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Chapter 4

Investigate the condition of an asset

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ABSTRACT

Monitoring the technical state of an urban drainage (UD) system is at the core of asset management, the deployment of visual inspection technology (either using direct visual access for inspection of applying photo and/or video cameras) was and has remained the main method of gathering information on the technical state. Despite some known fundamental shortcomings visual inspection is expected to remain the main source of information for inspection for the foreseeable future. This chapter discusses the virtues of visual inspection but also provides insight into other technologies that have been tried and/or deployed on a more limited scale but do offer access to more and more exact information when compared to the visual methods. Although not much experience is available, inspection techniques for nature-based solutions will be discussed as well.

Keywords: inspection techniques, condition assessment, visual inspection, outlook.

4.1 INTRODUCTION

4.1.1 Background

Urban drainage (UD) systems are capital intensive structures and, in most cases, installed along other types of networks (e.g., roads, potable water, power/energy supply). The order of magnitude of their overall length is millions of km (e.g., 392,000 km of sewer pipes in France alone in 2008, Enquête Eau, 2008). Such systems can be divided into several different asset types, as discussed in Section 3.3.1 of Chapter 8. They comprise both buried assets such as pipes and surface measures such as storm water controls.

UD infrastructure will, like any asset, deteriorate with time and use. These assets are often many decades old and remain in place beyond their expected life duration. Causes of their deterioration vary with the type of structure. However, there are common processes: ageing of the structures themselves, corrosion/erosion, loadings and impacts from the surrounding environment, lack of maintenance, errors induced by improper maintenance or upgrades in the sewer system and misuse of the facilities by citizens. Interested readers can refer to Chapter 5 which considers these processes in detail.

It is important to understand the condition of UD assets to ensure that their capacity remains sufficient and to minimize the risk of catastrophic failures. A UD network should convey wastewater and storm water runoff to a treatment facility to prevent pollution and health risks and should also reduce the likelihood of flooding. An asset in poor condition will often have a reduced capacity usually due to a reduction in cross-sectional area, increased roughness, and/or increased head loss. Poor understanding of asset condition can lead to underestimation of network repairs, renovation, and renewal costs. There will be a moment in time at which it will be more cost effective to replace an asset rather than to continue to use a deteriorating asset which is beyond its expected service life. This is especially the case where a utility faces regulatory fines for causing pollution and compensation pay-outs for flooding, but even increased infiltration will have a cost impact due to increased pumping costs.

Climate change is likely to increase the pressure on UD assets. In most design standards, sewer pipe diameters/shapes are often chosen to ensure a sufficient velocity during dry weather conditions (in order to reduce sedimentation and hence the likelihood of H_2S production) and provide capacity for the design flow. Climate change is expected to result in more extreme droughts, heat waves and rain events, thus leading to more favorable H_2S production conditions and higher velocities during rain events. Thus, corrosion and erosion processes will likely increase during the coming decades. Knowledge of asset condition and how it is changing will therefore become more important as processes affecting deterioration change and potentially even accelerate.

There is an increasing use of blue/green infrastructures which are often multi-use spaces, for example, the land is also used for sport or leisure activities, gardening, and so on. Such plural purposes can lead to degradation/soil compaction and therefore, decreasing hydraulic/infiltration capacities. Any infiltration-based solution can be affected by decreasing infiltration capacity due to clogging of pore spaces.

Engineered drainage structures suffer from a range of defects: the structure can deform or crack, the material can corrode and erode, joints can move and become non-water tight, allowing roots and soil ingress, debris can build up along the pipe invert as well as become attached to the walls, and the structure can be damaged due to work on surrounding infrastructure, or be subject to poor modifications – for example, adding new pipe connections. Inspections are vital to understand the current condition of assets and to plan future maintenance, rehabilitation, and replacement. The comparatively low value attributed to water and the complexities associated with buried pipes in a range of materials has resulted in UD inspection receiving less attention than pipes for higher value and higher risk activities such as the transport of oil and gas. As a consequence, apart from CCTV inspection, not many inspection technologies (Figure 4.1) are applied on a wide scale in UD.

The first part of this section gave a general overview (but not exhaustive) of the main causes of sewer system degradation. Overall, such processes lead to reduction of UD service through decreased capacities. Consequences are wide ranging: pollution of surface/bathing water with possible impacts on public health, urban flooding events, increased energy consumption of pumps, structural collapses that could lead to above ground road or building damage.

4.1.2 Which data to collect

It has been established that UD network assets deteriorate in different ways, are made of different materials and come in different shapes and sizes, which are not always properly recorded in asset databases. Furthermore, the date at which an asset had been originally constructed will have an impact

Figure 4.1 Typical CCTV inspection crawlers showing differing sizes (left) and tethered crawler entering pipe from a benched manhole (right). (Courtesy Will Shepherd).

on many parameters, for example, concrete technology, pipe jointing and manufacturing techniques have changed with time. Traditionally, inspections have been visual, and hence subjective and narrative based, however, sensor technology is developing rapidly allowing objective measurements, albeit with some degree of uncertainty.

Table 4.1 gives a very brief overview of some of the most frequent defect types. Defects can broadly be divided into those which are primarily structural, that is, their main impact is on the structural integrity of the sewer; and operational, that is, their main impact is on the functioning of the sewer, usually through reduced capacity. Some inspections record other information, such as the presence of vermin, or water colour, which have no clear impact on either the structure or serviceability. Clearly there are linkages between structural and operational defects and some defects fall into both categories, especially a well progressed structural defect which can reduce the pipe cross section and hence reduce capacity. This chapter cannot exhaustively list all the required data to assess the status of UD systems and Chapter 8 is focusing on this subject. However, general specifications of needed data are included.

Table 4.1 Example defects.

Category	Defect Type	Details
Structural	Deformation	The pipe cross-sectional shape has been deformed, quantified by a percentage change in dimension and orientation.
Structural	Crack	The pipe wall is displaying a crack. The magnitude varies from a surface crack to an open crack, the orientation can be longitudinal, circumferential, helical, or a combination.
Structural	Joint defects	The joint is displaced perpendicularly or longitudinally with respect to the pipe direction. The magnitude in millimetres or relative to the pipe wall thickness is recorded
Operational	Roots	Plant roots have entered the sewer through joints or defects, the size of the roots and magnitude of cross-sectional area reduction is recorded.
Operational	Debris	Foreign solid materials are present in the pipe, the nature of the material – fine, coarse, grease, and so on and the reduction in cross-sectional area is recorded.
Operational	Infiltration	Water is entering the pipe at a joint or defect, the rate of the infiltration is recorded.

To conduct investigations into the status of systems, high-quality data are required. 'High quality' implies that two aspects need to be respected: objectivity and accuracy of data. Objectivity is rather important, especially in the common case of visual inspections. Dirksen *et al.* (2013) demonstrated that the output of visual inspection could be quite different depending on the operator in charge of coding the defects. Subjective data interpretation might therefore lead to erroneous decisions. To ensure the quality of data, a validation step is vital. Clemens-Meyer *et al.* (2021) discuss this aspect in detail. Important considerations include the plausibility and consistency of the data. Clearly, the quality and maintenance status of any equipment used for the collection of data will impact on the accuracy of the data collected, as will the training and experience of the operators.

Additionally, to the clearly stated needs of objectivity and accuracy and despite the technological capabilities of new sensors, a few limitations of inspection techniques should be highlighted. At the time we write this chapter, some relevant data cannot currently be practically and non-destructively measured in the field at large scales: for example, wall thickness (i.e., the previous example assumes the initial thickness of the pipe) nor infiltration rates over a large basin or trench.

Depending on the technologies and the design of the inspection devices, some blind spots remain for example, CCTV cameras cannot take footage below the water level, or a fixed camera will not be able to see behind an intrusive connection. The size of blind spots can be reduced with the combination of different technologies, smarter design of inspection devices and/or improved inspection procedures (e.g., one survey from downstream to upstream and another one in the opposite direction). Data users must be aware of those limitations prior to using such data, for example, for planning maintenance operations.

4.1.3 Layout of the chapter

The present chapter gives a non-exhaustive overview of the existing (Section 4.2) and emerging (Section 4.3) technologies for inspection of key UD assets. The boundary between both categories (i.e., existing and emerging) is blurred, and strongly depends on the expertise of the reader. The authors applied the following rule to distinguish as to what is presented: while existing technologies seem mature enough to be deployed at a larger scale (having received prior effort in the development of industrial solutions), emerging method still require research effort to (un)validate those techniques for asset inspection. This chapter ends with conclusions about the technologies presented in this book.

4.2 EXISTING INSPECTION TECHNIQUES

4.2.1 Background and overview

Until the 1950s, the only method for sewer pipe inspection was person-entry, which not only has health and safety implications, but also limits the minimum pipe size that can be surveyed (which is likely to be 900–1800 mm, subject to local working practices and occupational health and safety requirements). Clearly, in the early years before electric lighting provided good illumination, visual inspections would be challenging to complete efficiently. Furthermore, these large diameter pipes generally only account for a small proportion of the network, for example, the WRc Sewerage Rehabilitation Manual estimated that only 5% of the UK sewer network was large enough for manual inspection. Early camera inspections used black and white cameras fitted to a sled dragged through the pipe and could survey pipes down to 200 mm in diameter. As with all video technologies, sewer CCTV has developed significantly, enabling nowadays high-quality colour images and recording, initially to VCRs and later digitally.

Whether by person-entry or using remote CCTV, visual inspections are subjective and limited to visible features, that is, nothing beyond the internal pipe surface, or below the water surface can be inspected.

This section considers inspection techniques that are commercially available, even though some might be rarely used. The techniques are divided into functionality-oriented and defect-oriented inspections. Functionality-oriented inspections are where the inspection is directly measuring a parameter that can represent the structural or operational performance, for example, internal size or infiltration, whereas defect-oriented inspections use techniques which identify a range of different defects in the pipe, such as cracks and blockages, but might not accurately measure them.

4.2.2 Functionality-oriented inspection

This section is divided into different parameters being measured and within each section a selection of the more commonly used techniques is described.

4.2.2.1 Geometry

The internal geometry of a pipe is vital to maintain its design capacity, but it can change due to deformation, corrosion, and erosion processes. Several techniques can be applied to measure the inner geometry of sewer pipes: choice among them is mainly driven by the expected accuracy, pipe materials, available budget and the time required to conduct the inspections. Several techniques or prototypes have been published during the last decades, with a wide range of applications; they mainly differ with respect to costs, detectable defects, and accuracies.

Acoustic technologies have been developed and tested since the late 1970s (Morgan & Crosse, 1978). They offer quick and cheap inspections but only a few defects are detectable (i.e., rough estimation of their location and barely any quantification is possible). While using a speaker and several microphones along a reach, Bin Ali *et al.* (2011) highlighted the feasibility of lateral connection and blockage mapping with a signal processing algorithm (time and frequency domain). Acoustic measurements could also be performed with sonar – such a technology allows accurate measurement of the inner geometry below the free surface and in pressurized pipe (for more details, see Section 4.2.2.8).

Optical measurements are feasible using Manhole Zoom Camera (MZC). Such cameras, accurately positioned in the middle of the cross section allow the recording of footage or video from which defects and geometry anomalies can be detected. However, the maximal inspection distance varies from 20 to 30 m and the accuracy is relatively low. Plihal *et al.* (2016) compared both acoustic and MZC measurements: acoustic measurements seemed less sensitive to inspection conditions (e.g., flow, displaced joints) and offered a maximal inspection distance two orders of magnitude larger than the optical ones. The combination of both types of measurement remained highly suggested by the authors.

