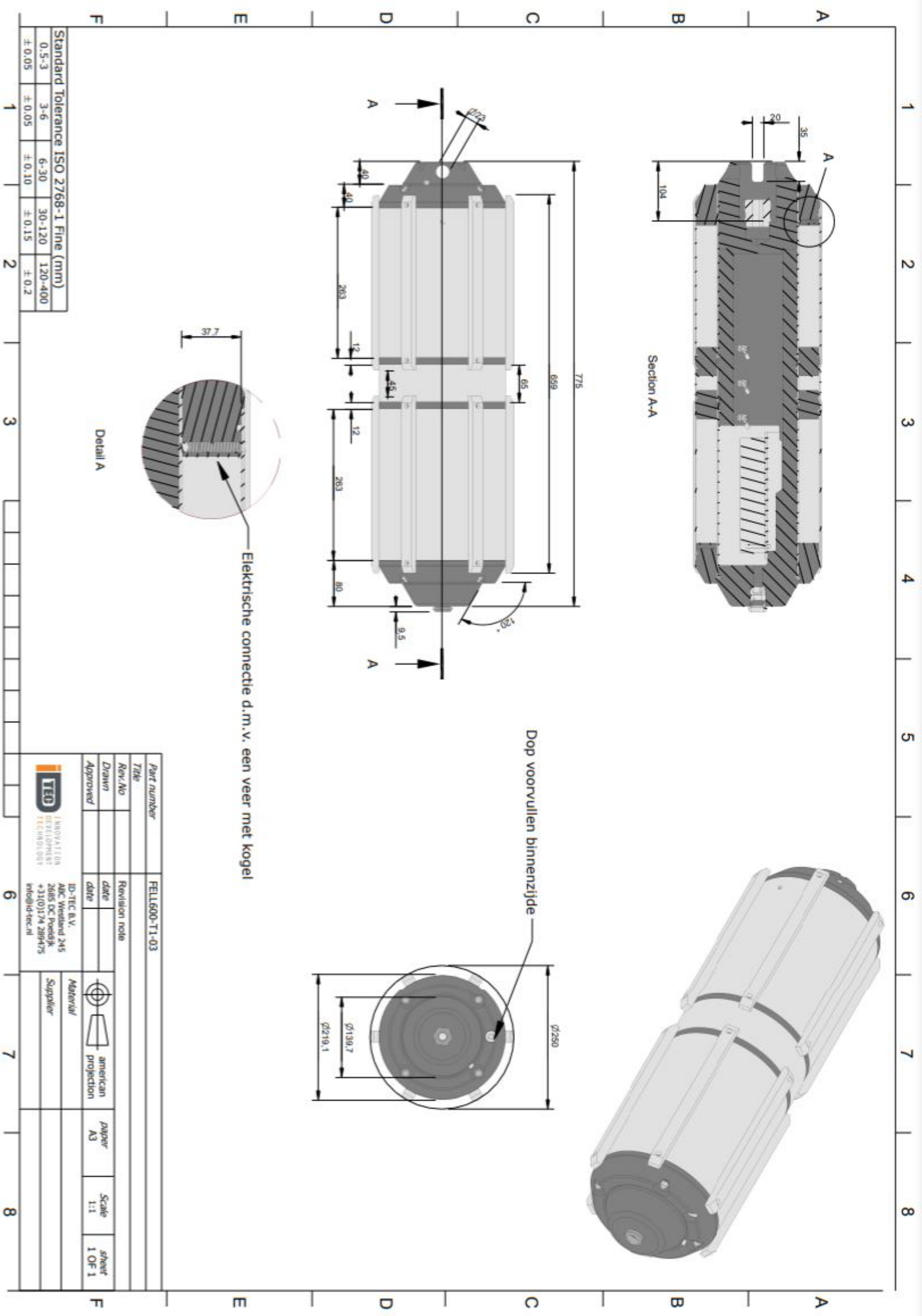
Another example of a multi-sensor system mounted on a pipe robot is SAM (Eiswirth & Heske, 2000). This system uses next to CCTV and a laser scanner a microwave sensor (in-pipe GPR) and radioactive sensors (gamma gamma probe). These sensors are used inspect the soil behind the pipe for changes in moisture content and voids. The gamma gamma probe acts as a source of gamma radiation. The backscatter of gamma rays, together with natural radiation is also recorded with the probe. The backscatter can be related to the density of the surrounding soil. Voids change the density and can therefore be detected (Heske, 2003). The rotatable microwave sensor records changes of the dielectric constant, which are different for dry and wet soil (Munser & Hartrumpf, 2003). Hydrochemical sensors (conductivity, pH and temperature) and an acoustic sensor (Herbst, 2002) are also installed on the robot to detect cracks and voids (based on impact echo). In this method sound waves are introduced in a concrete pipe wall with e.g. an automatic hammer. The sound waves, reflected by internal flaws and external surfaces, are subsequently recorded. A geo-electrical probe is installed on a cable attached to the back of the robot to detect and locate leakages (Wolf, 2003). The latter is now commonly referred to as Focussed Electro Leak Location or electroscanning.

A.2 Design of the FELL prototype 2.0 illustrated by pictures





A.3 Design of the probe



B

Appendix B

B.1 Protocol of the FELL prototype 2.0

1. Open up the manhole covers
2. Make sure the sewer pipe is free of obstacles in advance
3. Make sure the generator is running or there is electricity in surroundings
4. Spray the steelcable through the pipe and connect the probe to the cable
5. Put the plugs in the socket
6. Turn on the black box (PC)
7. Boot the laptop
8. PC: shows position probe [0.1 mm], at the beginning it shows a number, this number can be set to zero by holding the p and enter and releasing the keys
9. After the laptop booted, you log in by filling in the user name ‘Bstegeman1’ and password ‘$opranoS001’
10. Plug in the usb cables, these are labelled so it is known which cable should be left (FELL prototype 2.0) and which cable should be right
11. Push grounding pin into the ground and make sure the soil is wet and everything is connected
12. Make sure to pump the FELL prototype 2.0 before measuring
13. Launch the program ‘Delft measure’ and start with checking the measurement number (write this down so you know which measurement this is)
14. Launch the program ‘FELL control’ to adjust the frequency to 400 or 600 Hz and 3 V (20.000 Hz means that 20.000 times per second is measured)
15. First set the settings to 100 Ohm, on and measuring from the middle electrode and click on ‘send settings to fell’
16. Now again adjust the settings to 10 or 1 Ohm (depending on the moisture in the ground), this is the resistance that should be measured from (the Voltage is measured and the Ampere is calculated)
17. Write down settings in logbook: frequency, measuring resistance, voltage etc.
18. Turn on the conductivity meter
19. Make metadatasheet
20. Settings: adjust frequency, sample rates: 20.000 Hz and 60 seconds, working in the field maybe more minutes
21. Pull the FELL prototype 2.0 by the steelcable to the other side of the pipe
22. Start measuring
23. Pull FELL prototype 2.0 through the pipe towards the trailer
24. Stop measuring
25. Read bin-file (meetdata – users schijf C – bstegeman1 – data – meet2FELL – meet2FELL – alle bestanden)
26. File new – to next measuring
27. Copy meetdata from map meet2FELL3 to opslag2 – matlab – dataPro_NP2
28. Launch Matlab (2019b) and change end and start in code & reading file
29. Run the script (automatically graphs are made)

NOTE: It is important to back-up every day, after performing the experiments

B.2 Protocol of pressure tests for a complete sewer pipe

1. Cleaning pipelines and manholes (wells, gullies and line drainage/trough)
2. Fill sewer pipe with water on the specific place of the defect (time depends on the type of defect)
3. After filling the specific part of the pipe with water, that part of the pipe is pressurized. The overpressure to be applied is at least 1 meter water column, at the top of the highest part of the pipe
4. Stabilize the pipe with water for about 30 minutes
5. Leave the system filled with liquid for 2 hours
6. Check whether the level has changed after 2 hours by reading a measuring rod with a scale in mm (This measuring rod is mounted vertically in the facility to be inspected, with the scale both below and above the water level. At the start and after the measurement time is the value is read and registered on the measuring rod and it is determined whether there is a loss of water)
7. When the level remains the same, it can be assumed that the sewage is tight and there is no infiltration and ex-filtration. And the sewer or valve has been found to be liquid tight.

Explanation joint test

The joint tester that can be used in the second part of this project, is a pressure test system for single joint tests from 200 till 600 mm. First the test will be carried out with air and next the test is carried out with water, where the test sleeves are separately filled. The joint tester contains the control unit Premus 600, supplemented by Kampac test packer according to the diameter of the pipe. Between the sleeves, a Plexiglas is constructed within a camera which records a 360 degrees view. The Kampac packer is connected to a crawler and thereby driven to the joint to be tested. The controls, i.e. the pressure transmitter is connected directly at the packer and operated through a magnetic valve. Therefore, the pressure is measured directly at the packer which results in the fact that the volume of air inside the hose doesn't have any effect on the measurement. The standard that is adhered to during the performance of the pressure test is EN1610 (Rausch, 2021).

The following is stated in the NEN-EN1610 – Construction and testing of drains and sewers (Technical Committee CEN/TC 165, 2013):

‘*14.3 Testing with water (method "W")*
14.3.1 Test pressure
For the pipeline the test pressure shall be the pressure equivalent to or resulting from filling the test section up to the ground level of the downstream or upstream manhole, as appropriate, with a maximum pressure of 50 kPa and a minimum pressure of 10 kPa measured at the invert of the pipe. Unless otherwise specified by the designer, the reference level to test manholes and inspection chambers shall be under cover slabs and adjusting

unit. Test pressure shall correspond to a filling height to 100 mm below this reference level. Higher test pressures may be specified for pipelines which are designed to operate under permanent or temporary surcharge (see EN 805).

14.3.2 Conditioning time

After the pipelines and/or manholes are filled and the required test pressure applied, conditioning may be necessary. NOTE Usually 1 h is sufficient. A longer period can be needed for example for dry climatic conditions in the case of concrete pipes.

14.3.3 Test requirements

Pressure shall be maintained within 1 kPa of the test pressure defined in 14.3.1. The variation of volume of water during the test shall be measured with an accuracy of 0,1 l and recorded with the head of water at the required test pressure. The test requirement is satisfied if the variation of volume of water during the test is not greater than:

- 0,15 l/m2 during 30 min for pipelines;
- 0,20 l/m2 during 30 min for pipelines including manholes;
- 0,40 l/m2 during 30 min for manholes and inspection chambers.

NOTE m2 refers to the wetted internal surface.

14.3.4 Testing time

The testing time shall be (30 ± 1) min. Test may be stopped if the total amount of water allowed to be added during 30 min is exceeded.

14.4 Testing individual joints

Unless otherwise specified, testing of individual joints instead of testing the whole pipeline can be accepted for pipelines, usually larger than DN 1000. For individual pipe joints to be tested, the surface area for test "W" is taken as that represented by 1 m length of pipe, if not otherwise specified. Test requirements shall be as given in 14.3.3 with a test pressure of 50 kPa at the invert of the pipe. The conditions for test "L" shall follow the principles given in 14.2 and be specified individually.’

Used joint test

The above described joint test protocol is used during the measurements at test set-up B. A construction has been designed in collaboration with Vandervalk+degroot, so that joint test can be performed. The set-up looked like the following:

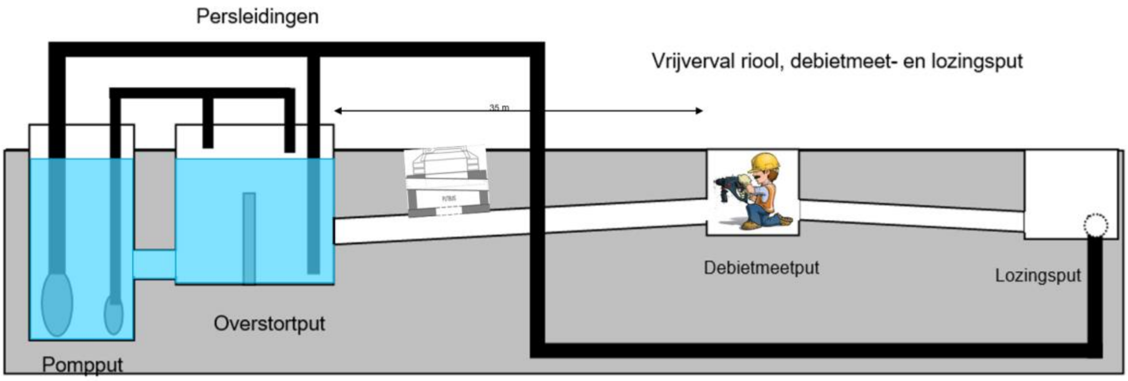
B.3 Logbook used during field experiments

Experiment name + operator	
Street address / location	
Date	
Time	
Soil type	
Groundwater level	
Manhole name start and end	
Intermediate manhole	
Measured distance	
Direction of the probe related to sewer probe	
Percentage of water(flow) in pipe	
Pipe material	
Pipe diameter	
Obstacles in pipe	
Probe size	
Pipe length	
Time it took in total	