Laser profiling of the internal parts of a pipe is commonly used for checking ovality and deformation. A laser beam or beams measure(s) the internal cross section of the pipe, thus any differences from the expected shape and size can be inferred to be a defect. As reported by Clemens *et al.* (2015), the alignment and orientation of the laser is however critical to ensure accuracy. Clemens *et al.* (2015) went on to suggest a method for correcting for alignment and orientation; this was further developed and described by Stanić *et al.* (2017), who showed an increase in measurement accuracy of 5–10 times. Testing by Lepot *et al.* (2017b) showed that the technology was robust to most types of challenges, except for reflective and transparent materials which are not common in sewers. Meijer *et al.* (2022) report on the application of stereovision to identify anomalies in sewer pipes realizing comparable accuracies as Lepot *et al.* (2017a, 2017b, 2017c).

Investigating the use of vision-based and laser-based techniques for 3D mapping of sewers, Bahnsen *et al.* (2021) carried out a review of the different technologies. They also assessed the impacts of available light and the in-pipe water level, concluding that the time-of-flight sensors provided superior output to camera-based systems.

4.2.2.2 Roughness

The hydraulic roughness of pipes is often considered as an important (design) parameter related to the hydraulic performance of UD systems (for both the hydraulic capacity and the minimum dry weather flow velocity). In the course of time the hydraulic capacity can decrease due to sedimentation, FOG deposits and for certain materials corrosion (see also Chapter 5). This notion, however, is only

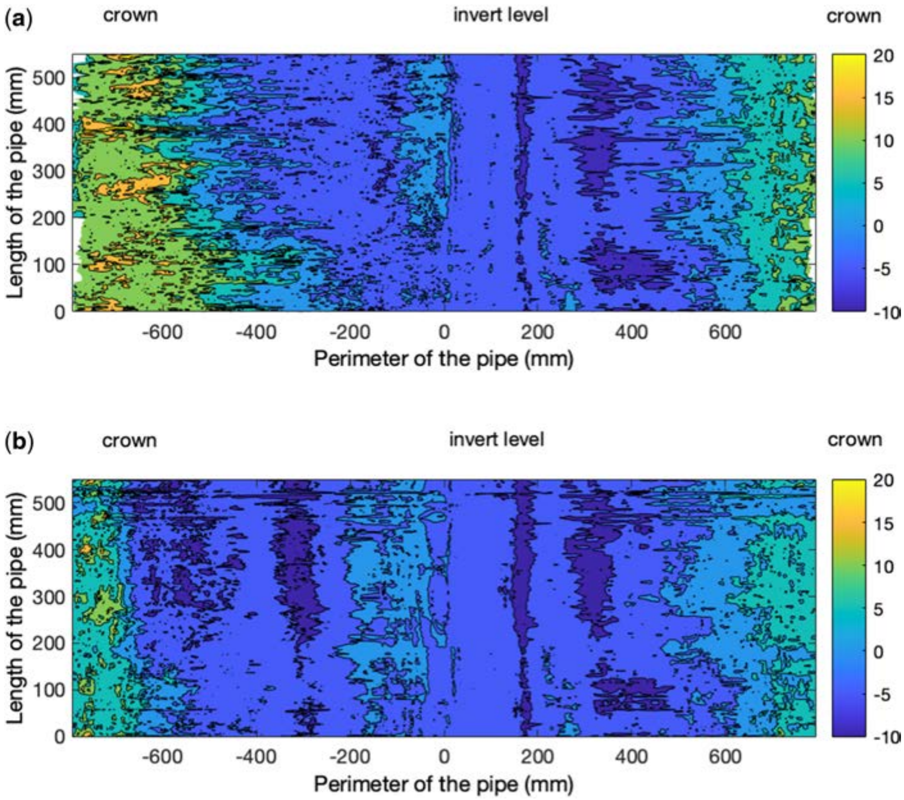


Figure 4.2 Mapping 3D inner geometry in order to derive K_n values from a first (top) and second (bottom) version of a laser scanning prototype. (*Source*: Stanić *et al.*, 2017).

seldom taken into account when making a new design (even though design manuals often prescribe a material dependent value for either manning's 'n', or Nikuradse's k_n equivalent roughness value). Determining the in-situ wall roughness as such of a sewer pipe seems for now a practical impossibility, determining the overall hydraulic capacity based on for example, calibration of a hydraulic model using measurements has been shown to be possible (see also Chapter 5). Stanić *et al.* (2017) reported on the application of laser scanning (Figure 4.2) of excavated concrete sewer pipes that had seen ~ 90 years of service in a combined sewer system that showed clear signs of crown-corrosion and found that the uncorroded parts of the pipe wall had k_n value of ~ 1.5 mm while the corroded parts (upper half of the pipes) showed k_n values of up to 12 mm. This implies that the generally accepted design values of 1.5 mm seem to hold true for sustained periods for the DWF situation; however, when the system fills up the hydraulic roughness increases significantly. For a case study Stanić ($k_n = 20$ mm) estimated a 100% increase of the head losses compared to the design situation (even without taking into consideration the presence of sediments and/or FOG deposits).

4.2.2.3 Inclination/invert levels

Measuring the invert elevations of individual pipe segments of a stretch of sewer may become important in situations in which subsidence may occur. Given that sewer inclinations can be as little as 0.2%, measurement resolution and accuracy is important. In the course of time uneven settling may

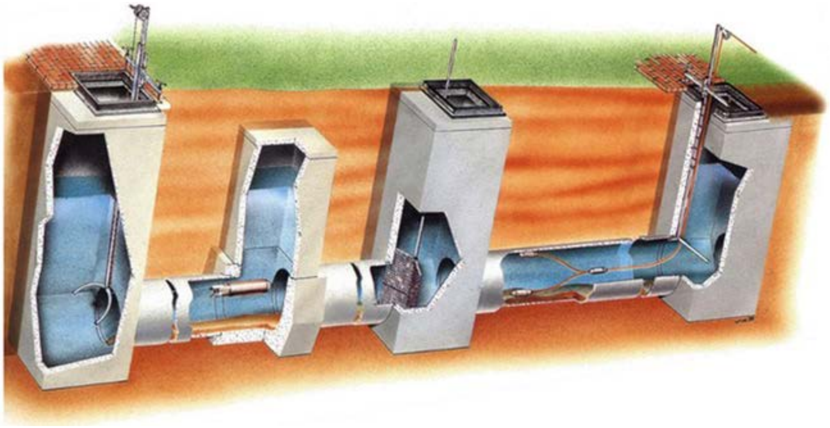


Figure 4.3 ATU system layout in a sewer. (Courtesy van der Valk + de Groot).

lead to the formation of stagnant pockets of (waste)water where sediments may accumulate giving rise to anaerobic conditions triggering biochemical induced corrosion (see also Chapter 5) and H_2S generation/emissions leading to potentially deadly working environment for practitioners. This can be done using the ATU method (Afzetting Traceer Unit (Dutch)/Deposition Tracking Unit (English)), see Figures 4.3 (system layout), 4.4 (surface setup) and 4.5 (measurements). An alternative method based on inclination measurement was described in some detail by Dirksen *et al.* (2014).

When making estimations of the amount of work involved in cleaning out a stretch of sewer from either sediments or FOG encrustations, a method based on pressure measurement is deployed in practice. The basic idea is simple: two pressure sensors are slowly dragged through a stretch of sewer (filled with water). One of these sensors is dragged along the bottom while the other, lighter than water, is dragged along the soffit of the pipe. When recording the location (i.e., its position along the length of the pipe), an indication of the amount of material to be cleaned out is obtained. As part of the procedure, a torpedo is sent through the pipeline with a pulling wire directed to the reception manhole (see Figure 4.3). After calibration of the equipment with a third sensor, the sensors can be pulled through the pipeline and the measurement can be started.

Figure 4.4 shows an example of the measuring set up. Figure 4.5 shows an example of the measuring results.

This asks, however, for prior detailed knowledge of the original profile of the sewer to be investigated. There are some limitations to the application:

- The stretch of sewer must be filled with water, so it is ideal for application in inverted siphons or pressure mains.
- As the variation in thickness of sedimentation and/or encrustation can be small (i.e., order of magnitude 1–2 cm) the pressure sensors must be accurately calibrated and have a high accuracy and resolution.
- The latter demand implies that accurate results can only be obtained when the sensors are dragged at a low pace to avoid disturbances on the pressure read out, caused by the movement of the sensors.

When interpreting the results, the following aspects have to be taken into account:

- Dragging a sensor over a sediment bed is an invasive method, this implies that the obtained results may show a systematic deviation (most likely an underestimation).

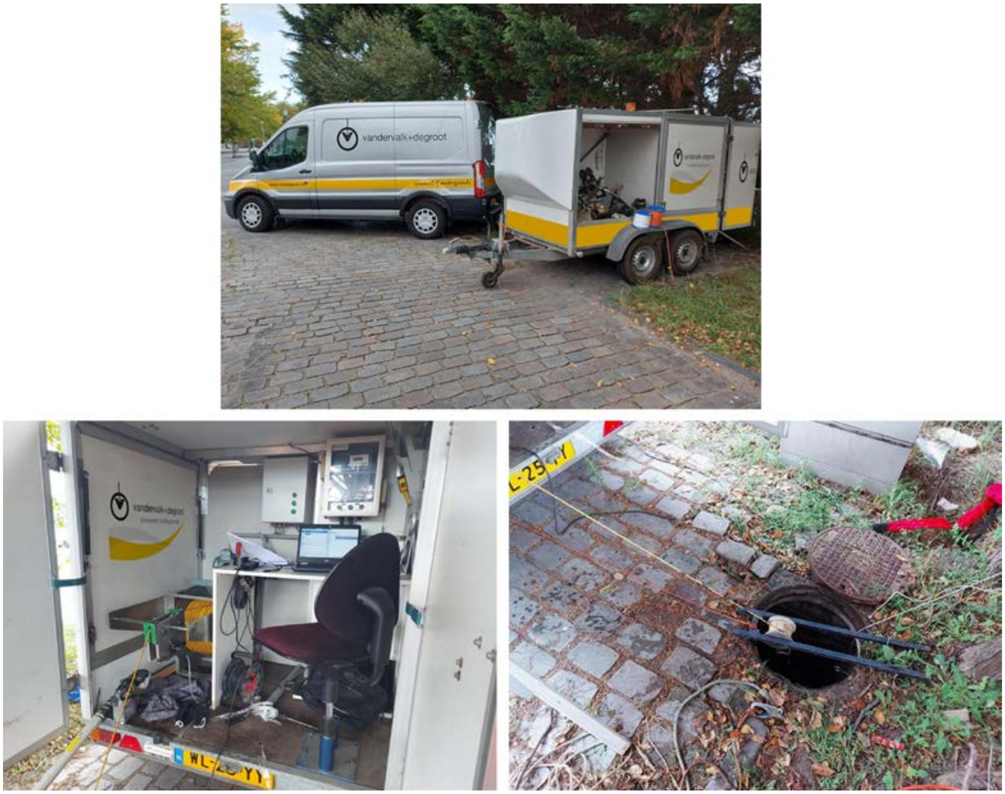


Figure 4.4 Set-up at the manhole. (Courtesy van der Valk + de Groot).