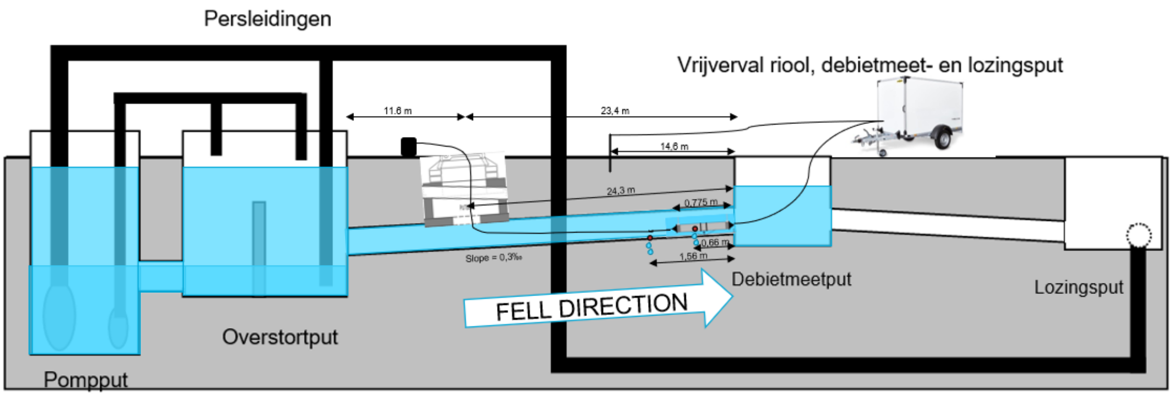
B.4 Impression camera inspection

B.5 Impression of drilling holes and the FELL prototype 2.0 measurement

DRILLING HOLES



FELL MEASUREMENTS



B.6 List of materials

- Trailer with the FELL prototype 2.0, pull rope, cable, PC, laptop, charged generator, and CTD diver
- Concrete drill bits of 4, 5, 6, 8, 10, 12, 14, 16, and 20 mm
- Hook to open the manholes
- Car to move the trailer at the workplace
- Sufficient availability of water to fill the sewer pipe
- Ruler to measure the distance of the grounding pin and constructed holes
- Valve that fits on a 600 mm pipe with a mounted ruler to measure the height of the water level during pressure testing and valves to shut off the pipe
- Camera to inspect sewer in advance
- Phone to set timer and to make light
- Soil moisture sensors (3 TEROS-12 VWC water content sensors, ZL6 Cellular Data Logger and ZENTRA cloud standard plan)

C
Appendix C

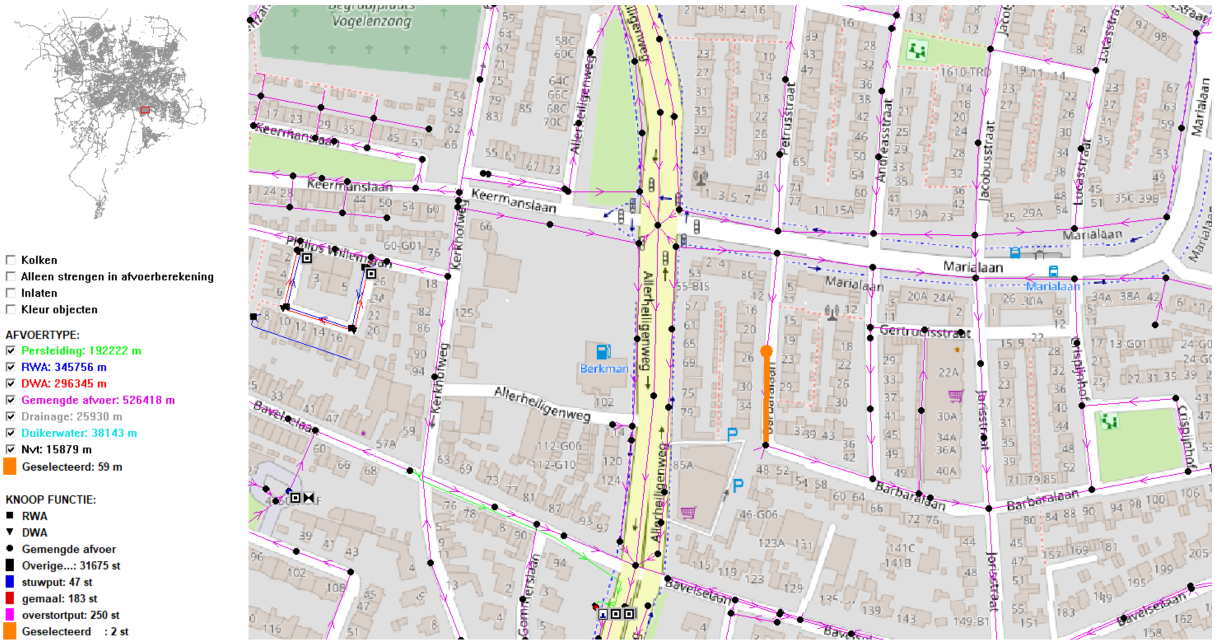
Infiltration class 2 = sweating
Infiltration class 3 = dripping
Infiltration class 4 = inflowing
Infiltration class 5 = gushing in

Note: Below a selection of the most useful concrete pipe in the city Breda, however it is best if PVC sewer pipes with leaks are available for optimal results using the joint tester. Old concrete pipes have a rough pipe wall, which can cause water leakage while performing the joint test. This again causes the joint tester results very inaccurate. During this investigation, only concrete sewer pipes could be used because there were no leaking PVC pipes with recent camera inspection images available to test.

C.1 Selected pipe locations and logbook with aspects

Pipe 0-0879 – 0-0878 Barbaralaan Breda (Ø400 concrete and length 60 meters)

- Construction year 1959
- Inspection date 26-7-2021
- Infiltration classes 2 and 3
- Average groundwater level is 1.5 m



Logbook:

Aspect [0-0879 naar 0-0878]	R	Begin	Eind	Klok	Meting
Begin knooppunt - rioolput	2	0.00	0.00	00-00	0-0878
Gesloten aansluiting - samenkomst	2	2.00	0.00	12-00	125
Waterpeil troebel en verkleurd afvalwater (1E), h<= 10%	2	4.50	60.10	00-00	3
Gesloten aansluiting - samenkomst	2	6.10	0.00	12-00	125
Open vlakke aansluiting - gebeiteld	2	8.30	0.00	12-00	120
Opp.schade (5IA), ontbrekende wand, mechanisch	2	8.30	0.00	12-00	onbekend
Infiltratie (2A.C), doorzwetend via aansluiting	2	8.30	0.00	12-00	onbekend
Infiltratie (2A), doorzwetend	2	11.20	0.00	9-12	onbekend
Gesloten vlakke aansluiting - gebeiteld	2	12.00	0.00	02-00	120
Opp.schade (5IA), ontbrekende wand, mechanisch	2	12.00	0.00	02-00	onbekend
Infiltratie (2A.C), doorzwetend via aansluiting	2	12.00	0.00	02-00	onbekend
Instekende inlaat (2), insteeklengte <= 10% van de leidinghoogte	2	12.00	0.00	02-00	5
Gesloten aansluiting - samenkomst	2	12.60	0.00	12-00	125
Infiltratie (3B.C), druppelend via aansluiting	2	12.60	0.00	12-00	onbekend
Opp.schade (5IA), ontbrekende wand, mechanisch	2	12.60	0.00	12-00	onbekend

Open vlakke aansluiting - gebeiteld	2	13.20	0.00	12-00	120
Opp.schade (5IA), ontbrekende wand, mechanisch	2	13.20	0.00	12-00	onbekend
Defecte aansluiting (2E.A), aansluitende buis geblokkeerd doorsnede <= 10 %	2	13.20	0.00	12-00	onbekend
Infiltratie (2A.C), doorzwetend via aansluiting	2	13.20	0.00	12-00	onbekend
Defecte aansluiting (5A), plaats van de aansluiting onjuist	2	13.20	0.00	12-00	onbekend
Binnendringen van grond (2C) oer, minder dwarsdoorsnede <=5%	2	15.00	0.00	11-01	2
Gesloten aansluiting - samenkomst	2	15.00	0.00	12-00	125
Infiltratie (3B.C), druppelend via aansluiting	2	15.00	0.00	12-00	onbekend
Opp.schade (2CC), zichtbare toeslagstoffen, chemisch boven waterpeil	2	16.60	59.70	08-04	onbekend
Open vlakke aansluiting - gebeiteld	2	17.60	0.00	12-00	120
Opp.schade (5IA), ontbrekende wand, mechanisch	2	17.60	0.00	12-00	onbekend
Infiltratie (2A.C), doorzwetend via aansluiting	2	17.60	0.00	12-00	onbekend
Gesloten aansluiting - samenkomst	2	18.20	0.00	12-00	125
Aangehechte afzettingen (1C) vervuiling, vermindering dwarsdoorsnede <= 5%	2	20.60	59.70	05-07	3
Infiltratie (2A), doorzwetend	2	23.30	0.00	12-12	onbekend
Gesloten vlakke aansluiting - gebeiteld	2	23.60	0.00	12-00	120
Opp.schade (5IA), ontbrekende wand, mechanisch	2	23.60	0.00	12-00	onbekend
Infiltratie (2A.C), doorzwetend via aansluiting	2	23.60	0.00	12-00	onbekend
Open aansluiting - samenkomst	2	24.30	0.00	12-00	120
Open vlakke aansluiting - gebeiteld	2	26.90	0.00	02-00	120
Infiltratie (2A.C), doorzwetend via aansluiting	2	26.90	0.00	02-00	onbekend
Opp.schade (5IA), ontbrekende wand, mechanisch	2	26.90	0.00	11-03	onbekend
Gesloten vlakke aansluiting - gebeiteld	2	28.80	0.00	12-00	160
Opp.schade (5IA), ontbrekende wand, mechanisch	2	28.80	0.00	12-00	onbekend
Open vlakke aansluiting - gebeiteld	2	29.40	0.00	12-00	120
Opp.schade (5IA), ontbrekende wand, mechanisch	2	29.40	0.00	12-00	onbekend
Infiltratie (2A.C), doorzwetend via aansluiting	2	29.40	0.00	12-00	onbekend
Gesloten aansluiting - samenkomst	2	30.40	0.00	12-00	125
Open vlakke aansluiting - gebeiteld	2	31.10	0.00	12-00	120
Opp.schade (5IA), ontbrekende wand, mechanisch	2	31.10	0.00	12-00	onbekend
Infiltratie (2A.C), doorzwetend via aansluiting	2	31.10	0.00	12-00	onbekend
Scheur (4BA), zichtbare scheurlijnen, in langsrichting	2	31.20	0.00	12-00	12
Infiltratie (3B.B), druppelend via breuk	2	31.20	0.00	12-00	onbekend
Open vlakke aansluiting - gebeiteld	2	32.79	0.00	12-00	120
Opp.schade (5IA), ontbrekende wand, mechanisch	2	32.79	0.00	12-00	onbekend
Infiltratie (2A.C), doorzwetend via aansluiting	2	32.79	0.00	12-00	onbekend

Gesloten aansluiting - samenkomst	2	34.00	0.00	12-00	125
Infiltratie (3B.C), druppelend via aansluiting	2	34.00	0.00	12-00	onbekend
Infiltratie (2A), doorzwetend	2	35.29	0.00	12-12	onbekend
Open aansluiting - samenkomst	2	36.29	0.00	12-00	120
Open vlakke aansluiting - gebeiteld	2	37.20	0.00	12-00	120
Opp.schade (5IA), ontbrekende wand, mechanisch	2	37.20	0.00	12-00	onbekend
Infiltratie (2A.C), doorzwetend via aansluiting	2	37.20	0.00	12-00	onbekend
Gesloten vlakke aansluiting - gebeiteld	2	40.50	0.00	12-00	125
Opp.schade (5IA), ontbrekende wand, mechanisch	2	40.50	0.00	12-00	onbekend
Gesloten aansluiting - samenkomst	2	42.60	0.00	12-00	125
Infiltratie (2A.C), doorzwetend via aansluiting	2	42.60	0.00	12-00	onbekend
Open vlakke aansluiting - gebeiteld	2	43.90	0.00	12-00	120
Opp.schade (5IA), ontbrekende wand, mechanisch	2	43.90	0.00	12-00	onbekend
Infiltratie (2A.C), doorzwetend via aansluiting	2	43.90	0.00	12-00	onbekend
Open vlakke aansluiting - gebeiteld	2	45.70	0.00	12-00	125
Opp.schade (5IA), ontbrekende wand, mechanisch	2	45.70	0.00	12-00	onbekend
Gesloten aansluiting - samenkomst	2	48.50	0.00	12-00	125
Waterpeil troebel en verkleurd afvalwater (1E), h<= 10%	2	49.20	0.00	00-00	10
Open vlakke aansluiting - gebeiteld	2	50.10	0.00	12-00	120
Opp.schade (5IA), ontbrekende wand, mechanisch	2	50.10	0.00	12-00	onbekend
Infiltratie (2A.C), doorzwetend via aansluiting	2	50.10	0.00	12-00	onbekend
Scheur (5CB), zichtbaar open scheuren, in de omtrek	2	50.10	0.00	12-12	3
Infiltratie (2A.B), doorzwetend via breuk	2	50.10	0.00	12-12	onbekend
Open vlakke aansluiting - gebeiteld	2	51.10	0.00	12-00	120
Opp.schade (5IA), ontbrekende wand, mechanisch	2	51.10	0.00	12-00	onbekend
Infiltratie (2A.C), doorzwetend via aansluiting	2	51.10	0.00	12-00	onbekend
Open vlakke aansluiting - gebeiteld	2	54.30	0.00	12-00	120
Opp.schade (5IA), ontbrekende wand, mechanisch	2	54.30	0.00	12-00	onbekend
Infiltratie (2A.C), doorzwetend via aansluiting	2	54.30	0.00	12-00	onbekend
Open aansluiting - samenkomst	2	54.60	0.00	12-00	120
Open vlakke aansluiting - gebeiteld	2	56.00	0.00	12-00	120
Opp.schade (5IA), ontbrekende wand, mechanisch	2	56.00	0.00	12-00	onbekend
Infiltratie (2A.C), doorzwetend via aansluiting	2	56.00	0.00	12-00	onbekend
Waterpeil troebel en verkleurd afvalwater (1E), h<= 10%	2	56.10	0.00	00-00	5
Opp.schade (2BA), afbrokkelen van het oppervlak, mechanisch	2	59.70	0.00	11-01	onbekend
Eind knooppunt - rioolput	2	60.10	0.00	00-00	0-0879

Pipe 0-0070 – 0-0063 Valentijnlaan Breda (Ø400 concrete and length 61 meters)

- Construction year 1968
- Inspection date 20-7-2021
- Infiltration classes 2, 3 and 4
- Average groundwater level is 1.5 m

Logbook:

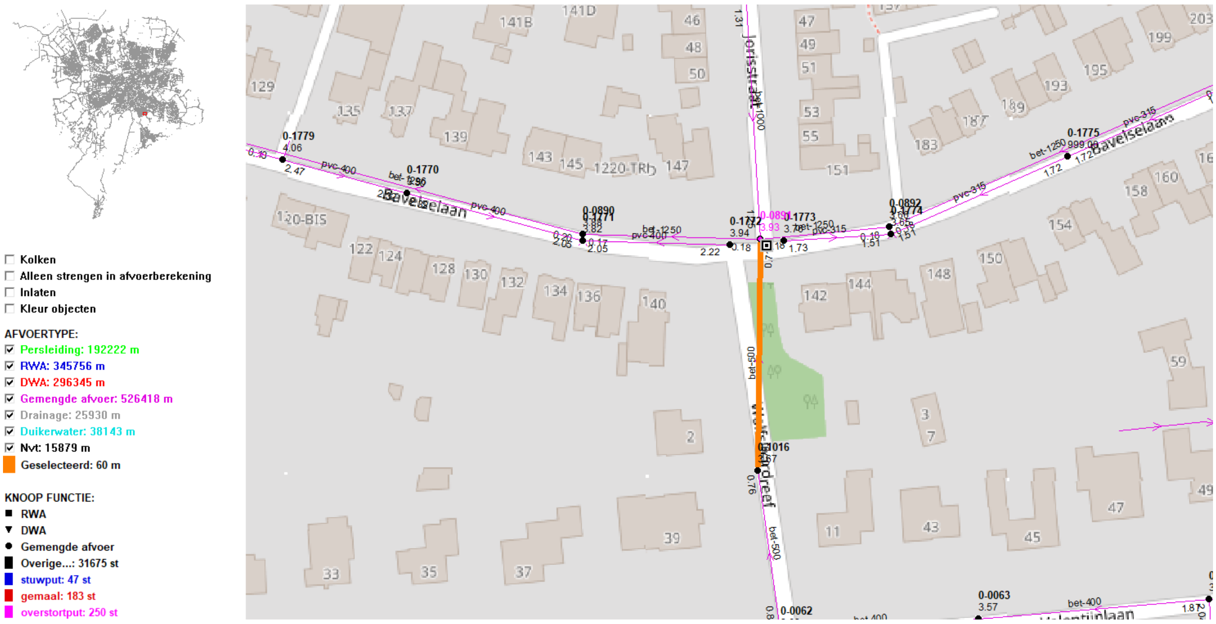
Aspect [0-0070 naar 0-0063]	R	Begin	Eind	Klok	Meting
Begin knooppunt - rioolput	1	0.00	0.00	00-00	0-0070
Waterpeil troebel en verkleurd afvalwater (1E), h<= 10%	1	0.00	61.60	00-00	3
Infiltratie (2A), doorzwetend	1	2.50	0.00	12-12	onbekend
Open vlakke aansluiting - gebeiteld	1	4.00	0.00	12-00	125
Opp.schade (5IA), ontbrekende wand, mechanisch	1	4.00	0.00	12-00	onbekend
Infiltratie (2A.C), doorzwetend via aansluiting	1	4.00	0.00	12-00	onbekend
Infiltratie (2A), doorzwetend	1	6.60	0.00	09-12	onbekend
Open aansluiting - samenkomst	1	7.60	0.00	12-00	125
Open vlakke aansluiting - gebeiteld	1	8.30	0.00	12-00	125
Opp.schade (5IA), ontbrekende wand, mechanisch	1	8.30	0.00	12-00	onbekend
Infiltratie (2A), doorzwetend	1	12.70	0.00	09-03	onbekend
Gesloten aansluiting - samenkomst	1	13.70	0.00	12-00	125
Open vlakke aansluiting - gebeiteld	1	16.50	0.00	12-00	125
Opp.schade (5IA), ontbrekende wand, mechanisch	1	16.50	0.00	12-00	onbekend
Infiltratie (2A.C), doorzwetend via aansluiting	1	16.50	0.00	12-00	onbekend
Open aansluiting - samenkomst	1	19.80	0.00	12-00	125
Scheur (5CB), zichtbaar open scheuren, in de omtrek	1	19.80	0.00	12-12	4
Infiltratie (4C.B), instromend via breuk	1	19.80	0.00	12-12	onbekend
Waterpeil troebel en verkleurd afvalwater (1E), h<= 10%	1	20.30	0.00	00-00	5
Infiltratie (2A), doorzwetend	1	22.70	0.00	12-12	onbekend
Open aansluiting - samenkomst	1	23.50	0.00	12-00	125
Defecte aansluiting (5E), aansluitende buis geblokkeerd	1	23.50	0.00	12-00	onbekend

Infiltratie (3B.C), druppelend via aansluiting	1	23.50	61.60	12-00	onbekend
Opp.schade (5IA), ontbrekende wand, mechanisch	1	23.50	0.00	12-00	onbekend
Open aansluiting - samenkomst	1	25.80	0.00	12-00	125
Infiltratie (2A), doorzwetend	1	26.80	0.00	12-12	onbekend
Waterpeil troebel en verkleurd afvalwater (1E), h<= 10%	1	28.40	0.00	00-00	2
Gesloten aansluiting - samenkomst	1	29.80	0.00	12-00	125
Gesloten aansluiting - samenkomst	1	33.90	0.00	12-00	125
Open vlakke aansluiting - gebeiteld	1	35.79	0.00	12-00	120
Opp.schade (5IA), ontbrekende wand, mechanisch	1	35.79	0.00	12-00	onbekend
Scheur (4BB), zichtbare scheurlijnen, in de omtrek	1	35.79	0.00	12-12	1
Infiltratie (2A.B), doorzwetend via breuk	1	35.79	0.00	12-12	onbekend
Opp.schade (5IA), ontbrekende wand, mechanisch	1	36.40	0.00	12-00	onbekend
Scheur (4BA), zichtbare scheurlijnen, in langsrichting	1	36.60	0.00	12-00	1
Infiltratie (2A.B), doorzwetend via breuk	1	36.60	0.00	12-00	onbekend
Waterpeil troebel en verkleurd afvalwater (1E), h<= 10%	1	36.90	0.00	00-00	5
Gesloten aansluiting - samenkomst	1	37.90	0.00	12-00	125
Verplaatste verbinding (1C), hoekverdraaiing, > 0 en <= 2 graden	1	40.90	0.00	12-00	1
Gesloten aansluiting - samenkomst	1	41.80	0.00	12-00	125
Open aansluiting - samenkomst	1	43.90	0.00	12-00	125
Waterpeil troebel en verkleurd afvalwater (1E), h<= 10%	1	44.80	0.00	00-00	2
Gesloten aansluiting - samenkomst	1	48.00	0.00	12-00	125
Infiltratie (2A.C), doorzwetend via aansluiting	1	48.00	0.00	12-00	onbekend
Infiltratie (2A), doorzwetend	1	51.00	0.00	12-12	onbekend
Gesloten aansluiting - samenkomst	1	52.00	0.00	12-00	125
Infiltratie (2A.C), doorzwetend via aansluiting	1	52.00	0.00	12-00	onbekend
Gesloten aansluiting - samenkomst	1	56.10	0.00	12-00	125
Infiltratie (2A.C), doorzwetend via aansluiting	1	56.10	0.00	12-00	onbekend
Open vlakke aansluiting - gebeiteld	1	56.50	0.00	12-00	125
Defecte aansluiting (4E.C), aansluitende buis geblokkeerd 25% < doorsnede <= 50%	1	56.50	0.00	12-00	onbekend
Opp.schade (5IA), ontbrekende wand, mechanisch	1	56.50	0.00	12-00	onbekend
Infiltratie (2A), doorzwetend	1	57.10	0.00	12-12	onbekend
Eind knooppunt - rioolput	1	61.60	0.00	00-00	0-0063

Pipe 0-1016 – 0-0891 Wolfslaardreef Breda (Ø500 concrete and length 61 meters)

- Construction year 1960
- Inspection date 19-7-2021

- Infiltration classes 2 and 3
- Average groundwater level is 1.5 m



Logbook:

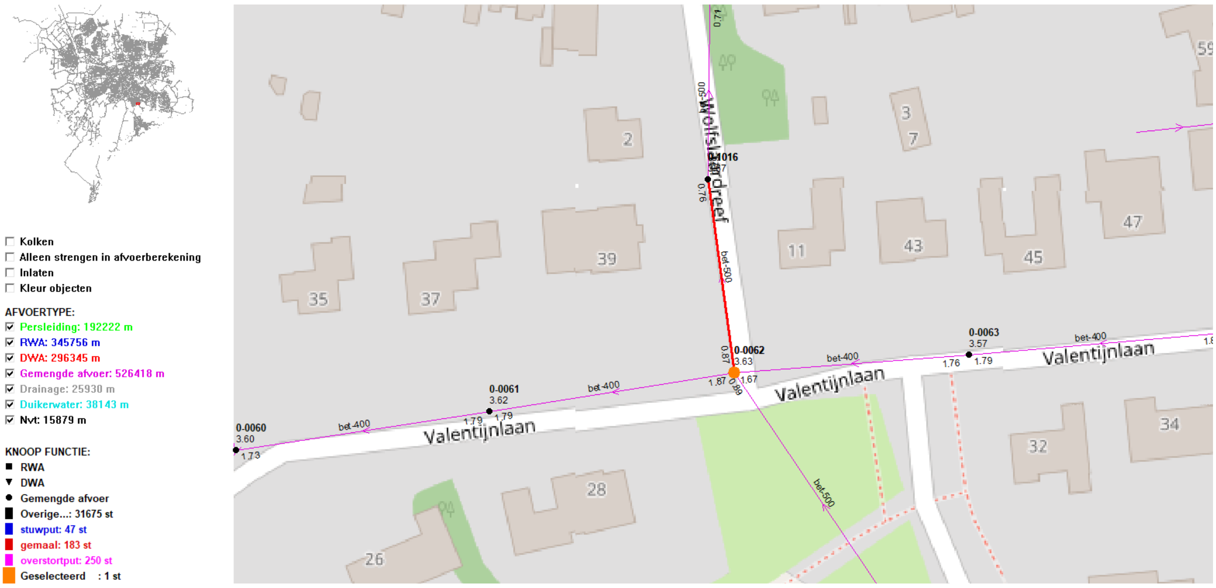
Aspect	R	Begin	Eind	Klok	Meting
Begin knooppunt - rioolput	1	0.00	0.00	00-00	0-1016
Infiltratie (3B.H), druppelend via put	1	0.00	0.00	12-12	onbekend
Waterpeil troebel en verkleurd afvalwater (1E), h<= 10%	1	0.50	61.30	00-00	5
Aangehechte afzettingen (1C) vervuiling, vermindering dwarsdoorsnede <= 5%	1	0.50	61.30	08-04	2
Opp.schade (2BA), afbrokkelen van het oppervlak, mechanisch	1	2.40	0.00	11-01	onbekend
Infiltratie (2A), doorzwetend	1	2.40	0.00	12-12	onbekend
Binnendringen van grond (2C) oer, minder dwarsdoorsnede <=5%	1	3.40	0.00	11-01	2
Gesloten aansluiting - samenkomst	1	3.40	0.00	12-00	125
Infiltratie (3B.C), druppelend via aansluiting	1	3.40	0.00	12-00	onbekend
Waterpeil troebel en verkleurd afvalwater (1E), h<= 10%	1	9.60	0.00	00-00	10
Open aansluiting - samenkomst	1	9.60	0.00	12-00	125
Defecte aansluiting (5D), aansluitende buis beschadigd	1	9.60	0.00	12-00	onbekend
Infiltratie (2A), doorzwetend	1	10.70	0.00	06-12	onbekend
Waterpeil troebel en verkleurd afvalwater (2E.D), 10% < h <= 25% verzakking	1	14.40	0.00	00-00	15
PLaatselijke reparatie - plaatselijke lining	1	14.40	14.80	12-12	onbekend
Binnendringen van grond (2C) oer, minder dwarsdoorsnede <=5%	1	15.50	0.00	11-01	2
Gesloten aansluiting - samenkomst	1	15.50	0.00	12-00	125
Infiltratie (3B.C), druppelend via aansluiting	1	15.50	0.00	12-00	onbekend
Infiltratie (2A), doorzwetend	1	16.80	0.00	12-12	onbekend
Infiltratie (2A), doorzwetend	1	18.80	0.00	12-12	onbekend
Binnendringen van grond (2C) oer, minder dwarsdoorsnede <=5%	1	21.70	0.00	08-04	2
Gesloten aansluiting - samenkomst	1	21.70	0.00	12-00	125
Infiltratie (3B.C), druppelend via aansluiting	1	21.70	0.00	12-00	onbekend
Waterpeil troebel en verkleurd afvalwater (1E.D), h<= 10% verzakking	1	22.60	0.00	00-00	5
Binnendringen van grond (2C) oer, minder dwarsdoorsnede <=5%	1	23.70	0.00	09-03	2
Gesloten aansluiting - samenkomst	1	23.70	0.00	12-00	125
Infiltratie (3B.C), druppelend via aansluiting	1	23.70	0.00	12-00	onbekend
Infiltratie (2A), doorzwetend	1	24.50	0.00	12-12	onbekend
Waterpeil troebel en verkleurd afvalwater (1E.D), h<= 10% verzakking	1	25.00	0.00	00-00	10
PLaatselijke reparatie - plaatselijke lining	1	26.20	26.90	12-12	onbekend
Infiltratie (2A), doorzwetend	1	28.90	0.00	03-09	onbekend
Open aansluiting - samenkomst	1	29.80	0.00	12-00	125
Defecte aansluiting (3E.B), aansluitende buis geblokkeerd 10% < doorsnede <= 25%	1	29.80	0.00	12-00	onbekend