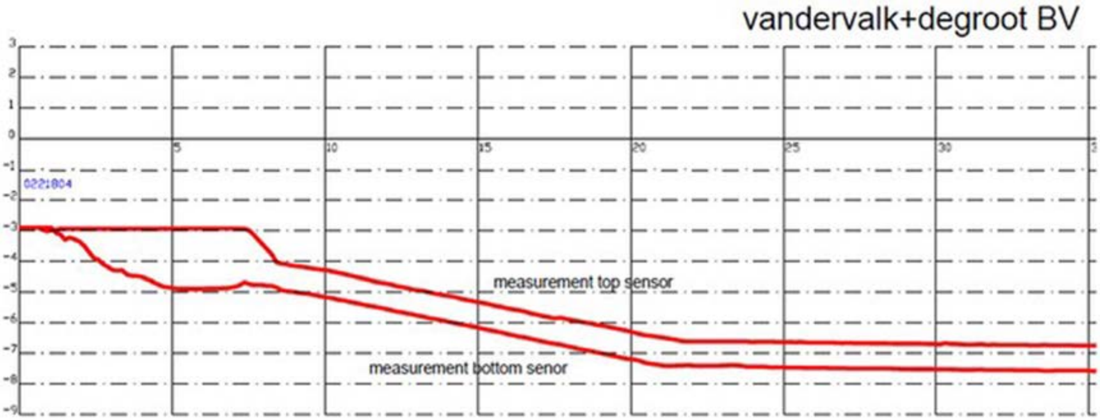


Figure 4.5 Start of the measurement of a culvert and a waterway. (Courtesy van der Valk + de Groot).

- The result is only valid at one point of the cross section, while the exact 3D position of this point is unknown.
- Given the previous point, when one wishes to estimate the volume of sediment the assumption of a homogeneous sediment level over the width has (implicitly) to be made.
- A further source of uncertainty is the position along the length of the pipe, although this seems to be relatively small compared to the other sources mentioned.

In spite of the limitations mentioned, the method described is applied with success in practice, has shown to be robust and produces results that at least allow indications of the amount of materials to be removed to be obtained. Apart from that, it also allows for a verification of the effectiveness of a cleaning operation and/or for performing an acceptance test after (re)construction.

The depth of pipelines and possible deformations of horizontal directional drilled pipelines can be reported. The ATU system shows the critical locations of subsidence and sludge deposits, so measures can be taken for preventive or corrective maintenance. In the context of this book, the most regular application of the ATU method is to determine the amount of FOG deposits in siphons, see for example, Chapter 5 (Section 5.8.2, Figure 5.44). However, other applications of the technology can be highlighted as well. For example, when raising a terrain in soft soil conditions, for example, at waste dump locations or at land reclamation sites the settlement of the area concerned can be measured by installing an HDPE pipeline at the location of the area to be filled. The monitoring of the settlements can be done with the ATU system by periodic measurement of the HDPE pipeline. No definite information on accuracy is available, but this is estimated to be in the order of magnitude of 1–2 cm in level. It is crucial to have the pressure sensors calibrated to a high level of accuracy in order to obtain useable results.

It has to be emphasized that there is no guarantee that the track followed by the sensors along the length of the pipe is always parallel to the length axis of the pipe under study; therefore, systematic deviations with an unknown magnitude may, and will, occur.

The method proposed by Dirksen *et al.* (2014) is only applicable in a cleaned-out sewer and utilizes a sewer tractor (IBAK KRA85) on which an inclinometer and a distance measuring device are mounted.

Figure 4.6 provides a sketch of the setup: the tractor is pulled, and the displacement is counted by the number of rotations of the pulley (with one revolution equal to 10 cm). The values for the distance and inclination measured are stored for further analysis.

Dirksen *et al.* (2014) showed that the tested equipment had an overall uncertainty of 0.05%, although when the tractor wheels are in different pipe sections, that is, straddling a joint (see Figure 4.7), the random error increased to 0.14%. A systematic error of 0.09% was determined; with this being close to the unit's 0.1% resolution, it was suggested that the resolution should be increased to 0.01%. Overall, it was suggested that as the random errors cancel out, these measurements of inclination can be useful and that systematic errors might be reduced by an improved calibration methodology.

From the measured inclinations and distances, an invert profile of the sewer can be derived. In a case study Dirksen *et al.* (2014) arrived at a confidence interval (95%) of 0.032 m (see also Figure 4.8).

4.2.2.4 Wall thickness

The remaining thickness of pipe walls is routinely monitored in industrial applications by techniques including guided waves and electro-magnetic acoustic resonance (EMAR); however, such technologies are rarely applicable to buried UD pipes because they had been developed for ferrous pipes and/or are applied from the outer surface of the pipe. The use of laser measurements, as discussed in Section 4.2.2.1 can be used to determine the difference between the expected and actual internal dimensions and thus infer remaining wall thickness; however, it cannot account for losses in the wall occurring outside the pipe. Pipe penetrating radar (PPR) is applied commercially and can provide accurate measurements of wall thickness, reinforcement location and developing voids outside the pipe (Ékes & Mahmood, 2019). PPR is however a contact method, and the accuracy is a function of environmental

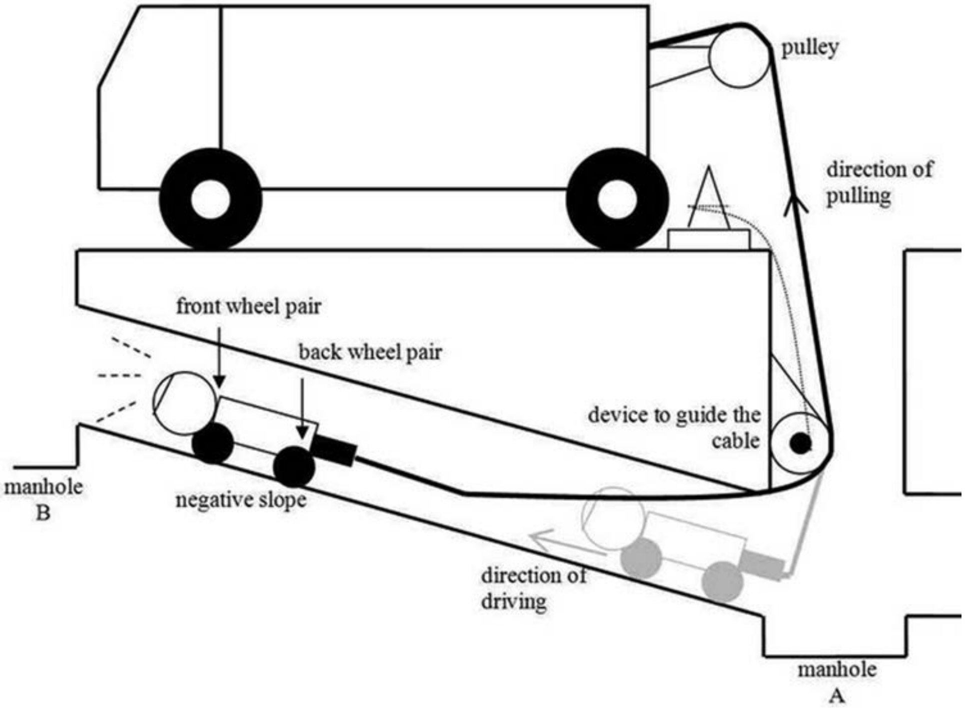


Figure 4.6 Set-up of the inclinometer. (Courtesy J. Dirksen).

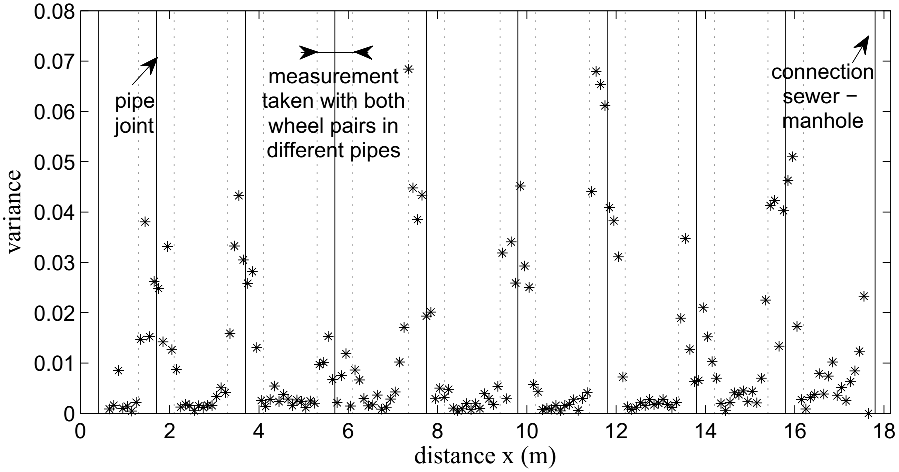


Figure 4.7 Variance in the slope measurement as a function of distance. The variance in the measurements increases around the individual pipe joints. This is due to very local differences in invert level around these joints.

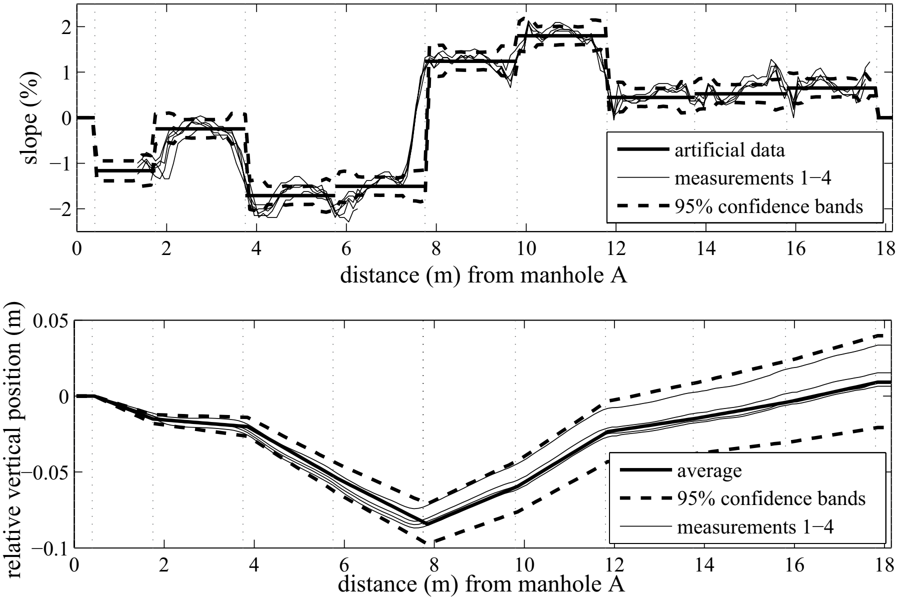


Figure 4.8 Confidence intervals for a case study over a sewer length of 17.35 m. (Courtesy J. Dirksen).

factors, calibration and survey quality. While good results have been obtained for concrete pipes, the presence of a layer of soft, deteriorated concrete reduces its accuracy. Such deteriorated concrete should therefore be scraped off to ensure an accurate measurement, further increasing the time and cost of such inspections. Wall thickness variations can be quite localized; thus, the survey technique needs to take this into account, otherwise uncertainties will be significant.

4.2.2.5 Material properties

When assessing material properties hitherto the most applied method is to take samples for lab testing, as in-situ methods are, to the authors' knowledge, lacking. There is some literature on the potential of applying in-situ acoustic methods to determine material properties of plastic pipes (see Makris *et al.* 2023); however, the uncertainties encountered are prohibitive for practical application so-far.

Even when taking core samples for determining material properties (i.e., tensile strength, porosity, density, etc.) in concrete, care has to be taken with the use of the data obtained. Stanić *et al.* (2016) reported on the effect of the heterogeneous nature of old concrete pipes with respect to the uncertainty of tensile strength results. They arrived at the following conclusions:

- The heterogeneity of concrete pipes increases with time; newly produced pipes show very homogeneous material properties (the latter may be contributed to the modern well-controlled production conditions, when compared to pipes produced on the construction site prior to ∼1960).
- In old pipes up to 112 samples per meter may be needed to obtain a reliable estimate of tensile splitting strength; for new pipes this would only be seven samples.

This implies that, given the fact that taking core samples is a destructive method; one has the choice between either taking a few samples and work with uncertain values or taking so many samples that one knows exactly how strong the pipe was prior to testing while having caused significant structural damage by the testing.

Another observation made relating to core samples is that the correlation between material properties as obtained from core samples and the results of CCTV inspection reported along generally accepted standards, is virtually absent (see Stanić *et al.* 2013), which underlines the notion that visual inspection does not necessarily relate to physical properties. This is also illustrated by a very detailed study published by Luimes *et al.* (2023) in which the penetration depth of corrosion processes in the wall of several old (used) concrete sewer pipes was quantified and proved to be very inhomogeneous.

These findings illustrate the need for the development of non-destructive methods for producing reliable estimates of material properties.

4.2.2.6 Infiltration and (il)licit inflows

Several techniques are available to measure unexpected flows entering a sewer (e.g., infiltration, illicit inflows, or cross-connections). They are mainly based on discharge measurements, tracer experiments, and thermography.

For decades, discharge measurements and their correlations with rainfall data have supported sewer managers in the investigation of infiltration and/or cross-connections in separate sewers. For combined or domestic sewage, the statistical analysis of discharge data during dry weather conditions over long-term time series is likely the widest applied method to quantify infiltration. Seasonal tendencies of the minimal flowrate (i.e., typically, in the middle of the night) deliver information on existing infiltration (de Bénédittis & Bertrand-Krajewski, 2005). In separate sewer systems, a positive correlation between discharges and rainfall data indicates cross-connections contributing toward the sewage.

Tracer experiments are widely used either to quantify infiltration or pinpoint cross-connections in separate sewers (Ellis & Butler, 2015). With regard to the latter, dye experiments, smoke tests (Beheshti *et al.*, 2015) or coloured and numbered 3D-printed pills (Lepot *et al.*, 2016) can be used. If dye experiments or pills require access to private property, smoke tests can be applied from the public area (see Figure 4.9).

Changes in temperature are a strong indication of an incoming flow, which could be infiltrated via licit or illicit connections. Thermography is mainly used for detecting infiltration or illicit connections. Fiber optics are deployed commercially at a relatively small scale offering distributed temperature sensing (DTS). DTS can detect inflows and illicit connections along a reach (Figure 4.10), while using the difference in thermal footprint of different water sources (see e.g., Hoes *et al.* 2009; Vosse *et al.* 2013). This method can provide measurements for a long period, but it is spatially limited by the length of the cable.

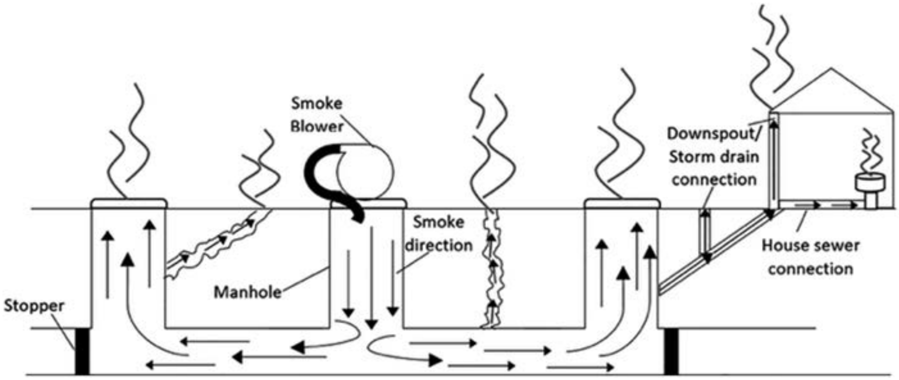


Figure 4.9 Principle of smoke test to pinpoint cross-connections in separate sewer system. (Reprinted with permission from Beheshti and Saegrov (2019).

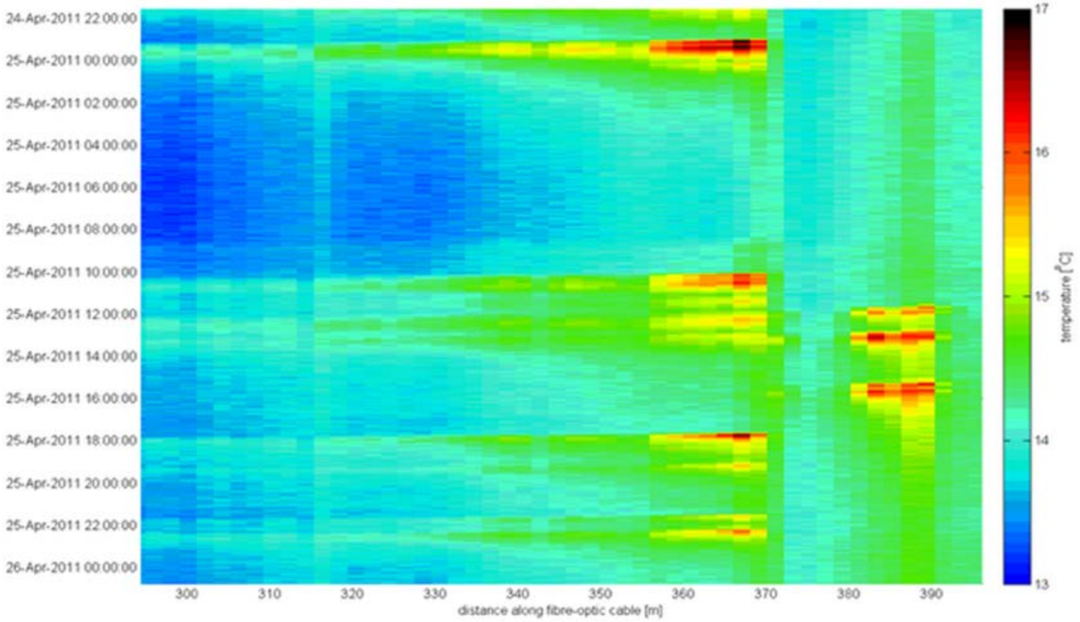


Figure 4.10 Example of connection locations with fibre optics (Courtesy R.P.S. Schilperoort).

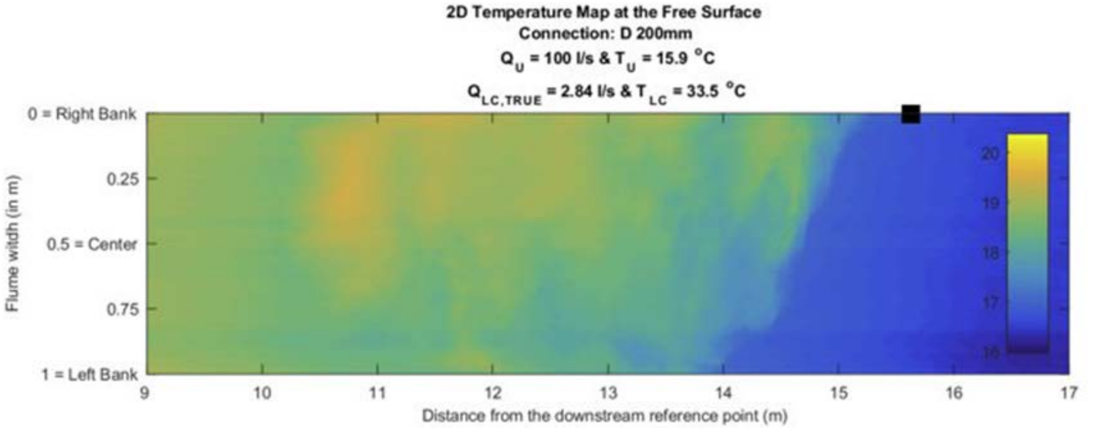
Mounting an infra-red camera (Lepot *et al.*, 2017a) on a moving/flying platform inside the pipe could increase the inspectable length. However, the inflows being detected are not always continuous as shown in Figure 4.10; as a result, this inspection will only identify active inflows (e.g., during a rain event or when an illicit connection is in use). This technique offers a good sensitivity but is sensitive to the type of connection, the rate between lateral and main discharges and the temperature difference between both flows (Figure 4.11).

Both solutions (DTS and internal use of an IR camera) deliver accurate inflow locations since the thermal effect of the lateral connection can be monitored immediately downstream and can be applied without service disruption. In comparison to CCTV footage, the thermal fingerprint allows the type of connection to be identified (i.e., warm or cold) giving an additional key to pinpoint the source of infiltration.

While only applicable to stormwater pipes, Chandler and Lerner (2015) developed a simple, low-cost method to identify some illicit connections. The method relies on the presence of optical brighteners, which do not occur naturally, but which are present in laundry detergents, toilet paper, and cleaning products. Optical brighteners have a strong affinity for fabrics such as cotton and can be seen under ultra-violet light. In the study, cotton tampons, free from optical brighteners were placed in stormwater pipes and shown to successfully identify illicit connections.

Panasiuk *et al.* (2022) directly compared a range of the aforementioned techniques, concluding that the methods studied showed variable performance and that a combination of two or three methods would improve the efficiency of investigations.

At a catchment scale, various methods to estimate the amount of groundwater infiltrating into a UD system over a long period are available (see e.g., Weiß *et al.* 2002). These methods use the measured inflow to a waste-water treatment plant (WWTP) and discriminate between days with and without rainfall. Further, it is assumed than on dry days the discharge equals the theoretical amount based on the number of inhabitants and known industrial contributions (see Figure 4.12). These methods



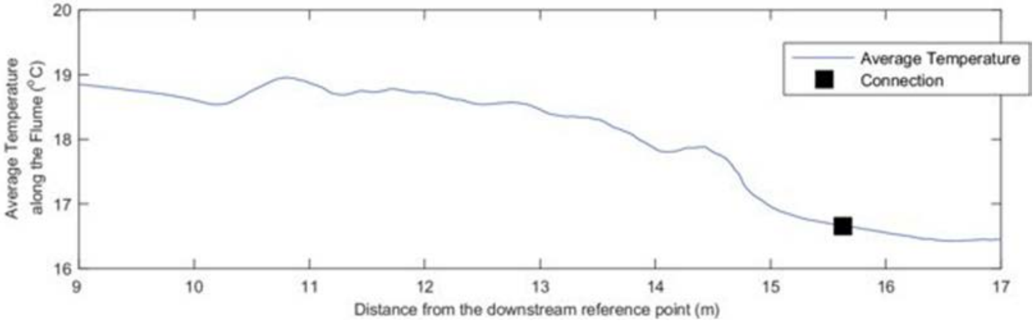


Figure 4.11 Temperature map reconstructed from IR camera footage for a warm lateral connection. (Source: Lepot *et al.*, 2017a).

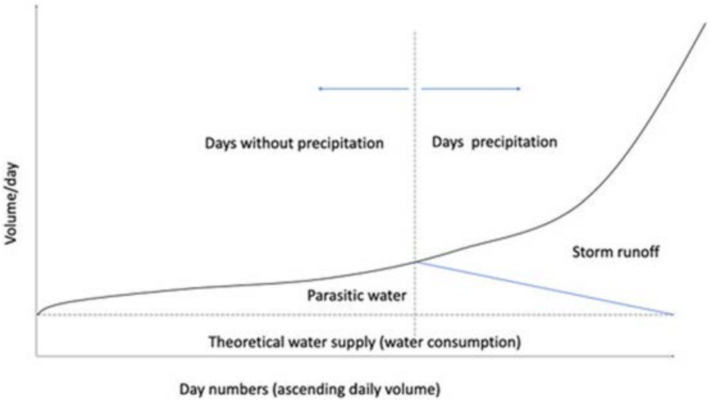


Figure 4.12 Illustration of the 'triangle method' to quantify inflow/infiltration based on very basic measurements. (Courtesy Deltares).

cannot be considered accurate, but they have the advantage of being simple to implement and use data that are generally readily available.