Infiltratie (2A), doorzwetend	1	30.80	0.00	12-12	onbekend
Infiltratie (2A.I), doorzwetend via wand	1	32.40	0.00	08-11	onbekend
Poreuze buis (5)	1	32.40	0.00	09-11	onbekend
Infiltratie (2A), doorzwetend	1	32.60	0.00	12-12	onbekend
Infiltratie (2A.I), doorzwetend via wand	1	34.40	0.00	09-00	onbekend
Poreuze buis (5)	1	34.40	0.00	09-00	onbekend
Infiltratie (2A), doorzwetend	1	34.70	0.00	12-12	onbekend
Waterpeil troebel en verkleurd afvalwater (1E.D), h<= 10% verzakking	1	36.00	0.00	00-00	5
Infiltratie (2A), doorzwetend	1	36.70	0.00	12-12	onbekend
Binnendringen van grond (2C) oer, minder dwarsdoorsnede <=5%	1	37.90	0.00	07-05	2
Gesloten aansluiting - samenkomst	1	37.90	0.00	12-00	125
Infiltratie (3B.C), druppelend via aansluiting	1	37.90	0.00	12-00	onbekend
Infiltratie (2A.I), doorzwetend via wand	1	40.29	0.00	09-00	onbekend
Poreuze buis (5)	1	40.29	0.00	09-00	onbekend
Infiltratie (2A), doorzwetend	1	40.70	0.00	12-12	onbekend
Infiltratie (2A), doorzwetend	1	42.90	0.00	07-11	onbekend
Binnendringen van grond (2C) oer, minder dwarsdoorsnede <=5%	1	43.80	0.00	09-03	2
Gesloten aansluiting - samenkomst	1	43.80	0.00	12-00	125
Infiltratie (3B.C), druppelend via aansluiting	1	43.80	0.00	12-00	onbekend
Open aansluiting - samenkomst	1	47.40	0.00	12-00	125
Binnendringen van grond (2C) oer, minder dwarsdoorsnede <=5%	1	50.00	0.00	08-04	3
Gesloten aansluiting - samenkomst	1	50.00	0.00	12-00	125
Infiltratie (3B.C), druppelend via aansluiting	1	50.00	0.00	12-00	onbekend
Waterpeil troebel en verkleurd afvalwater (1E.D), h<= 10% verzakking	1	54.40	0.00	00-00	10
Gesloten aansluiting - samenkomst	1	56.10	0.00	12-00	125
Binnendringen van grond (2C) oer, minder dwarsdoorsnede <=5%	1	56.10	0.00	07-05	2
Infiltratie (2A.C), doorzwetend via aansluiting	1	56.10	0.00	12-00	onbekend
Infiltratie (2A), doorzwetend	1	57.00	0.00	12-12	onbekend
Verplaatste verbinding (1C), hoekverdraaiing, > 0 en <= 2 graden	1	57.00	0.00	12-00	1
Infiltratie (2A), doorzwetend	1	59.10	0.00	12-12	onbekend
Binnendringen van grond (2C) oer, minder dwarsdoorsnede <=5%	1	60.00	0.00	11-01	2
Gesloten aansluiting - samenkomst	1	60.00	0.00	12-00	125
Infiltratie (3B.C), druppelend via aansluiting	1	60.00	0.00	12-00	onbekend
Infiltratie (2A), doorzwetend	1	60.80	0.00	03-09	onbekend
Algemene opmerking (..z), Vrije tekst met toelichting	1	61.10	0.00	00-00	onbekend
Eind knooppunt - rioolput	1	61.30	0.00	00-00	0-0891

Pipe 0-0062 – 0-1016 Wolfslaardreef Breda (Ø500 concrete and length 43 meters)

- Construction year 1960
- Inspection date 19-7-2021

- Infiltration classes 2 and 3
- Average groundwater level is 1.5 m



Logbook:

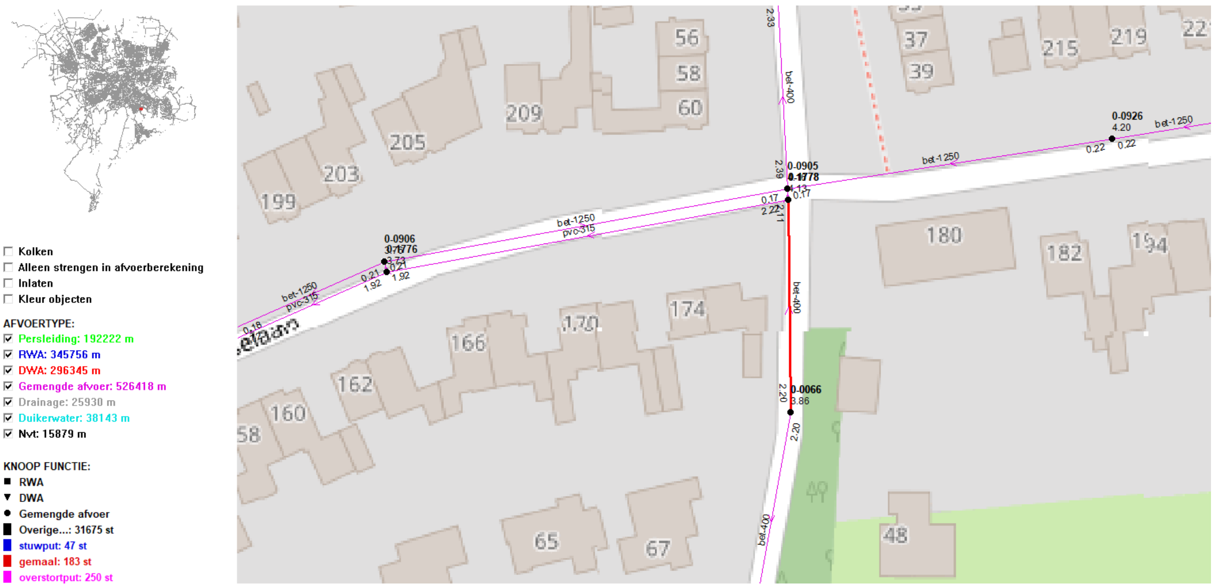
Aspect [0-0062 naar 0-1016]	R	Begin	Eind	Klok	Meting
Begin knooppunt - rioolput	1	0.00	0.00	00-00	0-0062
Bezonken afzettingen (2C) hard of vast, 5% < vermindering dwarsdoorsn. <= 10%	1	0.00	1.00	05-07	10

Waterpeil troebel en verkleurd afvalwater (1E), h<= 10%	1	1.00	43.40	00-00	5
Aangehechte afzettingen (1C) vervuiling, vermindering dwarsdoorsnede <= 5%	1	1.70	43.10	08-04	2
Infiltratie (2A), doorzwetend	1	2.60	0.00	12-12	onbekend
PLaatselijke reparatie - plaatselijke lining	1	4.20	4.90	12-12	onbekend
Open aansluiting - samenkomst	1	7.70	0.00	12-00	125
Defecte aansluiting (4E.C), aansluitende buis geblokkeerd 25% < doorsnede <= 50%	1	7.70	0.00	12-00	onbekend
Infiltratie (3B.C), druppelend via aansluiting	1	7.70	0.00	12-00	onbekend
Open aansluiting - samenkomst	1	13.80	0.00	12-00	125
Defecte aansluiting (2E.A), aansluitende buis geblokkeerd doorsnede <= 10 %	1	13.80	0.00	12-00	onbekend
Infiltratie (3B.C), druppelend via aansluiting	1	13.80	0.00	12-00	onbekend
Infiltratie (2A), doorzwetend	1	14.90	0.00	12-12	onbekend
Infiltratie (2A.I), doorzwetend via wand	1	15.90	0.00	09-00	onbekend
Poreuze buis (5)	1	15.90	0.00	09-00	onbekend
Binnendringen van grond (2C) oer, minder dwarsdoorsnede <=5%	1	19.80	0.00	11-01	3
Gesloten aansluiting - samenkomst	1	19.80	0.00	12-00	125
Infiltratie (3B.C), druppelend via aansluiting	1	19.80	0.00	12-00	onbekend
Infiltratie (2A), doorzwetend	1	20.90	0.00	07-08	onbekend
Infiltratie (3B.I), druppelend via wand	1	22.50	0.00	07-08	onbekend
Poreuze buis (5)	1	22.50	0.00	07-00	onbekend
Binnendringen van grond (2C) oer, minder dwarsdoorsnede <=5%	1	22.50	0.00	07-08	2
Infiltratie (2A), doorzwetend	1	22.70	0.00	02-06	onbekend
Infiltratie (2A), doorzwetend	1	25.00	0.00	12-12	onbekend
Binnendringen van grond (2C.C) oer via aansluiting, minder dwarsdoor. <= 5%	1	25.90	0.00	11-12	5
Gesloten aansluiting - samenkomst	1	25.90	0.00	12-00	125
Infiltratie (3B.C), druppelend via aansluiting	1	25.90	0.00	12-00	onbekend
Binnendringen van grond (2C) oer, minder dwarsdoorsnede <=5%	1	26.80	0.00	09-03	2
Open aansluiting - samenkomst	1	26.80	0.00	12-00	268
Infiltratie (3B.C), druppelend via aansluiting	1	26.80	0.00	12-00	onbekend
Defecte aansluiting (2E.A), aansluitende buis geblokkeerd doorsnede <= 10 %	1	26.80	0.00	12-00	onbekend
Infiltratie (2A), doorzwetend	1	29.10	0.00	12-12	onbekend
Infiltratie (2A), doorzwetend	1	31.00	0.00	12-12	onbekend
Binnendringen van grond (2C) oer, minder dwarsdoorsnede <=5%	1	32.00	0.00	09-03	5
Open aansluiting - samenkomst	1	32.00	0.00	12-00	125
Defecte aansluiting (2E.A), aansluitende buis geblokkeerd doorsnede <= 10 %	1	32.00	0.00	12-00	onbekend
Infiltratie (3B.C), druppelend via aansluiting	1	32.00	0.00	12-00	onbekend
Infiltratie (2A.H), doorzwetend via put	1	32.90	0.00	08-00	onbekend
Infiltratie (2A), doorzwetend	1	35.00	0.00	12-12	onbekend

Gesloten aansluiting - samenkomst	1	37.90	0.00	12-00	125
Binnendringen van grond (2C) oer, minder dwarsdoorsnede <=5%	1	37.90	0.00	10-02	5
Infiltratie (3B.C), druppelend via aansluiting	1	37.90	0.00	12-00	onbekend
Infiltratie (2A), doorzwetend	1	39.00	0.00	03-09	onbekend
Verplaatste verbinding (1C), hoekverdraaiing, > 0 en <= 2 graden	1	39.00	0.00	12-00	1
Infiltratie (2A), doorzwetend	1	41.00	0.00	03-09	onbekend
PLaatselijke reparatie - plaatselijke lining	1	42.30	42.90	12-12	onbekend
Infiltratie (2A.H), doorzwetend via put	1	42.90	0.00	12-00	onbekend
Infiltratie (3B.H), druppelend via put	1	43.00	43.10	12-12	onbekend
Algemene opmerking (..S), Inlaten in put	1	43.40	0.00	00-00	onbekend
Eind knooppunt - rioolput	1	43.40	0.00	00-00	0-1016

Pipe 0-1778 – 0-0066 Valentijnlaan Breda (Ø400 concrete and length 37 meters)

- Construction year 1968
- Inspection date 20-7-2021
- Infiltration classes 2 and 3
- Average groundwater level is 1.5 m



Logbook:

Aspect [0-1778 naar 0-0066]	R	Begin	Eind	Klok	Meting
Begin knooppunt - rioolput	1	0.00	0.00	00-00	0-1778
Open vlakke aansluiting - gebeiteld	1	2.70	0.00	12-00	125
Opp.schade (5IA), ontbrekende wand, mechanisch	1	2.70	0.00	12-00	onbekend
Binnendringen van grond (2C) oer, minder dwarsdoorsnede <=5%	1	4.59	0.00	10-02	2
Open aansluiting - samenkomst	1	4.59	0.00	12-00	125
Defecte aansluiting (3E.B), aansluitende buis geblokkeerd 10% < doorsnede <= 25%	1	4.59	0.00	12-00	onbekend
Infiltratie (3B.C), druppelend via aansluiting	1	4.59	0.00	12-00	onbekend
Open vlakke aansluiting - gebeiteld	1	4.70	0.00	12-00	125
Opp.schade (5IA), ontbrekende wand, mechanisch	1	4.70	0.00	12-00	onbekend
Infiltratie (2A.C), doorzwetend via aansluiting	1	4.70	0.00	12-00	onbekend
Infiltratie (2A), doorzwetend	1	9.69	0.00	12-12	onbekend
Binnendringen van grond (2C) oer, minder dwarsdoorsnede <=5%	1	10.60	0.00	09-03	2
Open aansluiting - samenkomst	1	10.60	0.00	12-00	125
Defecte aansluiting (2E.A), aansluitende buis geblokkeerd doorsnede <= 10 %	1	10.60	0.00	12-00	onbekend
Infiltratie (2A), doorzwetend	1	11.60	0.00	11-12	onbekend
Waterpeil troebel en verkleurd afvalwater (1E), h<= 10%	1	12.70	39.40	00-00	3
Infiltratie (2A), doorzwetend	1	13.60	0.00	12-12	onbekend
Infiltratie (2A), doorzwetend	1	15.60	0.00	12-12	onbekend
Gesloten aansluiting - samenkomst	1	16.60	0.00	12-00	125
Infiltratie (2A.C), doorzwetend via aansluiting	1	16.60	0.00	12-00	onbekend
Infiltratie (2A), doorzwetend	1	19.80	0.00	12-12	onbekend
Gesloten aansluiting - samenkomst	1	22.80	0.00	12-00	125
Infiltratie (2A.C), doorzwetend via aansluiting	1	22.80	0.00	12-00	onbekend
Infiltratie (2A), doorzwetend	1	23.80	0.00	12-12	onbekend