Kracht *et al.* (2003) presented an elegant method to quantify the infiltration at a catchment scale using small time windows. Their method relies on a difference in isotopic composition of the water in a UD system and the infiltrating groundwater. Basically, each waterbody has a specific ratio R between the isotopes of oxygen, defined as

$$ {}^{18}R(O) = \frac{\left[{}^{18}O\right]}{\left[{}^{16}O\right]} \tag{4.1} $$

The 'Vienna Standard Mean Ocean Water' or VSMOW, which is a world-wide reference water, defines the so-called δ value:

$$ {}^{18}\delta = \frac{{}^{18}_{s}R}{{}^{18}_{\mathrm{VSMOW}}R} - 1 \tag{4.2} $$

Hence, a negative value implies a lighter isotope composition; a positive value indicates a heavier isotope composition compared to the reference water composition. This can be seen as a 'fingerprint' of a water body. Provided that the values of the water in the UD system and the groundwater differ, this can be used to quantify the relative amount of groundwater infiltrating:

$$ b = \frac{{}^{18}_{\mathrm{DWF}}\delta - {}^{18}_{\mathrm{DW}}\delta}{{}^{18}_{\mathrm{INF}}\delta - {}^{18}_{\mathrm{DW}}\delta} \tag{4.3} $$

In which, DWF indicates dry weather flow, INF indicates infiltrating water (i.e., groundwater, surface water) and DW indicates drinking water. It is assumed that in a system without parasitic water the isotope composition of wastewater would be equal to that of drinking water and that the source of infiltration is known and stable in terms of its δ value.

Given the known uncertainty in the determination of the values, the uncertainty in the relative amount of infiltration can be determined. Of course, this method falls short when the composition of the groundwater is not homogeneous, or when the drinking water is produced from different sources. The advantage of this method, however, is that it is relatively cheap to perform and allows the evolution over time of the infiltration to be evaluated and relationships to be determined with, for example, the variation in groundwater levels. Schilperoort (2004) reports on the application of the isotope method in a number of case studies,

4.2.2.7 Exfiltration

Exfiltration phenomena can be detected with other technologies. Aerial thermography seems to be a rather effective way to pinpoint locations of leakage at a large scale (Park *et al.*, 2020): areas where exfiltration occurs present a different thermal pattern (i.e., two images are required: one in the morning, one in the afternoon). Even though this method appears promising, weather and local environment (e.g., shadows) could induce serious bias in the measurements.

Ground penetrating radar (GPR) presents capabilities to measure exfiltration and their consequences. The back-scattered electromagnetic signal allows the positioning of the pipe itself, voids induced by leakage and high soil moisture (Ghozzi *et al.*, 2018; Sonkamble & Chandra, 2021).

Sewer exfiltration can be quantified using tracers; this generally involves injection of tracers at two different locations and comparing the mass recovered at a downstream location. Through careful selection of tracers and analysis of the results, quantification of exfiltration volumes can be estimated with good accuracy, as discussed by Rieckermann *et al.* (2007). However, the methodology is time-consuming to apply on anything but a small scale and requires careful application to minimize uncertainties.

Mobile geo-electrical measurement involves moving an electrode through a (partially) filled pipe and inserting a second electrode (grounding pin) into the earth. Stegeman *et al.* (2022) have shown this method to accurately identify the location of a leak; however, there is no clear dependence between the recorded current and the size of or flow from the leak.

In addition to the application of isotopes as natural tracers, literature (e.g., Rieckermann *et al.*, 2007) also describes the use of injected tracers (typically lithium salts or heavy water) to determine in- and exfiltration. These methods, however, prove to be hard to apply in day-to-day practice, requiring specialized personnel and are therefore limited to special cases. For details the reader is referred to Ellis and Bertrand-Krajewski (2010), who provide a comprehensive text on methods to determine in- and exfiltration. Schilperoort (2004) provides a comparison between the isotope method and more conventional methods (like the method proposed by Weiß *et al.*, 2002) using a range of case studies.

Determining the location(s) of in- or exfiltration is less straightforward. The presence of cracks or defective joints indicates the possibility of in- or exfiltration; however, this is not a given fact (unless of course groundwater is observed to enter on CCTV footage, see e.g., Figure 4.13).

In literature various methods are described to identify leakages. Distributed temperature sensing (Hoes *et al.*, 2009) may be applied. Using a focussed electro leak location (FELL) (Eiswirth & Heske, 2000; Wilmut *et al.*, 2005; Wolf, 2003; Stegeman *et al.*, 2022) as shown in Figure 4.14, the location of leakages can be determined with some accuracy, the main assumption here is that electrical

Figure 4.13 Example of clearly observable infiltration.

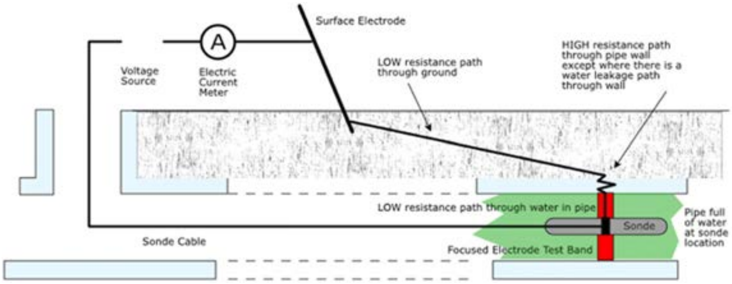


Figure 4.14 Simplified schema for FELL. (After Wilmut *et al.*, 2005).

conductivity is directly proportional to the in- or exfiltration of water, which has, to the authors' knowledge, not been proven. A detailed evaluation of the FELL is provided by Vermeulen (2022). Quantifying exfiltration is a subject on which not much literature exists. Vollertsen and Hvitved-Jacobsen (2003) report that the exfiltration rate at pilot scale experiments reached a stable value after some days and stayed constant over longer periods of time. They further report the formation of a clogging zone that strongly determines the exfiltration process.

Leakage in pressure mains can be detected at an early stage using a range of methods:

- Pressure testing (either with air or with water) allows a rough quantification.
- FELL.
- The use of tracer experiments as mentioned in Section 4.2.2.6 (these methods can, to a certain extent, quantify leakage; localization is possible but at a relatively low resolution determined by the accessibility of the system and assuming the leakage is near the injection point and the tracer is well mixed).
- Acoustic methods: leak noise correlation (Almeida *et al.*, 2014; Brennan *et al.*, 2016), allows localization, albeit very small leaks are still hard to pinpoint. The Smartball measuring system (Pure Americas Inc., 2011) passes through the mains recording the location of leaks to within 1.8 m; operators have however reported challenges in retrieving the un-tethered Smartball.
- Time domain reflectometry (see e.g., Fatemi Aghda, *et al.*, 2018).
- Distributed acoustic sensing (DAS) (see e.g., Stajanca *et al.*, 2019).
- Distributed strain sensing (DSS) (see e.g., Zhang *et al.*, 2019).

A disadvantage of the latter two methods is that wires need to be installed, preferably during construction which is mostly not an option for existing systems. Managing authorities are well advised to consider doing so in newly built situations, as TDR and DTS allow for relatively easy and almost continuous monitoring for leakages.

A recent and comprehensive overview on leakage detection is found in Sadeghikhah *et al.* (2022).

4.2.2.8 Sedimentation

Sediment deposits are detectable and, sometimes, quantifiable. Several technologies can be used for this purpose depending on the measuring conditions. If the pipe is dry (often implying a service disruption in the case of sanitary or combined sewer systems), standard CCTV or lately tested laser profiling/LIDAR detection offer capabilities to detect and, for the latter, measure sediment deposit volumes. Stanić *et al.* (2017) and Lepot *et al.* (2017b) demonstrated the capability of a laser profiler (Figure 4.15) to map in 3D and quantify sand deposits in a dry pipe with good accuracy (i.e., with a standard deviation between the real and estimated sand volumes less than 3.5%).

If the flow cannot be bypassed, acoustic sonar seems to offer a robust and reliable method to assess sediment volumes. Lepot *et al.* (2017c) tested an acoustic sonar placed on a floating platform in various sewer structures and pipes. Figure 4.16 depicts the output of a sonar mapping in a settling tank.

4.2.2.9 Infiltration capacity for permeable pavements

When testing the hydraulic capacity of pavement in terms of clogging, the question arises: 'what permeability should pavements have?' Referring to the guidelines in place when the system under investigation was originally designed (e.g., DIBt (2012), SLG (2020)) is a good starting point in the absence of better information. Many guidelines recommend using the ASTM D 3385-09 double-ring infiltration test to determine the infiltration rate of permeable pavement surfaces (Schmitt *et al.*, 2007; Schönberger *et al.*, 2005). It suggests undertaking a minimum of three different tests at three locations on the pavement. All three tests need to demonstrate an average infiltration rate of equal to or greater than 194 mm/h (540 L/s/ha) to be deemed to comply. Also, full-scale tests are used to visualize if the permeable pavement still performs satisfactorily over time (see Figure 4.17).

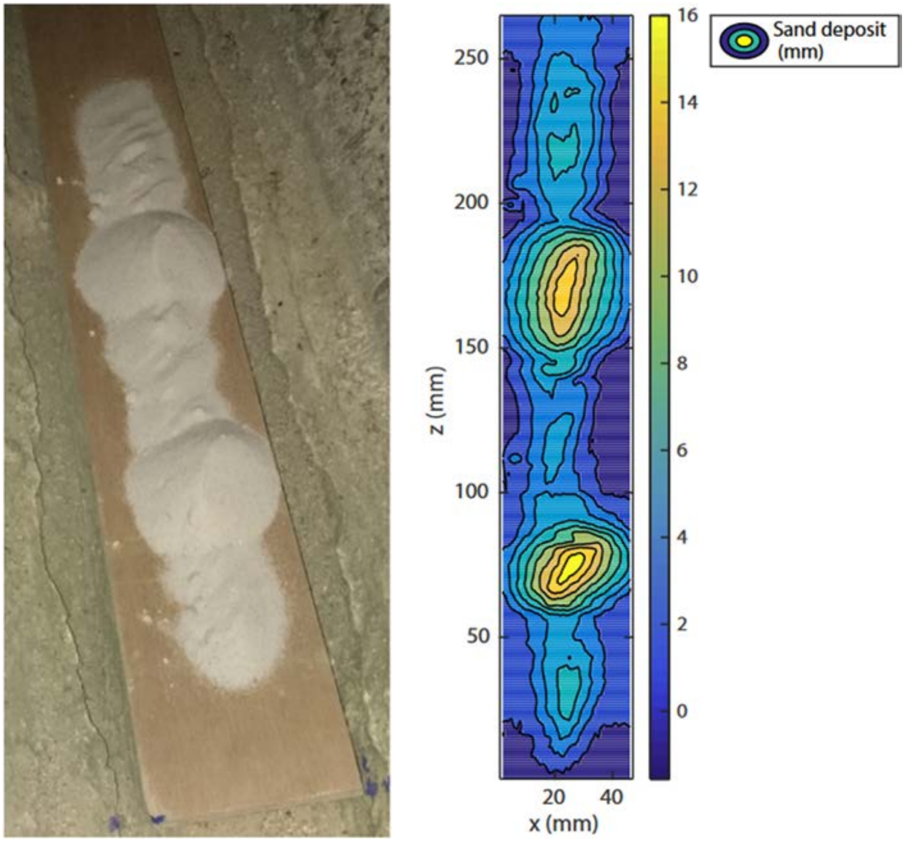


Figure 4.15 Quantification of the sand deposit volume using laser scanning: photo of the experiment (left) and scanned sand relief (right). (Source: Lepot *et al.*, 2017b).