Infiltratie (2A), doorzwetend	1	25.80	0.00	12-12	onbekend
Binnendringen van grond (2C) oer, minder dwarsdoorsnede <=5%	1	27.60	0.00	07-05	2
Open vlakke aansluiting - gebeiteld	1	27.60	0.00	12-00	125
Infiltratie (3B.C), druppelend via aansluiting	1	27.60	0.00	12-00	onbekend
Opp.schade (5IA), ontbrekende wand, mechanisch	1	27.60	0.00	12-00	onbekend
Infiltratie (2A), doorzwetend	1	27.80	0.00	12-04	onbekend
Verplaatste verbinding (1C), hoekverdraaiing, > 0 en <= 2 graden	1	27.80	0.00	12-00	1
Gesloten aansluiting - samenkomst	1	28.80	0.00	12-00	125
Infiltratie (2A.C), doorzwetend via aansluiting	1	28.80	0.00	12-00	onbekend
Infiltratie (2A), doorzwetend	1	29.90	0.00	12-12	onbekend
Infiltratie (2A), doorzwetend	1	33.90	0.00	12-12	onbekend
Binnendringen van grond (2C) oer, minder dwarsdoorsnede <=5%	1	34.90	0.00	07-05	2
Gesloten aansluiting - samenkomst	1	34.90	0.00	12-00	125
Infiltratie (2A.C), doorzwetend via aansluiting	1	34.90	0.00	12-00	onbekend
Opp.schade (5IA), ontbrekende wand, mechanisch	1	34.90	0.00	12-00	onbekend
Infiltratie (2A), doorzwetend	1	36.00	0.00	12-12	onbekend
Bezonken afzettingen (1C) hard of vast, vermindering dwarsdoorsnede <= 5%	1	38.60	39.40	05-07	5
Infiltratie (2A.H), doorzwetend via put	1	39.00	0.00	12-12	onbekend
Algemene opmerking (..R), Inlaat in put	1	39.40	0.00	00-00	onbekend
Eind knooppunt - rioolput	1	39.40	0.00	00-00	0-0066

Pipe 0-0062 – 0-0061 Valentijnlaan Breda (Ø400 concrete and length 55 meters)

- Construction year 1968
- Inspection date 20-7-2021
- Infiltration classes 2, 3 and 4
- Note: there are 2 protruding inlets present (10-25% of the pipe)
- Average groundwater level is 1.5 m

Logbook:

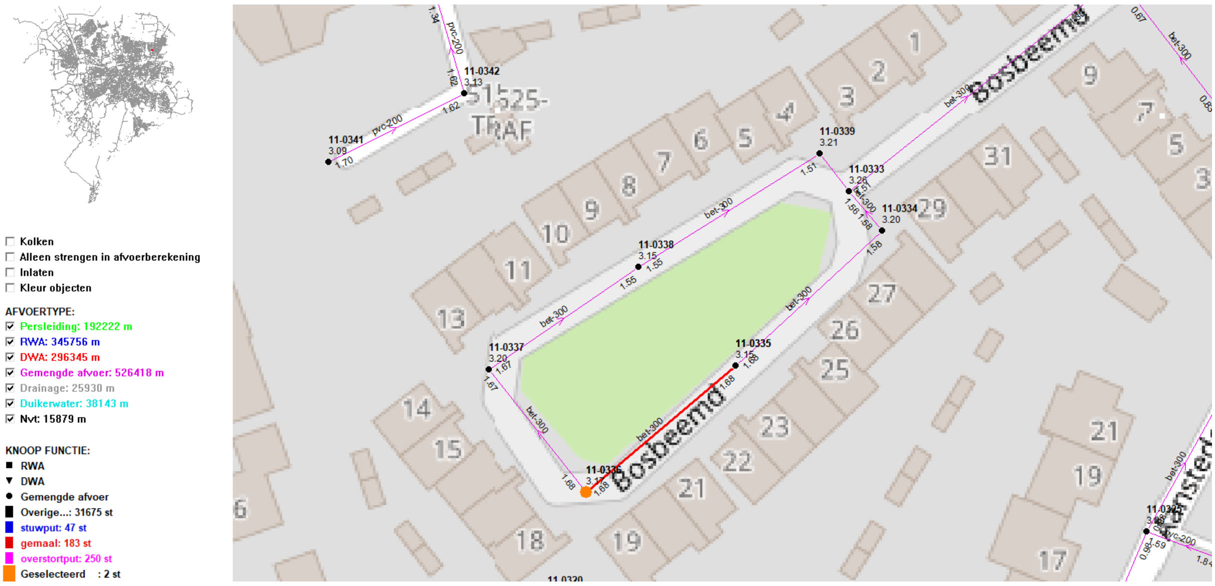
Aspect [0-0062 naar 0-0061]	R	Begin	Eind	Klok	Meting
Begin knooppunt - rioolput	2	0.00	0.00	00-00	0-0061
Waterpeil troebel en verkleurd afvalwater (1E), h<= 10%	2	0.40	55.20	00-00	5
Algemene foto	2	1.20	0.00	12-12	onbekend
Infiltratie (4C.B), instromend via breuk	2	1.30	0.00	04-08	onbekend
Binnendringen van grond (3A.B) zand via breuk, 5% < dwarsdoorsnede <= 15%	2	1.30	0.00	04-08	10

Binnendringen van grond (2C.B) oer via breuk, minder dwarsdoorsnede <= 5%	2	1.30	0.00	07-12	2
Open vlakke aansluiting - gebeiteld	2	1.30	0.00	12-00	120
Opp.schade (5IA), ontbrekende wand, mechanisch	2	1.30	0.00	12-00	onbekend
Scheur (5CB), zichtbaar open scheuren, in de omtrek	2	1.30	0.00	12-12	3
Open aansluiting - samenkomst	2	3.30	0.00	12-00	125
Infiltratie (2A.C), doorzwetend via aansluiting	2	3.30	0.00	12-00	onbekend
Scheur (4BC), zichtbare scheurlijnen, gecompliceerd	2	8.19	8.30	10-12	1
Infiltratie (2A.B), doorzwetend via breuk	2	8.19	0.00	10-00	onbekend
Open vlakke aansluiting - gebeiteld	2	8.19	0.00	12-00	125
Opp.schade (5IA), ontbrekende wand, mechanisch	2	8.19	0.00	12-00	onbekend
Instekende inlaat (3), 10% < insteeklengte <= 25 % van de leidinghoogte	2	8.19	0.00	12-00	20
Infiltratie (2A), doorzwetend	2	8.30	0.00	12-12	onbekend
Gesloten aansluiting - samenkomst	2	9.40	0.00	12-00	110
Infiltratie (2A), doorzwetend	2	12.50	0.00	12-12	onbekend
Gesloten aansluiting - samenkomst	2	15.40	0.00	12-00	110
Infiltratie (2A), doorzwetend	2	16.50	0.00	12-12	onbekend
Infiltratie (2A), doorzwetend	2	20.50	0.00	12-12	onbekend
Open vlakke aansluiting - gebeiteld	2	20.60	0.00	12-00	125
Opp.schade (5IA), ontbrekende wand, mechanisch	2	20.60	0.00	12-00	onbekend
Infiltratie (2A.C), doorzwetend via aansluiting	2	20.60	0.00	12-00	onbekend
Gesloten aansluiting - samenkomst	2	21.50	0.00	12-00	110
Infiltratie (2A.C), doorzwetend via aansluiting	2	21.50	0.00	12-00	onbekend
Open vlakke aansluiting - gebeiteld	2	23.60	0.00	12-00	125
Opp.schade (5IA), ontbrekende wand, mechanisch	2	23.60	0.00	12-00	onbekend
Instekende inlaat (3), 10% < insteeklengte <= 25 % van de leidinghoogte	2	23.60	0.00	12-00	15
Infiltratie (2A), doorzwetend	2	24.40	0.00	12-12	onbekend
Open aansluiting - samenkomst	2	27.60	0.00	12-00	125
Infiltratie (2A.C), doorzwetend via aansluiting	2	27.60	0.00	12-00	onbekend
Infiltratie (2A), doorzwetend	2	30.60	0.00	08-10	onbekend
Infiltratie (2A), doorzwetend	2	32.60	0.00	12-12	onbekend
Gesloten aansluiting - samenkomst	2	33.60	0.00	12-00	110
Infiltratie (2A.C), doorzwetend via aansluiting	2	33.60	0.00	12-00	onbekend
Infiltratie (2A), doorzwetend	2	34.70	0.00	12-12	onbekend
Open vlakke aansluiting - gebeiteld	2	39.20	0.00	12-00	125
Opp.schade (5IA), ontbrekende wand, mechanisch	2	39.20	0.00	12-00	onbekend
Open aansluiting - samenkomst	2	41.70	0.00	12-00	125
Infiltratie (2A), doorzwetend	2	42.80	0.00	12-12	onbekend
Gesloten aansluiting - samenkomst	2	45.80	0.00	12-00	110

Infiltratie (2A.C), doorzwetend via aansluiting	2	45.80	0.00	12-00	onbekend
Infiltratie (2A), doorzwetend	2	46.70	0.00	12-12	onbekend
Gesloten aansluiting - samenkomst	2	49.90	0.00	12-00	125
Infiltratie (2A.C), doorzwetend via aansluiting	2	49.90	0.00	12-00	onbekend
Verplaatste verbinding (2B), radiaal, verplaatsing <= 10 mm	2	52.90	0.00	06-00	10
Infiltratie (2A), doorzwetend	2	52.90	0.00	12-12	onbekend
PLaatselijke reparatie - plaatselijke lining	2	54.20	54.90	12-12	onbekend
Eind knooppunt - rioolput	2	55.20	0.00	00-00	0-0062

Pipe 11-0336 – 11-0335 Bosbeemd Teteringen (Ø300 concrete and length 28 meters)

- Construction year 1977
- Inspection date 12-10-2021
- Infiltration classes 2 and 3
- Average groundwater level is 1.5 m



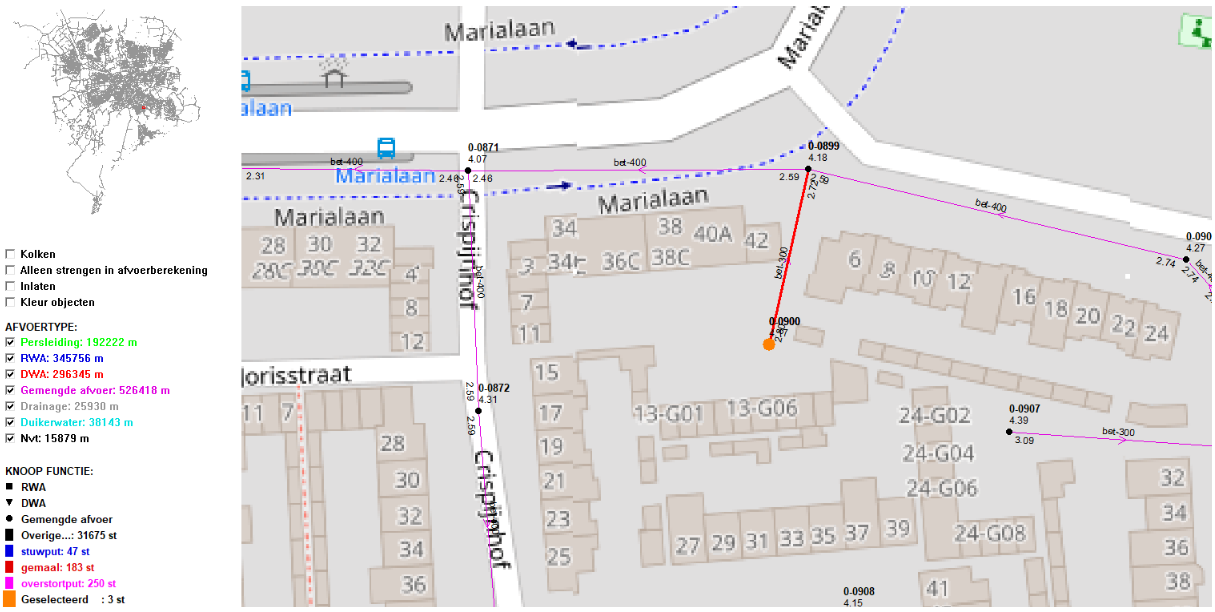
Logbook:

Aspect [11-0336 naar 11-0335]	R	Begin	Eind	Klok	Meting
Begin knooppunt - rioolput	1	0.00	0.00	00-00	11
Opp.schade (2CC), zichtbare toeslagstoffen, chemisch boven waterpeil	1	0.40	27.80	08-04	onbekend
Waterpeil troebel en verkleurd afvalwater (1E.D), h<= 10% verzakking	1	0.40	28.20	00-00	10
Verplaatste verbinding (1C), hoekverdraaiing, > 0 en <= 2 graden	1	1.70	0.00	12-00	2
Open aansluiting - samenkomst	1	1.70	0.00	12-00	125
Scheur (5CB), zichtbaar open scheuren, in de omtrek	1	1.70	0.00	12-12	3
Infiltratie (3B.B), druppelend via breuk	1	1.70	0.00	12-12	onbekend
Infiltratie (2A), doorzwetend	1	3.50	0.00	07-05	onbekend
Verplaatste verbinding (1C), hoekverdraaiing, > 0 en <= 2 graden	1	3.50	0.00	06-00	2
Waterpeil troebel en verkleurd afvalwater (1E.D), h<= 10% verzakking	1	3.50	0.00	00-00	5
Open aansluiting - samenkomst	1	3.70	0.00	12-00	125
Open aansluiting - samenkomst	1	11.80	0.00	12-00	125
Defecte aansluiting (5D), aansluitende buis beschadigd	1	11.80	0.00	12-00	onbekend
Infiltratie (2A.C), doorzwetend via aansluiting	1	11.80	0.00	12-00	onbekend
Waterpeil troebel en verkleurd afvalwater (1E.D), h<= 10% verzakking	1	16.20	0.00	00-00	10
Open aansluiting - samenkomst	1	17.89	0.00	12-00	125

Defecte aansluiting (5D), aansluitende buis beschadigd	1	17.89	0.00	12-00	onbekend
Infiltratie (2A.C), doorzwetend via aansluiting	1	17.89	0.00	12-00	onbekend
Open vlakke aansluiting - gebeiteld	1	20.00	0.00	12-00	125
Opp.schade (5IA), ontbrekende wand, mechanisch	1	20.00	0.00	12-00	onbekend
Infiltratie (2A.C), doorzwetend via aansluiting	1	20.00	0.00	12-00	onbekend
Instekende inlaat (2), insteeklengte <= 10% van de leidinghoogte	1	20.00	0.00	12-00	10
Defecte aansluiting (5D), aansluitende buis beschadigd	1	20.00	0.00	12-00	onbekend
Open aansluiting - samenkomst	1	24.00	0.00	12-00	125
Scheur (5CB), zichtbaar open scheuren, in de omtrek	1	24.00	0.00	12-12	4
Infiltratie (2A.B), doorzwetend via breuk	1	24.00	0.00	12-12	onbekend
Wortels (2B), kleine wortels 1% < dwarsdoorsnede <= 10%	1	24.00	0.00	09-12	2
Verplaatste verbinding (1C), hoekverdraaiing, > 0 en <= 2 graden	1	25.80	0.00	12-00	2
Waterpeil troebel en verkleurd afvalwater (1E.D), h<= 10% verzakking	1	27.10	0.00	00-00	5
Eind knooppunt - rioolput	1	28.20	0.00	00-00	11