The requirements will differ by jurisdiction. For example, newly installed permeable pavements in the Netherlands should demonstrate a minimum infiltration capacity of 194 mm/h. Over time the infiltration capacity will become lower due to clogging. In Germany, according to the DWA-A 138 (2005), the dimensioning of a surface infiltration system without above-ground storage facilities uses a rainfall intensity which corresponds to a rain event of 10-minute duration ($T = 10$ min), which is reached or exceeded once every 5 years ($n = 0.2$).

As the number of permeable pavement installations increases, the need for a proper tool to measure their surface infiltration functionality, especially with respect to clogging, is also increasing (Veldkamp *et al.*, 2022; Winston *et al.*, 2012). Measuring infiltration rates accurately in the field is not easy to do and a variety of infiltration test procedures have been utilized in the past. However, the results have generally been inconsistent, and have shown a large variation in the range of infiltration rates measured. Currently, there is no single standard agreed method for measuring the surface infiltration through permeable pavements even though numerous studies have tried to measure the surface infiltration rate of permeable pavement systems (e.g., Bean *et al.*, 2007; Fassman & Blackbourn, 2010). This has generally been done by measuring the infiltration rate of water through a particular section of the pavement surface. While a variety of infiltration test procedures have been used, most are based on some type of modified single- or double-ring infiltrometer test.

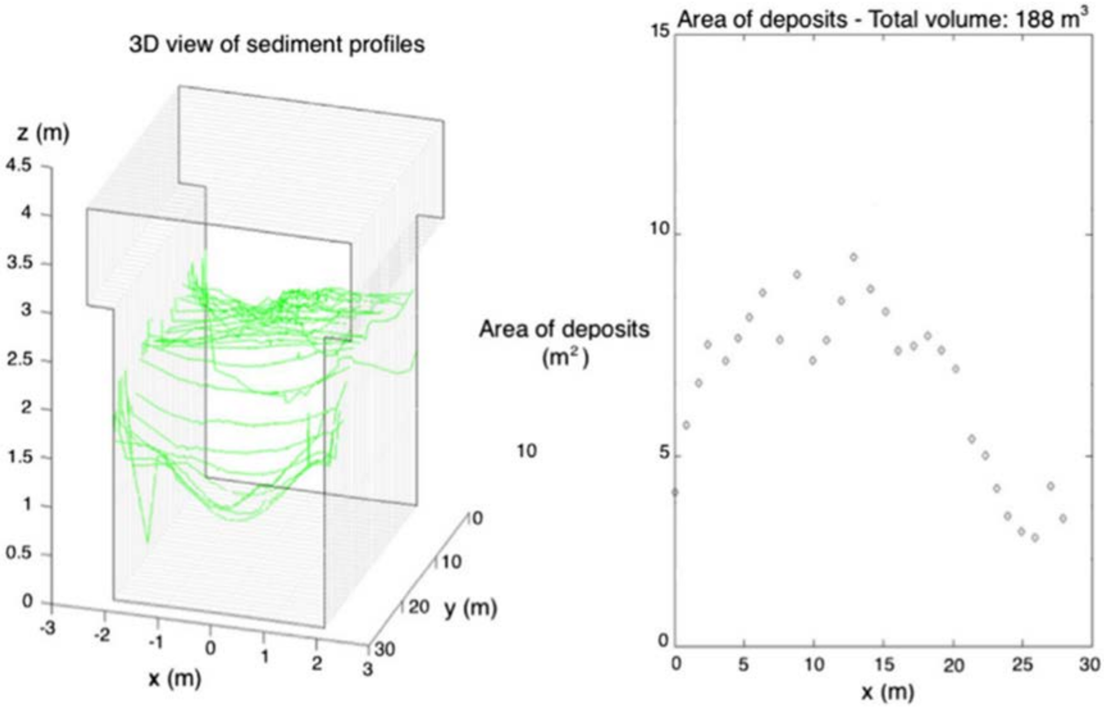


Figure 4.16 Sediment volume in a settling tank: 3D left on the left, area of deposits along different cross sections on the right. (Source: Lepot *et al.*, 2017c).

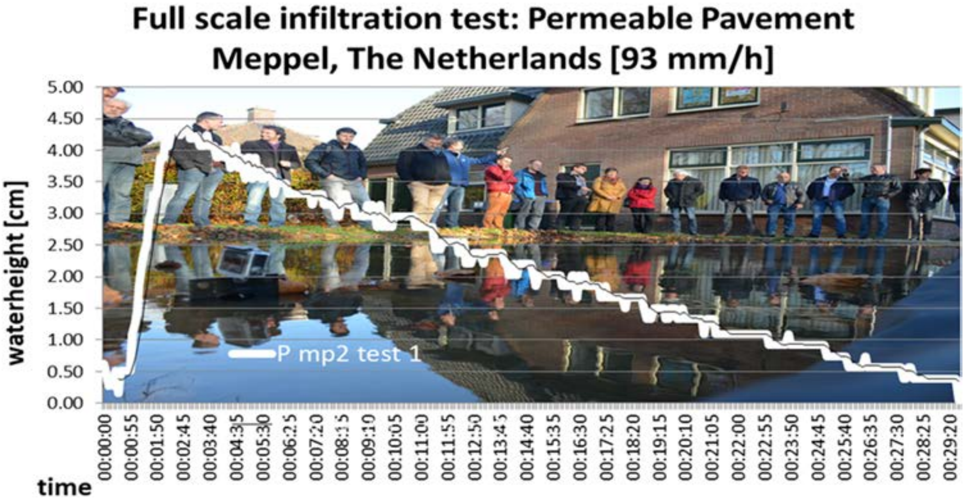


Figure 4.17 Full-scale test with stakeholders from municipality and water authority waiting for the water to infiltrate through permeable pavement in Meppel, The Netherlands. (Courtesy F. Boogaard).

Figure 4.18 In-situ test for infiltration of a permeable pavement in Germany. (Courtesy F. Boogaard).

Ring infiltrometer tests (e.g., ASTM C 1701/C 1701M, 2009) and variations to this (Li *et al.*, 2013) were originally developed to determine the hydraulic conductivity of in-situ field soils for evaluation of their irrigation properties. Water is generally supplied to the rings using either a constant head or a falling head method (see Figure 4.18 illustrating the practice in Germany). The flow rate of the water is then divided by the cross-sectional area of the ring to calculate the infiltration rate (usually reported in mm/h). Several studies have demonstrated a high degree of spatial variability between different infiltration measurements performed on the same pavement location (e.g., Boogaard, 2015; Borgwardt, 2006; García-Serrana *et al.*, 2017; Pezzaniti *et al.*, 2009). The single- and double-ring infiltrometer tests are based on the infiltration rate through a small area of the pavement that is used to represent the infiltration rate of the total pavement area. For example, the area of the inner ring of the test (ASTM C 1701/C 1701M, 2009) is 0.0707 m^2. The minimum area recommended by Dutch guidelines is even smaller, at only 0.01 m^2. Using such small areas for testing could potentially lead to erroneous results, as several studies have demonstrated a high degree of spatial variability between different infiltration measurements undertaken on the same pavement installation.

Previous research demonstrated that more accurate infiltration results may be produced by significantly increasing the area of the pavement surface being tested (Boogaard & Lucke, 2019). By inundating a much larger area of pavement during testing, it was shown that any spatial variations in infiltration capacity were effectively averaged out, and this produced more reliable infiltration data. A full-scale infiltration testing (FSIT) method (see Figure 4.19) was applied by most of the studies to determine the surface infiltration rate of over 100 existing permeable pavement installations in the Netherlands (Veldkamp *et al.*, 2022).

4.2.2.10 Infiltration capacity for bioswales

The infiltration capacity of swales is usually estimated by measuring the rate at which water soaks away at small test pits or boreholes (Palhegyi, 2010) or ring infiltrometer tests. Several studies have demonstrated a high degree of spatial variability between different infiltration measurements since the results were based on the infiltration rate through a very small area that is used to represent the total infiltration area (Boogaard, 2015). Studies showed large spatial variation in infiltration rates with individually measured infiltration values varying by a factor of 100, concluding that about 20 measurements at each swale are needed to reduce the uncertainty (Ahmed *et al.*, 2015;

Figure 4.19 Full-scale infiltration test (FSIT) where a large part of permeable pavement is flooded is applied in the Netherlands. (Courtesy F. Boogaard).

Boogaard, 2022). Previous research demonstrated that more accurate research results on the infiltration capacity of sustainable UD systems can be collected by significantly increasing the test area as discussed in last paragraph with permeable pavement (Boogaard & Lucke, 2019). By inundating the whole swale or a large area of the swale during testing, it was shown that any spatial variations in infiltration capacity were effectively averaged out, and this produced more reliable infiltration data. The full-scale infiltration testing (FSIT) method (see Figure 4.20) was applied by most of the studies to determine the surface infiltration rate of over 100 existing swale installations in the Netherlands (Boogaard, 2022).

Figure 4.20 Example of hydraulic test on a swale with the full-scale test in Groningen (tank truck on the right), measurements by loggers in the swale and hand measurement of students from Hanze Applied University of Groningen. (Courtesy F. Boogaard).

4.2.3 Defect-oriented inspection

The inspection techniques discussed in the previous section focused on the measurement of specific parameters related to UD system functionality. This section focuses on techniques which provide a broader, but often less specific and/or more subjective description of pipe deterioration. In the majority of cases these methods are based on the interpretation of images and/or footage. These so-called vision-based inspection techniques applied in practice (most notably CCTV) suffer from a spectrum of disadvantages:

- Only the internal surface of buried assets is observed, so damage or corrosion at the outer wall of a pipe is not observed; similarly, only the top surface of an infiltration basin can be inspected.
- No physical quantification can be accurately made (e.g., the loss of wall thickness due to corrosion cannot be quantified, nor can the hydraulic roughness be quantified, nor the clogging level of an infiltration system).
- What is observed is the result of an unknown combination of deterioration processes, giving no clues on time scales or rates of deterioration.

In addition, the normally applied standards (e.g., EN 13508-2, 2011) are formulated in such a manner that they are prone to errors made by inspectors, as these norms rely heavily on human observation, which is known to be unreliable (see Dirksen *et al.*, 2013). In the past few years, the development of computer vision combined with deep learning technology has shown the potential to outperform human observers in terms of consistency, thus showing potential to reduce error rates. Nevertheless, the main disadvantages of vision-based inspection remain. It has to be acknowledged however that in the course of the past 40 years a lot of CCTV data has been collected and has been shown to be valuable where it comes to planning of replacements and/or rehabilitation for the mid- and long term (i.e., >5 years ahead) and for larger areas.

4.2.3.1 Vision-based inspection

As discussed earlier in this section, inevitably visual inspection was the original form of inspection, and this remains the most used technique. This technique can be broadly divided into static and mobile techniques.

4.2.3.1.1 Static vision-based inspection

A static inspection is usually carried out at a manhole from the ground surface. The simplest basic technology solution is a mirror-based solution which involves a 45-degree mirror and a light source. This gives a basic view of the pipe closest to the manhole but is very limited for inspecting long lengths of pipe due to the lack of adequate lighting, potential deviations in the line of the pipe and the detail that can be seen. Where resources are constrained, mirror-based inspections can still provide valuable information.

Zoom cameras, or stationary CCTV are not new, but are not widely used. The approach consists of inserting a camera with a controllable focal length lens into a manhole to take images. Two key advantages are that there is no need to clean the pipe and the inspection is quick, both meaning that the inspection is significantly cheaper than a full CCTV survey. There are however clearly limitations in the distance that can be seen from the manhole, the proper identification of defects and the need for the pipe to be straight – without any horizontal or vertical deviations. Zoom cameras could be, however, a useful tool to prioritize defects for inspection. They have also been used in planning sewer cleansing strategies (Plihal *et al.*, 2014).

4.2.3.1.2 Mobile vision-based inspection

The advent of cameras which could relay an electronic image to a screen, termed closed circuit television (CCTV), led to the first applications in sewers in the 1950s. While the earliest CCTV cameras were dragged on a sled using winches at the upstream and downstream manhole, the CCTV

Figure 4.21 Picture of a mobile vision-based inspection system showing the lights (in front), the camera (between the lights), the swivel head (camera + lights), and the motorized crawlers (left part). (Courtesy F. Cherqui).

camera soon became mounted on motorized crawlers, thus reducing deployment time and allowing the inspection to take place from a single manhole (Figure 4.21). The crawlers themselves have developed with time, allowing the camera to be centered within the pipe and also to rotate to focus on defects. CCTV crawlers can commonly travel up to 500 m along a pipe, they can pass through manholes, but due to the tether cannot negotiate anything other than shallow radius bends. The smallest CCTV cameras are 'push cameras' which are deployed without a crawler just being pushed along the pipe by the operator; however, the orientation of the camera can change, and the jerky motion can be an issue. Some crawlers that allow deployment of lateral surveying cameras are now available.

CCTV cameras are operated from above ground, usually in a specially fitted vehicle, from which the cable is deployed, and which includes a display showing the camera image and controls for the crawler. The recording systems allow the video to be annotated with locations and highlighting defects during the survey, although the survey analysis can also take place afterwards based on pre-recorded footage. The former approach can allow manipulation of the camera to better assess any defects, while the latter allows a faster survey, minimizing time spent blocking traffic and maximizing the survey distance. The cable drum incorporates a counter, which is converted to a distance travelled by the crawler which is also recorded on the video images. In recent years, alternative methods to deploy CCTV have been used, including floating platforms and drones (or unmanned autonomous vehicles), particularly in larger diameter pipes. This has been reported to increase the daily inspection length by up to 50% to 900 m (Flyability, 2023).

Another alternative visual inspection technique, known as digital scanning or side scanning uses high-definition wide-angle cameras to record the entire pipe wall as the crawler moves through the pipe without stopping. These images can be viewed live but are best suited for recording later analysis where the images can be unwrapped to view the entire pipe wall in a way not possible with conventional CCTV recordings (Feeney *et al.*, 2009). The images produced with digital scanning do need careful processing to avoid distortion, but this is automated. As with other vision techniques, only the pipe above the waterline is inspected. While the operator cannot pan and zoom the camera, the resulting processed images will generally be more comprehensive.

Sewer inspection using CCTV was a logical step from person-entry visual inspection and has developed a strong place in the market, with defect codes being developed around this dominant inspection method. However, beyond the limitations of subjective analysis and subsequent aggregation, visual inspection – especially via CCTV – cannot provide a full description of pipe condition. A key limitation is what cannot be seen; first, to enable the crawler to pass through the pipe and to remove elements that would foul the lens or mask defects; the sewer is usually pre-cleaned. While Thornhill and Wildbore (2005) noted that higher reporting accuracies were obtained after cleaning, that cleaning will inevitably wash away evidence such as ingress of soil and sedimentation which can indicate network defects and performance issues. Second, the entire internal surface of the pipe is rarely visible, particularly in combined and wastewater sewers due to a continuous level of flow (unless flow is temporarily bypassed or blocked). Third, the inside of the pipe is not all of the pipe; the external walls of the pipe can be affected by corrosion; the bedding of the pipe can deteriorate, and voids can form in the surrounding ground which impact on both the structural stability of the pipe and that of the ground itself. Furthermore, the pipe material can appear to be visually intact, but has in fact lost structural integrity. It should also be considered that the image recorded by a camera lens can be subject to varying degrees of distortion, which may affect the perception of a defect. This is discussed further by Martins *et al.* (2020), along with suggestions as to how this can be overcome.

4.2.3.1.3 Direct visual inspection

When possible, the operator can perform the visual inspection directly by walking through the sewer pipes, without the need for a closed-circuit television. Regarding pipes, this method is commonly used for large-diameter sewer pipes (i.e., >1.8 m although the definition of 'large' remains subjective) where robotic crawlers might have limitations due to the size of the pipes or the complexity of the sewer network. During their inspections, operators can capture detailed visual information about the condition of the sewer (including nuances that automated methods might miss). Such activity remains however challenging due to the hazardous environment (i.e., it being a confined space entry environment subject to potential flooding, toxic gases, limited oxygen, bacteria, and other contaminants), limited access entry or exit points, limited reach with some areas of the pipes difficult to see because they are located too high or are not accessible, and time and costs as they require more time and resources than CCTV inspection. Man-made visual inspections are therefore limited to large diameter pipes (which are often the oldest ones) for which no mobile vision-based inspection is possible or pertinent. Defect inventory is often based on the same system as that used for televised pipe inspections, for example, most man-made pipe inspections in Europe are based on the EN 13508-2 coding system (although this coding system seems to be mainly dedicated to CCTV inspections).

When considering other drainage solutions ranging from swales to underground detention basins, direct visual inspection remains the main investigation method. To the knowledge of the authors, no norm or national guideline provides recommendations on visual inspection of stormwater control measures (SCMs). Inspection reports range from free text (describing the observations) to detailed checkbox forms (requiring the operator to give a condition to each component of the solution). For example, AECOM (2015) provides for each type of SCM a maintenance form divided into six sections (i.e., general inspection, inlet structure, pre-treatment, main treatment, outlet structure, and emergency overflow) containing each a list of items for which the condition should be chosen (i.e., either 'good,' 'marginal,' 'poor,' or 'N/A') with the possibility to add a comment. Seattle Public Utilities (2009) guidelines provide a very detailed description (with illustrative pictures) to assess the level of service (from A – excellent effort to D – poor effort) for the landscape and vegetation (i.e., aesthetics, vegetation, mulch, weeds, erosion, and bare spots), system functionality (e.g., bioretention, biofiltration, bioretention, conveyance, etc.), the hardscape and infrastructure (e.g., sedimentation structures, grates and debris screens, outlet structures, flow control structures, etc.), porous pavement, and other elements (e.g., culverts, irrigation systems, etc.). The Melbourne Water (Browne *et al.*, 2017)

WSUD Audit Guidelines and associated toolkit (Excel spreadsheet including macros) provide a very exhaustive audit form dedicated to assessing each SCM using a scale that awards each item (e.g., erosion, blockage, damage or removal of structures, sediment accumulation, erosion, standing water, rubbish, plant health, plant cover, etc.) from one point (good condition) to three points (poor condition). For each item, a detailed description is provided to help the operator choose the most pertinent condition. Each audit is uploaded in the database: individual assessment of items is used to identify maintenance (for 'moderate' condition) and rectification actions (for 'poor' condition). The overall condition of the asset is used for prioritizing maintenance and corrective works; however, other factors (such as significance of the asset, catchment sensitivity, and visibility) are also considered. Meijer *et al.* (2022) reported on the application of stereo vision method on sewer inspection; they concluded that stereo vision can be a good source of information in terms of recognizing defects. A precondition for stereo vision-based methods is that enough texture on the surface of the pipe wall is present, which normally is no problem for elements that have seen a few years of service. For new elements this may not be the case; hence, applications in determining the quality of newly built systems are not recommended.

4.2.3.1.4 Defect coding and uncertainty

The physical inspection of assets is only part of the answer. As CCTV surveying has traditionally been a purely subjective visual approach to assessing the condition of sewer pipes, coding systems have been developed to enhance uniformity in the reporting of asset conditions. Such coding also results in a level of compatibility between surveys that can allow some understanding of overall network condition and allows prioritization of maintenance. The earliest defect coding system was developed in the UK in the late 1970s following an identified need to significantly enhance information about sewer system conditions to allow cost-effective rehabilitation. The resulting Manual of Sewer Condition Classification (MSCC), currently in its fifth edition (WRc, 2013), introduced a standardized recording system incorporating condition codes (e.g., cracked; fractured; collapsed) and service codes (e.g., root intrusion; deposits (attached or settled); infiltration) and a clock system for specifying the location of the defect around the circumference of the pipe. MSCC also suggests a comprehensive set of survey headers to give a full understanding of the survey and traceability. The MSCC was complemented by the Sewerage Rehabilitation Manual (SRM) in 1983 (now an online handbook, retitled Sewerage Risk Management (WRc, 2022)). SRM introduced the concept of critical sewers and devised a scoring system for each defect, which forms the basis for the Internal Condition Grading (ICG), which ranks sewers into 5 grades where 1 is 'Acceptable Structural Condition' and 5 is 'Collapsed or Collapse Imminent'. This ICG can be extended into a Structural Performance Grade, considering additional factors, such as frequency of surcharge conditions and the surrounding soil type.

The MSCC and SRM have been a strong inspiration for different codes internationally. Thornhill and Wildbore (2005) provided a comprehensive summary, but it suffices to say that Australia, Canada, the United States, and many countries in Asia and the Pacific Rim follow similar principles, with appropriate modifications for local conditions.

The European Standard, EN 13508-2 (2011), developed from various standards from different countries in Europe, has also been influential in more recent developments around the world. Within Europe, EN13508-2 allows national annexes which tend to fuse each country's pre-existing codes with the standard, thus creating a very large number of possible codes, many of which are not directly relevant to the condition and performance of the sewer (e.g., presence of vermin, colour of water). The EN 13508-2 coding system uses a combination of letters and numbers to identify defects. The letters indicate the type of defect, while the numbers indicate the severity of the defect. The main code starts with the letter B when the observation concerns a drain or sewer. The second letter indicates a category of observation: BA for codes related to the fabric, BB related to operation, BC are inventory codes and BD are other codes. The last letter of the main code corresponds to a specific observation (e.g., BAA for a deformation, BBA for roots, BCA for a connection, or BDC for a finishing node). Figure 4.22 provides two examples of observations and associated codes according to the EN 13508-2 (2011) norm.

Figure 4.22 Example of observations coded according to the EN 13508-2 (2011) norm. On the left, BAB C A 03 & BAB B A 04: one fracture (BAB C) longitudinal (A) located at 3 h, and one crack (BAB B) longitudinal (A) located at 4 h. On the right, BBH A B 1: vermin (BBH), rat (A) in a connection (B) and one corresponds to the number of vermin observed.

In contrast, the Japanese standard was developed independently and focuses on identifying and quantifying defects which relate directly to hydraulic performance. As a result, the Japanese standard has a much smaller and hence simpler set of defect codes (Tait & Kazemi, 2022; van der Steen *et al.*, 2014). The Japan defect classification system for sewer pipe inspection (Japanese Sewerage Works Association, 1998) classifies the defects into 10 categories: crack, delamination (i.e., separation of the pipe wall into layers), scour (i.e., erosion of the pipe bottom or sides), corrosion (i.e., deterioration of the pipe wall by chemical or electrochemical reactions), erosion (i.e., gradual wearing away of the pipe wall by flowing water), collapse (i.e., complete or partial failure of the pipe wall), deformation (i.e., change in shape of the pipe wall), foreign object, tree root intrusion, and other. The severity of each defect is rated on a scale of 1–5, with 1 being the least severe and 5 being the most severe. The severity rating is based on the size, location, and type of defect. The classification system also provides recommendations on the speed of inspection, based on the severity of the defect. Severe defects (with rating of 4 or 5) should be inspected at a slow speed, so that the inspector can get a good look at the defect and identify its cause. Less severe defects (with rating of 1 or 2) can be inspected at a faster speed.

Table 4.2 (Tscheikner-Gratl *et al.*, 2019) presents an inventory of existing protocols to classify the pipe condition into several possible states depending on the level of complexity and the states considered. The condition(s) are usually assessed by aggregating all defects (with their respective importance). The scoring method is very often a weighted sum of the defects which is then divided by the length of the pipe (to enable the comparison of pipes of different lengths). Such a method is simple and easy to understand and can be improved by specifically considering major defects that lead to the pipe being considered to be in a poor condition.