Pipe 0-0900 – 0-0899-1 Brigidastraat Breda (Ø300 concrete and length 31 meters)

- Construction year 1959
- Inspection date 26-7-2021
- Infiltration classes 2, 4 and 5
- Note: there are protruding inlets present (<10% of the pipe)
- Average groundwater level is 1.5 m



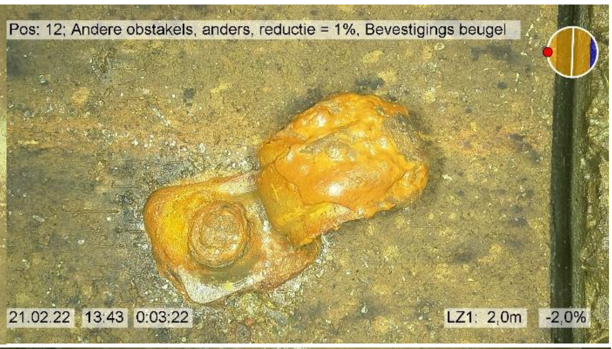
Logbook:

Aspect [0-0900 naar 0-0899]	R	Begin	Eind	Klok	Meting
Begin knooppunt - rioolput	1	0.00	0.00	00-00	0-0900

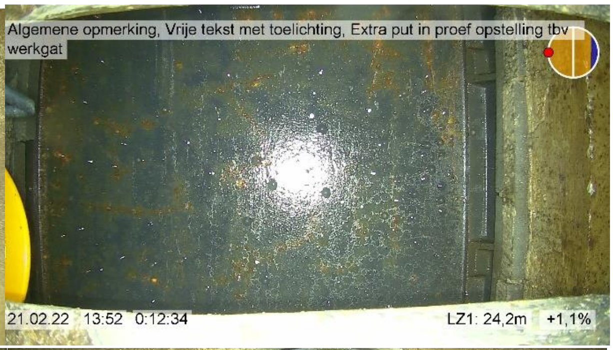
Waterpeil troebel en verkleurd afvalwater (1E.D), h<= 10% verzakking	1	0.00	31.50	00-00	10
Open vlakke aansluiting - gebeiteld	1	1.70	0.00	10-00	120
Opp.schade (5IA), ontbrekende wand, mechanisch	1	1.70	0.00	10-00	onbekend
Infiltratie (2A.C), doorzwetend via aansluiting	1	1.70	0.00	10-00	onbekend
Instekende inlaat (2), insteeklengte <= 10% van de leidinghoogte	1	1.70	0.00	10-00	10
Open aansluiting - samenkomst	1	2.29	0.00	12-00	125
Infiltratie (2A.C), doorzwetend via aansluiting	1	2.29	0.00	12-00	onbekend
Gesloten aansluiting - samenkomst	1	3.40	0.00	12-00	125
Gesloten aansluiting - samenkomst	1	7.30	0.00	12-00	125
Gesloten aansluiting - samenkomst	1	11.30	0.00	12-00	125
Opp.schade (5IE), ontbrekende wand, oorzaak onduidelijk	1	11.40	0.00	04-09	onbekend
Infiltratie (4C.I), instromend via wand	1	11.40	0.00	04-09	onbekend
Binnendringen van grond (4A.B) zand via breuk, 15% < dwarsdoorsnede <= 25%	1	11.50	0.00	03-08	25
Infiltratie (5D.I), binnengutsend via wand	1	11.50	0.00	04-09	onbekend
Waterpeil troebel en verkleurd afvalwater (1E.D), h<= 10% verzakking	1	11.90	0.00	00-00	2
Open vlakke aansluiting - gebeiteld	1	14.40	0.00	12-00	120
Opp.schade (5IA), ontbrekende wand, mechanisch	1	14.40	0.00	12-00	onbekend
Infiltratie (2A.C), doorzwetend via aansluiting	1	14.40	0.00	12-00	onbekend
Gesloten aansluiting - samenkomst	1	15.50	0.00	12-00	125
Open aansluiting - samenkomst	1	19.50	0.00	12-00	125
Algemene foto	1	21.70	0.00	12-12	onbekend
Gesloten aansluiting - samenkomst	1	23.50	0.00	12-00	125
Infiltratie (2A.I), doorzwetend via wand	1	24.40	0.00	09-12	onbekend
Poreuze buis (5)	1	24.40	0.00	09-12	onbekend
Gesloten aansluiting - samenkomst	1	27.60	0.00	12-00	125
Infiltratie (2A), doorzwetend	1	31.10	0.00	12-12	onbekend
Eind knooppunt - rioolput	1	31.50	0.00	00-00	0-0899

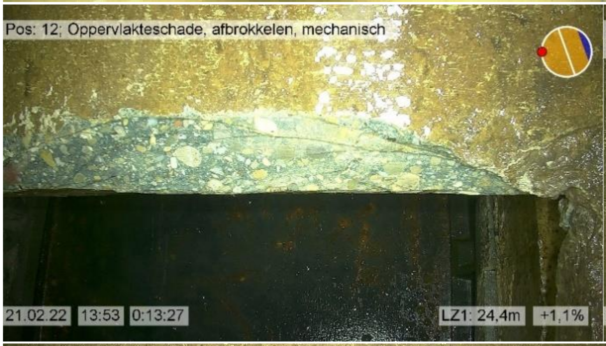
C.2 Test set-up concrete sewer pipe logbook with observations and images

Foto nr.	Afst.[m]	Code	V	Waarneming	Klok
	0,00	BCD.A..		Beginknooppunt, rioolput A , Zakput	
	0,00	BBE.Z..		Begin: Andere obstakels 1 , Kabel op bodem tbv onderzoek	06-00
001	0,00	BDD.E..		Begin: Waterpeil, troebel en verkleurd 3 %,	
002	0,00	BAF.C.C.		Begin: Oppervlakteschade, zichtbare toeslagstoffen, chemisch - bovenin	07-05
003	2,00	BBE.Z..		Andere obstakels 1 , Bevestigings beugel	12-00
004	2,00	BAJ.C..	A	Verplaatste verbinding, hoekverdraaiing 3 °,	12-00
005	3,20	BBE.Z..		Andere obstakels 1 , Bevestigings beugel	12-00
006	11,40	BDA...		Algemene foto	12-12
007	13,70	BCA.A.A.		Aansluiting, samenkomst, open aansluiting 125 mm, 125 mm,	12-00
008	22,70	BDA...		Algemene foto	12-12
009	24,20	BDB...Z		Algemene opmerking, Vrije tekst met toelichting Extra put in proef opstelling tbv werkgat	
	24,50	BBE.Z..		Einde: Andere obstakels 1 , Kabel op bodem tbv onderzoek	06-00
010	24,40	BAF.B.E.		Oppervlakteschade, afbrokkelen, oorzaak onduidelijk Tpv extra put	12-00
	24,20	BAF.C.C.		Oppervlakteschade, zichtbare toeslagstoffen, chemisch - bovenin	07-05
011	26,00	BCA.A.A.		Aansluiting, samenkomst, open aansluiting 125 mm, 125 mm,	12-00
012	28,40	BCA.A.A.		Aansluiting, samenkomst, open aansluiting 125 mm, 125 mm,	12-00
	35,10	BDD.E..		Einde: Waterpeil, troebel en verkleurd 3 %,	
013	35,10	BAF.C.C.		Einde: Oppervlakteschade, zichtbare toeslagstoffen, chemisch - bovenin	07-05
014	35,10	BCE.Z..		Eindknooppunt B , Pompput	

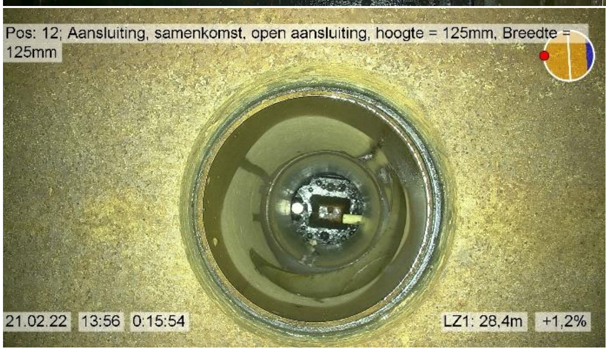


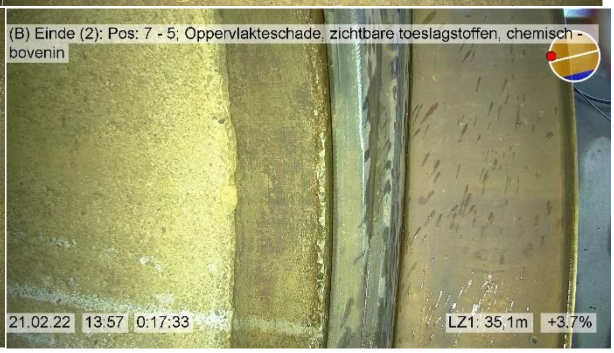

Pos: 12 - 12; Algemene foto
21.02.22 13:51 0:11:03
LZ1: 22,7m +0,1%


Algemene opmerking, Vrije tekst met toelichting, Extra put in proef opstelling tbv werkgat
21.02.22 13:52 0:12:34
LZ1: 24,2m +1,1%


Pos: 12; Oppervlakteschade, afbrokkelen, mechanisch
21.02.22 13:53 0:13:27
LZ1: 24,4m +1,1%


Pos: 12; Aansluiting, samenkomst, open aansluiting, hoogte = 125mm, Breedte = 125mm
21.02.22 13:55 0:15:02
LZ1: 26,0m +0,4%


Pos: 12; Aansluiting, samenkomst, open aansluiting, hoogte = 125mm, Breedte = 125mm
21.02.22 13:56 0:15:54
LZ1: 28,4m +1,2%

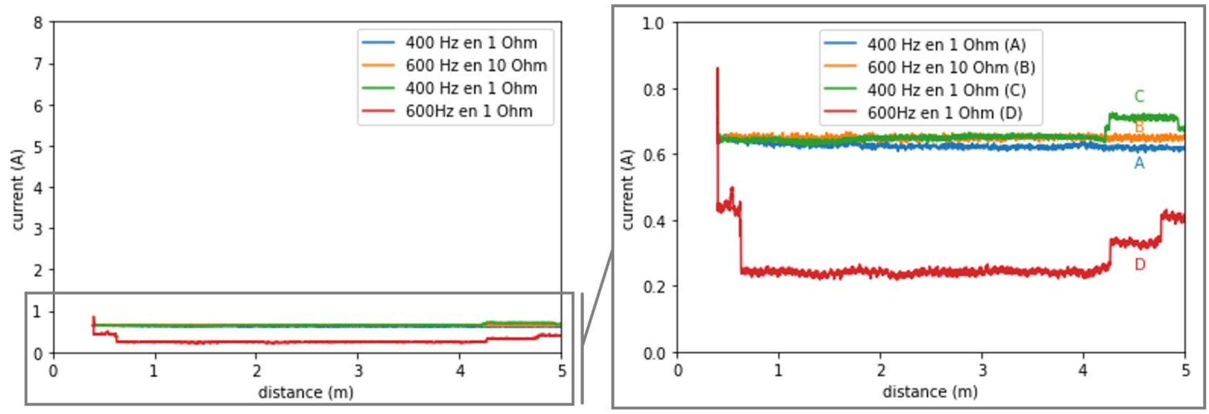

(B) Einde (2): Pos: 7 - 5; Oppervlakteschade, zichtbare toeslagstoffen, chemisch - bovenin
21.02.22 13:57 0:17:33
LZ1: 35,1m +3,7%

D

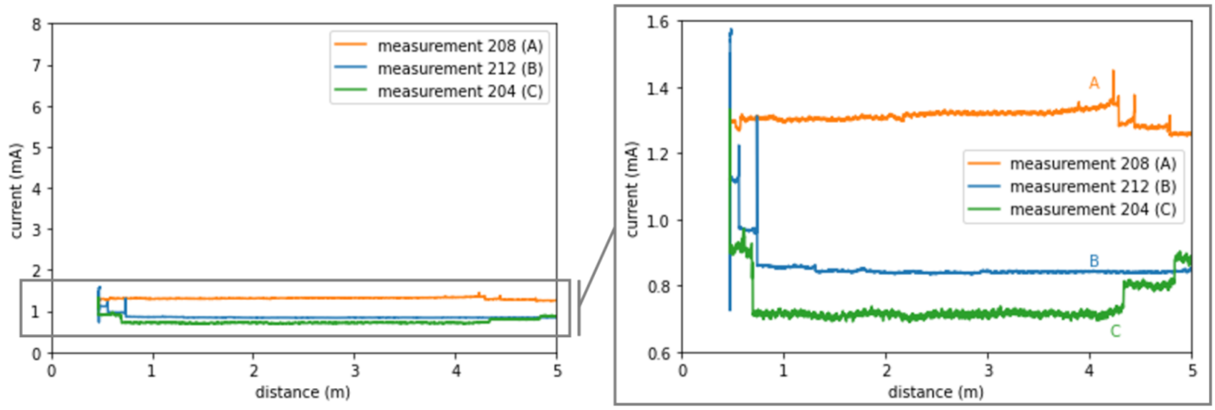
Appendix D

D.1 Results FELL prototype 2.0 measurements at test set-up B

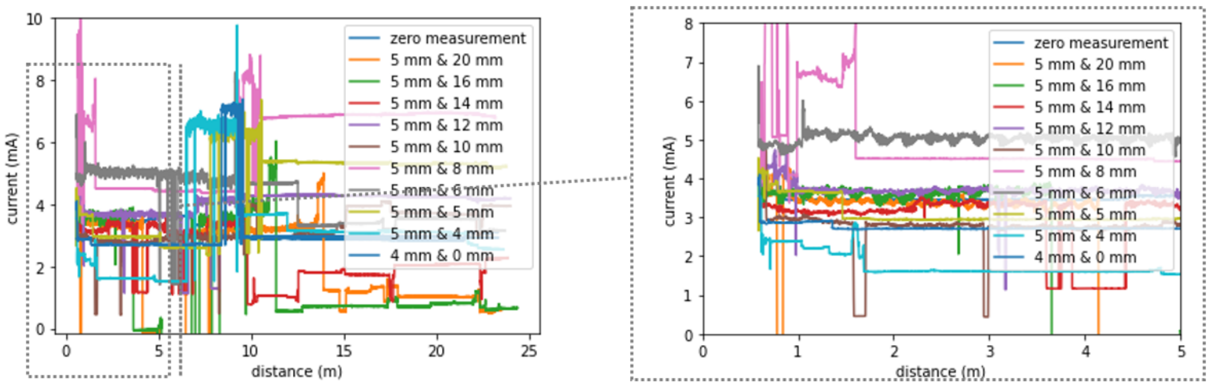
Zero measurements with different settings, showing the first 5 meters



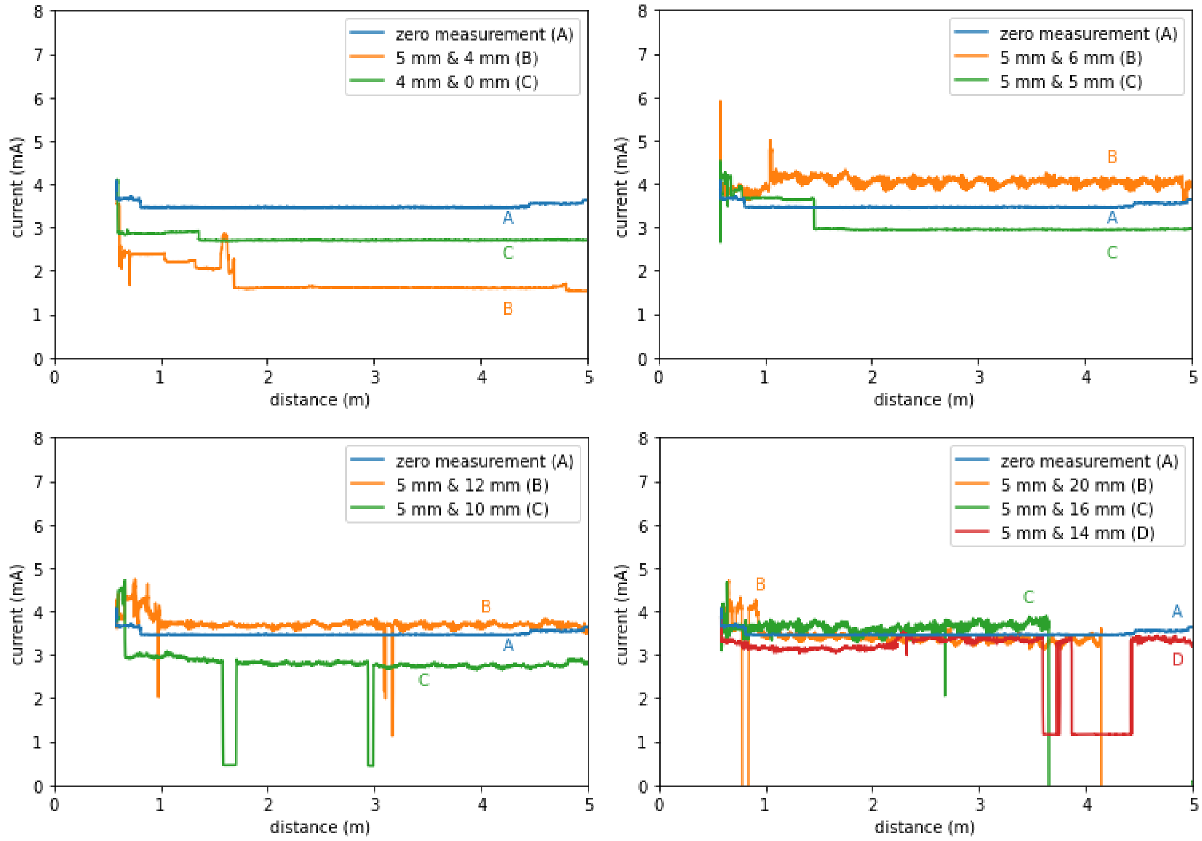
Zero measurements with setting 600 Hz, 1 Ohm and 3 V, showing the first 5 meters



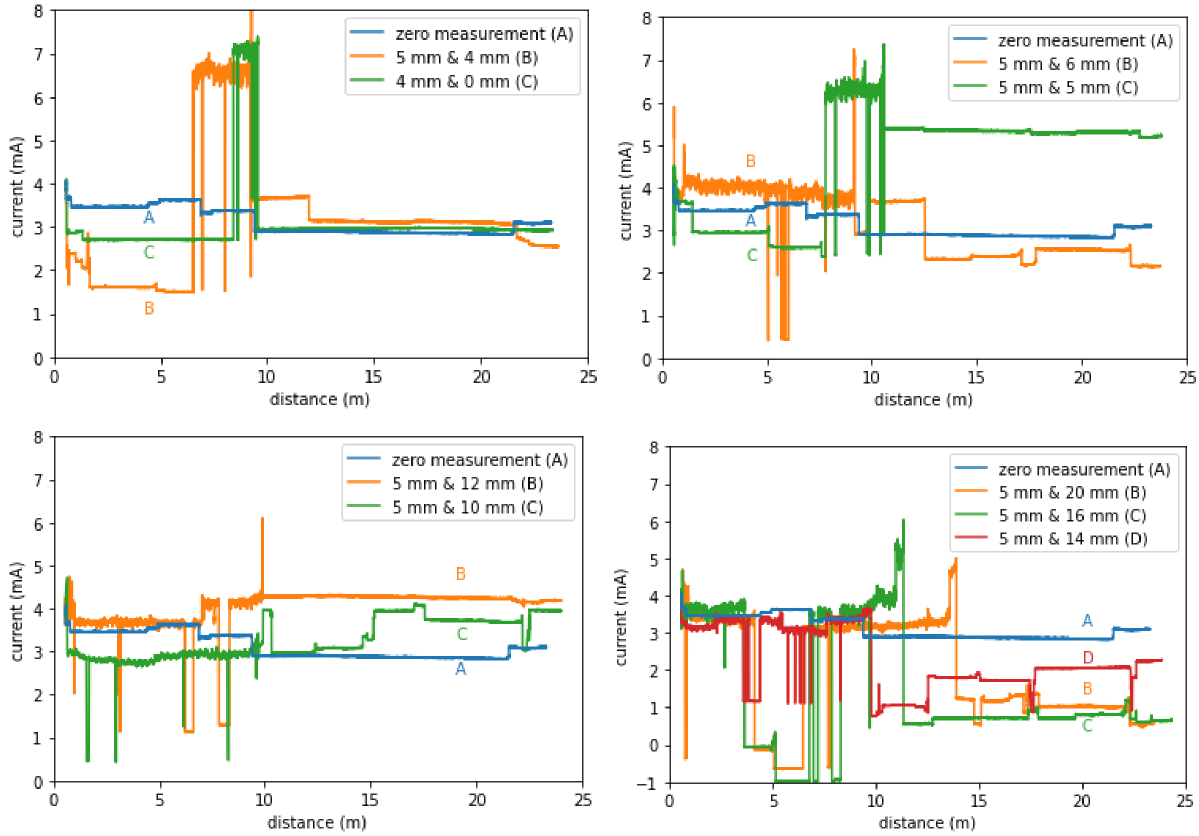
Measurements over the total length and first 5 meters of the sewer pipe with all hole sizes (setting: 600 Hz 1 Ohm 3 V)



Measurements over the first 5 meters of the sewer pipe where the holes are located (setting: 600 Hz 1 Ohm 3 V)

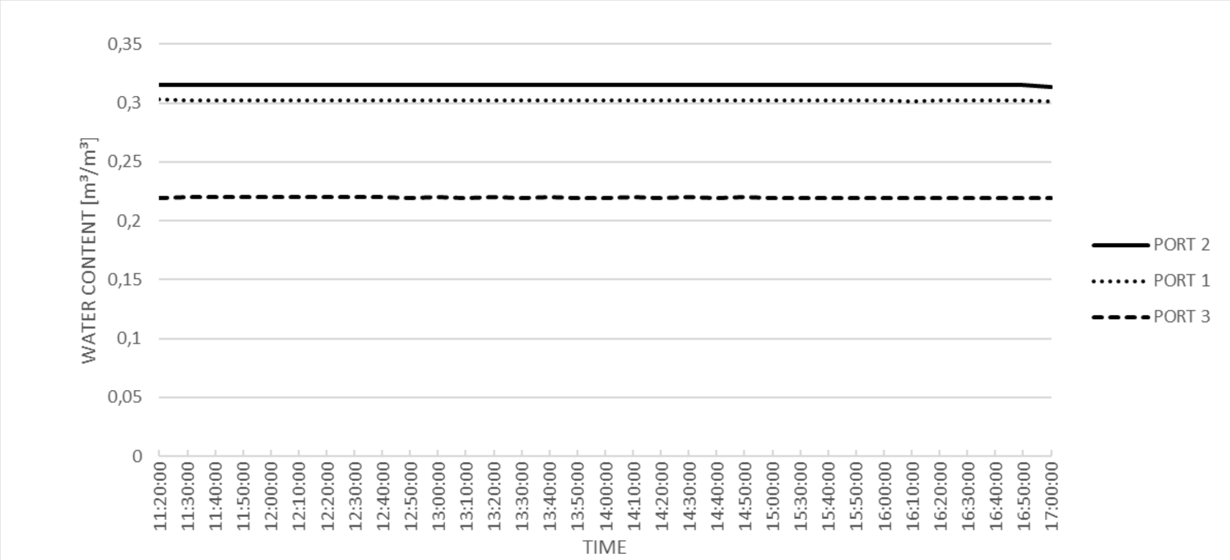


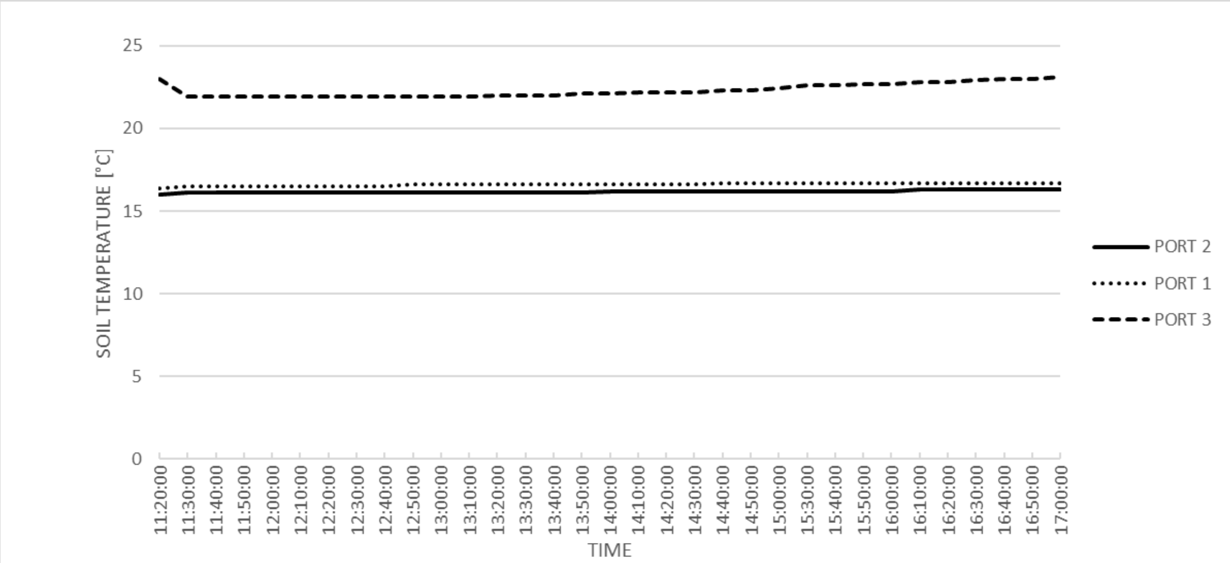
Measurements over the total length of the sewer pipe (setting: 600 Hz 1 Ohm 3 V)

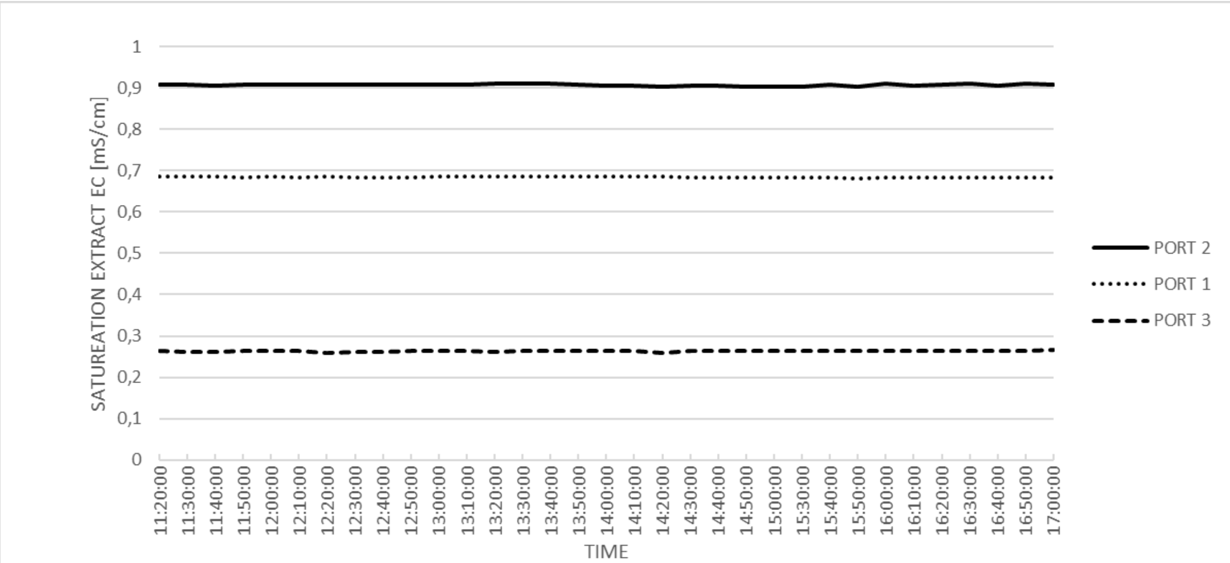


D.2 Results soil moisture sensors at test set-up B

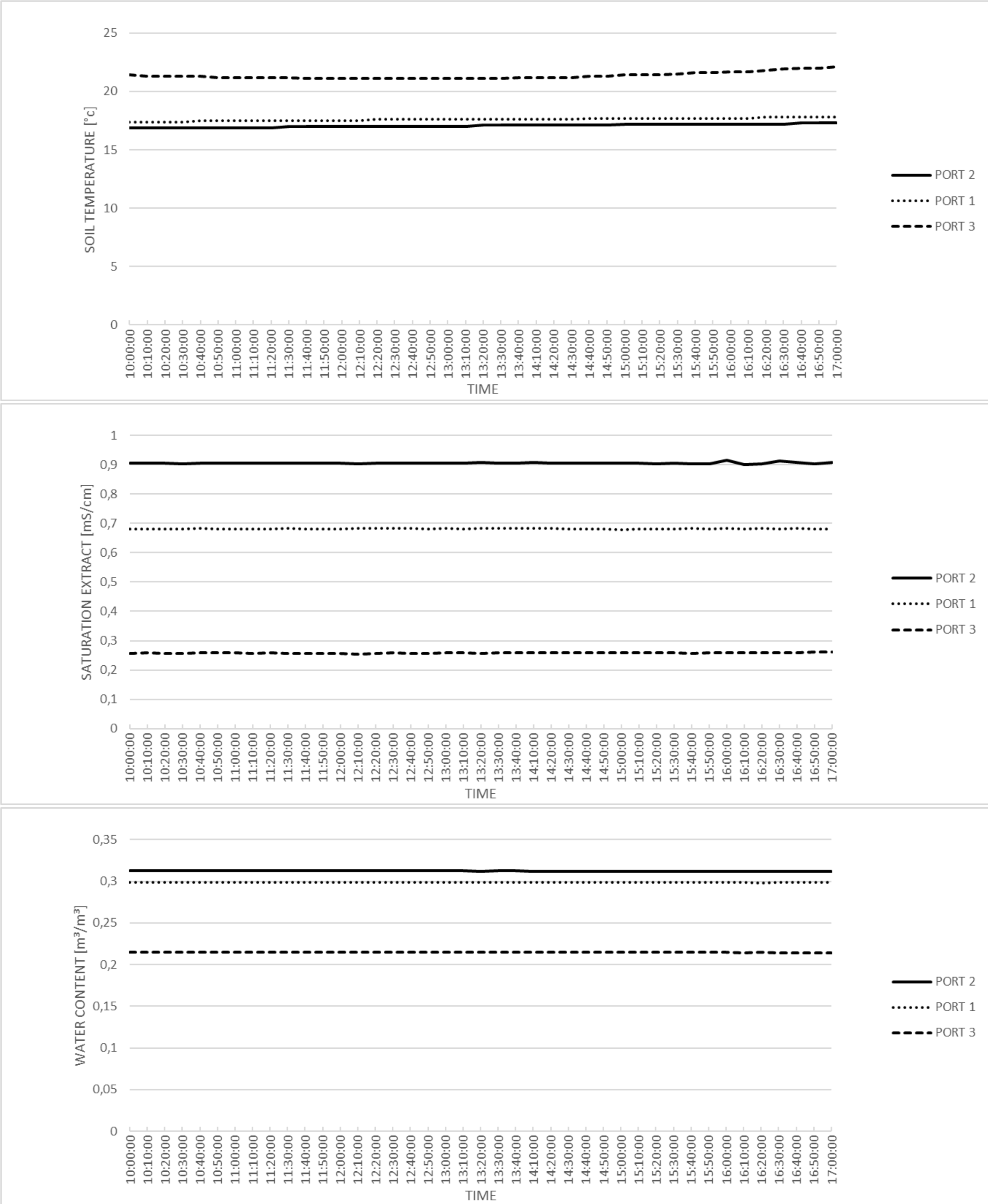
Soil moisture sensor data on the 10th of May 2022







Soil moisture sensor data on the 13th of May 2022



D.3 Python script of the normalisation of the data output of the measurements

The model that was implemented in Matlab used in this study creates, among others, excel files with the distance (or time) and current output. Then, in this study, further work (normalising the data) is done in Python to register the data output in a manageable way.

PVC pipe at test set-up A example

```
import matplotlib.pyplot as plt
import numpy as np
import pandas as pd

wb1 = pd.read_excel("Export_reeks_meet2FELL5145_new.xlsx") #24 cm
time1 = pd.DataFrame(wb1, columns= ['time (s)'])
timeArray1 = pd.DataFrame.to_numpy(time1)
current1 = pd.DataFrame(wb1, columns= ['IT (A)']) * 1000
currentArray1 = pd.DataFrame.to_numpy(current1)

wb2 = pd.read_excel("Export_reeks_meet2FELL5147_new.xlsx") #34 cm
time2 = pd.DataFrame(wb2, columns= ['time (s)'])
timeArray2 = pd.DataFrame.to_numpy(time2)
current2 = pd.DataFrame(wb2, columns= ['IT (A)']) * 1000
currentArray2 = pd.DataFrame.to_numpy(current2)

#_______________________________________________________________________
# y axis values (24 cm second peak)
y = currentArray1
# corresponding x axis values
x = timeArray1

#Find the maximum
maximumY = np.max(y)

#Find corresponding time
for i in range(len(y)):
  if (y[i] == maximumY):
    correspondingTime = x[i]
    break
    break
minTime = correspondingTime - 5 #substract 5 sec from the peak
maxTime = correspondingTime + 5 #add 5 sec to the peak

newY = []
newX = []

newIndex = -1

for i in range(len(x)):
    if (x[i] >= minTime and x[i] <= maxTime ):
        newIndex = newIndex + 1
        newYnumber = y[i]
        newXnumber = x[i]
        newY.append(newYnumber)
        newX.append(newXnumber)
________________________________________________________________________
# y axis values (34 cm second peak)
# we need the second peak, since that is the movement from left to right
# so read in a time range up to 20 instead of the whole x-axis for 34 cm
y2 = currentArray2[1272:]
# corresponding x axis values
x2 = timeArray2[1272:]

#Find the maximum
maximumY2 = np.max(y2)

#Find corresponding time
for i in range(len(y2)):
  if (y2[i] == maximumY2):
    correspondingTime2 = x2[i]
    break
    break
minTime2 = correspondingTime2 - 5 #substract 5 sec from the peak
maxTime2 = correspondingTime2 + 5 #add 5 sec to the peak
```

```
newY2 = []
newX2 = []

newIndex2 = -1

for i in range(len(x2)):
    if (x2[i] >= minTime2 and x2[i] <= maxTime2 ):
        newIndex2 = newIndex2 + 1
        newYnumber2 = y2[i]
        newXnumber2 = x2[i]
        newY2.append(newYnumber2)
        newX2.append(newXnumber2)

#___________________________________________________________________________
# get two graphs (of 10 seconds each) on the same vertical starting point (Y)

startingYpointGraph1 = newY[0]
startingYpointGraph2 = newY2[0]

difference = startingYpointGraph1 - startingYpointGraph2

newnewYgraph2 = []
for i in range(len(newY2)):
    newYnumber = newY2[i] + difference
    newnewYgraph2.append(newYnumber)
#_____________________________________________________________________________
# get two graphs (of 10 seconds each) on the same horizontal starting point (X)
startingXpointGraph1a = newXa[0]
startingXpointGraph2a = newX2a[0]

differencea = startingXpointGraph2a - startingXpointGraph1a

newnewXgraph1a = []
for i in range(len(newXa)):
    newXnumbera = newXa[i] + differencea
    newnewXgraph1a.append(newXnumbera)

#______________________________________________________________________________
f, (ax1, ax2) = plt.subplots(1, 2)
ax1.plot(newnewXgraph1a,newYa, label = "Depth pin: 24 cm")
ax1.plot(newX2a,newnewYgraph2a, label = "Depth pin: 34 cm")
#ax1.set_title('Moving: Right to left')

ax1.set_ylim([0, 1]) #can be adjusted to 8 instead of 1

ax2.plot(newnewXgraph1,newY, label = "Depth pin: 24 cm")
ax2.plot(newX2,newnewYgraph2, label = "Depth pin: 34 cm")
#ax2.set_title('Moving: Left to right')

ax2.set_ylim([0, 1]) #can be adjusted to 8 instead of 1

plt.tight_layout()
plt.legend(loc='best')

plt.rcParams['ytick.right'] = True
plt.rcParams['ytick.left'] = False
ax2.yaxis.tick_right()

ax1.set(ylabel='current (mA)')
ax1.set(xlabel='proxy distance [mm]')
ax2.set(xlabel='proxy distance [mm]')

plt.show();
```

Concrete pipe at test set-up B example

```
import matplotlib.pyplot as plt
import numpy as np
import pandas as pd

wb1 = pd.read_excel("Export_reeks_Meet2FELL5204_new.xlsx") #16mei2022 - 600Hz en 1 Ohm
time1 = pd.DataFrame(wb1, columns= ['distance (m)'])
timeArray1 = pd.DataFrame.to_numpy(time1)
current1 = pd.DataFrame(wb1, columns= ['IT (A)']) * 1000
currentArray1 = pd.DataFrame.to_numpy(current1)

wb2 = pd.read_excel("Export_reeks_Meet2FELL5193_new.xlsx") #16mei2022 - 400 Hz en 1 Ohm
time2 = pd.DataFrame(wb2, columns= ['distance (m)'])
timeArray2 = pd.DataFrame.to_numpy(time2)
current2 = pd.DataFrame(wb2, columns= ['IT (A)']) * 1000
currentArray2 = pd.DataFrame.to_numpy(current2)

wb3 = pd.read_excel("Export_reeks_Meet2FELL5169_new.xlsx") #13mei2022 - 600 Hz en 10 Ohm
time3 = pd.DataFrame(wb3, columns= ['distance (m)'])
timeArray3 = pd.DataFrame.to_numpy(time3)
current3 = pd.DataFrame(wb3, columns= ['IT (A)']) * 1000
currentArray3 = pd.DataFrame.to_numpy(current3)

wb4 = pd.read_excel("Export_reeks_Meet2FELL5185_new.xlsx") #13mei2022 - 400 Hz en 1 Ohm
time4 = pd.DataFrame(wb4, columns= ['distance (m)'])
timeArray4 = pd.DataFrame.to_numpy(time4)
current4 = pd.DataFrame(wb4, columns= ['IT (A)']) * 1000
currentArray4 = pd.DataFrame.to_numpy(current4)

y = currentArray1
x = timeArray1
xmin = x[:].min()
xminloc = np.argmin(x)

y2 = currentArray2
x2 = timeArray2
x2min = x2[:].min()
x2minloc = np.argmin(x2)

y3 = currentArray3
x3 = timeArray3
x3min = x3[:].min()
x3minloc = np.argmin(x3)

y4 = currentArray4
x4 = timeArray4
x4min = x4[:].min()
x4minloc = np.argmin(x4)
```

```
# get four graphs on the same vertical starting point (Y)
startingYpointGraph1 = y[xminloc]
startingYpointGraph2 = y2[x2minloc]
startingYpointGraph3 = y3[x3minloc]
startingYpointGraph4 = y4[x4minloc]

difference = startingYpointGraph2 - startingYpointGraph1 - 1

newnewYgraph1 = []
for i in range(len(y)):
    newYnumber = y[i] + difference
    newnewYgraph1.append(newYnumber)


difference3 = startingYpointGraph2 - startingYpointGraph3 - 1

newnewYgraph3 = []
for i in range(len(y3)):
    newYnumber3 = y3[i] + difference3
    newnewYgraph3.append(newYnumber3)

difference4 = startingYpointGraph2 - startingYpointGraph4 - 1

newnewYgraph4 = []
for i in range(len(y4)):
    newYnumber4 = y4[i] + difference4
    newnewYgraph4.append(newYnumber4)

# get four graphs on the same horizontal starting point (X)
startingXpointGraph1 = x[:].min()
startingXpointGraph2 = x2[:].min()
startingXpointGraph3 = x3[:].min()
startingXpointGraph4 = x4[:].min()
```

```
difference1 = startingXpointGraph3 - startingXpointGraph1

newnewXgraph1 = []
for i in range(len(x)):
    newXnumber1 = x[i] + difference1
    newnewXgraph1.append(newXnumber1)

difference2 = startingXpointGraph3 - startingXpointGraph2

newnewXgraph2 = []
for i in range(len(x2)):
    newXnumber2 = x2[i] + difference2
    newnewXgraph2.append(newXnumber2)

difference4 = startingXpointGraph3 - startingXpointGraph4

newnewXgraph4 = []
for i in range(len(x4)):
    newXnumber4 = x4[i] + difference4
    newnewXgraph4.append(newXnumber4)

plt.ylim(0, 8) #can be adjusted to 1 instead of 8
#plt.xlim(0,5) to check the first 5 meter of the sewer pipe
plt.plot(newnewXgraph4, newnewYgraph4, label = "13mei2022 - 400 Hz en 1 Ohm")
plt.plot(x3, newnewYgraph3, label = "13mei2022 - 600 Hz en 10 Ohm")
plt.plot(newnewXgraph2, y2 - 1, label = "16mei2022 - 400 Hz en 1 Ohm")
plt.plot(newnewXgraph1, newnewYgraph1, label = "16mei2022 - 600Hz en 1 Ohm")

plt.xlabel('distance (m)')
plt.ylabel('current (mA)');
```