While the coding systems bring some uniformity into the collection of CCTV inspection data, as with any use of data and models, the underlying quality and related uncertainties must be taken into account. Dirksen *et al.* (2013) studied the uncertainty of subjective human operation and interpretation by separating error sources into three categories: first, the collection of images whereby the collected images do not show defects which are present due to lens fouling, insufficient lighting or an inspection carried out too quickly. Second, the accuracy of identifying the defect or lack of defect, an error being represented as either: a false positive (FP) where a defect is recorded that does not exist in reality; or a false negative (FN) where a defect is present in the pipe but not recorded. FPs might be due to markings on the pipe, inadequate lighting/shadows, and so on. FNs could arise

Table 4.2 Existing protocols to assess the condition of a sewer pipe.

Type	Description	References
Comprehensive	Overall assessment of pipe's need for rehabilitation based directly on observed defects or combining the conditions below	Chughtai and Zayed (2011); EN 752 (2017); Kley *et al.* (2013); WRc (2013); Zhao *et al.* (2001)
Structural	Assessment of pipe physical condition by considering defects leading to deterioration and ultimately the collapse of the pipe	Ahmadi *et al.* (2014); Chughtai and Zayed (2011); EN 752 (2017); Khazraeializadeh *et al.* (2014); Kley *et al.* (2013); WRc (2013); Zhao *et al.* (2001)
Integrity (structural)	Assessment of structural condition with reference to strategic rehabilitation planning to determine remaining service life and structural integrity values of sewers (currently not standardized)	DWA-Themen T4 (2012); Kley *et al.* (2013)
Operational	Assessment of defects leading to an increase of operational interventions necessary on the pipe	Ahmadi *et al.* (2014); ATV-M 143–2 (1999); Chughtai and Zayed (2011); EN 13508–2 (2011); EN 752 (2017); NASSCO (2016); WRc (2013); Zhao *et al.* (2001)
Environmental	Assessment of defects leading to pollution of water (groundwater or surface water)	DWA-M 149–7 (2016); EN 752 (2017)
Hydraulic or serviceability	Assessment of defects that will perturbate the flow	Ahmadi *et al.* (2014); Arbeitshilfen Abwasser (2018); EN 752 (2017); Micevski *et al.* (2002); ÖWAV-RB 22 (2015)
Malfunctions	Consequences of defects on facility operations, for example ongoing corrosion, blockage, excessive spillage, sand silting, and so on.	Ahmadi *et al.* (2014); Kley *et al.* (2013); Le Gauffre *et al.* (2007)

Source: Tscheikner-Gratl *et al.* (2019).

from operators being distracted, there being multiple defects meaning the operator misses some or the operator fails to spot a less common defect. Third, errors in the description of the defect can be due to human error, ambiguity in the defect classification codes or improper understanding of the codes. Dirksen *et al.* (2013) presented a study of the effectiveness of condition surveys, showing that in identifying the presence of a defect FPs are rare; however, FNs have a probability of around 25%. When combined with the defect description, incorrect observations were over 50%. These data should therefore be treated as having a significant degree of uncertainty. Dirksen *et al.* (2013) listed a series of recommendations including the use of simpler coding systems and the use of other sources of data to assess sewer condition and performance. In order to reduce or eliminate operator errors, many utilities are now requiring CCTV data to be viewed by two operators in order to provide verification.

Caradot *et al.* (2018) investigated inspection uncertainties through a statistical approach. They found that the condition of the pipe has an impact on the probability of an incorrect condition grade but added a note of caution that their results were from a single city. Roghani *et al.* (2019) reproduced a comprehensive table listing 14 factors which can affect visual inspection results, many of which overlap with observations by Dirksen *et al.* (2013) but it is perhaps useful to stress the potential importance of time constraints and fatigue.

Beyond the fallibility of operators and coding systems themselves, further uncertainty can be incorporated in the inspection results through the aggregation process. Rahman and Vanier (2004) presented a useful comparison of how different condition assessment protocols can result in significantly different assessments of the same sewer network, even if the basis of the protocols is the same (i.e., MSCC). For example, in Canada, the City of Edmonton's modifications to MSCC showed 18% of sewers to be in poor condition, compared to only 3% if WRc's standard methodology was applied.

It should be noted that most if not all defect classification codes have been developed based on the assumption of visual, usually CCTV, inspection data. While many techniques discussed in this chapter provide measurement of a defect, the amalgamation and classification of data collected from one or more of these techniques continue to present some challenges.

4.2.3.1.5 AI-based assessment of CCTV data

The preceding section clearly identified limitations of CCTV analysis due to the human assessment of the captured images. As the power and storage of computers increased rapidly in the 2000s, interest in automating the analysis of CCTV gained traction.

Due to the time consuming and therefore costly nature of visual inspection of CCTV data, combined with acknowledged uncertainty in the subjective analysis, AI algorithms for analysing CCTV data have been investigated for several years with varying degrees of success. One of the earliest examples was the work of Sinha and Fieguth (2006) who used a neuro-fuzzy classifier with promising results. This area has received significant attention over the intervening years with Moradi *et al.* (2019) and Li *et al.* (2022) providing significant reviews of automated analysis of CCTV images. Many of these automated analysis techniques used image processing to identify potential defects and subsequently classified these using machine learning. More recent studies have used artificial neural networks and deep learning for feature extraction and classification. An example of such classifications is shown in Figure 4.23. Comparing the performance of different algorithms is challenging as they are not usually tested on the same dataset and different metrics are used; however, to give some indication, Li *et al.* (2022) report accuracies between 64.8% and 98.2%.

A key challenge in developing AI approaches to analyse CCTV images is the procurement of suitable datasets; furthermore, in order to provide confidence in the models, it is important for utilities to be able to compare outputs on a common dataset. Two open datasets are currently available, Sewer-ML from Denmark (https://vap.aau.dk/sewer-ml/), released in 2021 and containing 1.3 million images, and a UK database released in 2023 containing 27,000 images, but with the intention of extending the library to at least 1000 images per defect code

While clearly an area of ongoing research and development, the technologies are now sufficiently mature to have been commercialized by several companies, for example, the Swiss founded Pallon (https://www.pallon.com/) and the Australian founded Vapar (https://vapar.co/), both of whom cite significant customer bases. The apparent popularity of this technology no doubt hinges on strong water company knowledge around CCTV inspections and the existing capabilities to undertake such surveys. However good the automated analysis is, it is always limited by the quality of the CCTV data (e.g., lighting) and the inability to see below the water level

4.2.3.2 Acoustic inspection

Acoustic sensing has shown promise and some commercial applications. The method is based on the analysis of reflected sound intensities. Romanova *et al.* (2013) described a study comparing CCTV surveys with acoustic survey data and reported accuracies of 75–85% when considering four types of defects – connections, joints, cracks, and junctions. The surveys were conducted from a manhole at one end of the pipe; some defects can be missed due to a blind zone close to the sensor, overlapping reflections if there are many defects, weak reflections or shadowing from larger obstructions. Horoshenkov (2012) further presented results from the application of acoustic inspection for measuring water level, sediment levels and hydraulic roughness. Sewerbatt™ applied this technology commercially with some favorable trial results and worldwide sales (https://www.isleutilities.com/news/case-study-collaborative-trial-sewerbatt-acoustic-sensing-technology). Use of acoustic sensing for blockage detection has also been proven, with some analyses able to predict the cross-sectional

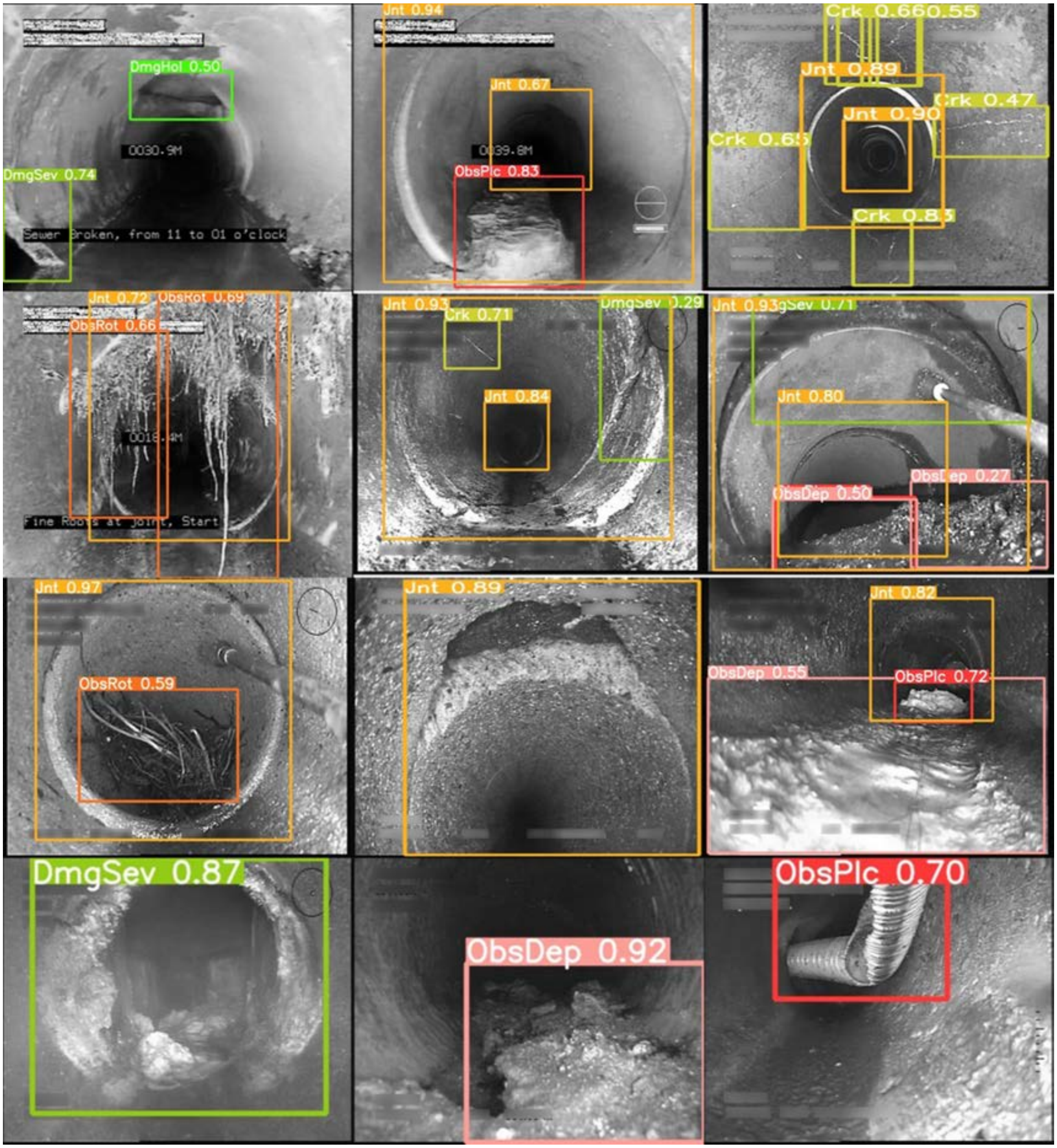


Figure 4.23 Examples of automated defect detection and classification. (After Tait and Kazemi, 2023).

area and length of the blockage with errors of less than 20% and 30%, respectively (Duan *et al.*, 2015). Development of acoustic sensing in sewer pipes is ongoing, with Yu *et al.* (2023) exploring the potential of microphone arrays to enhance the collected data and allow defect classification through data analytics techniques

Ultrasonic techniques, which use high-frequency inaudible acoustic waves, are widely used in non-destructive testing, but the materials and buried nature of UD pipes present challenges due to wave attenuation. Iyer *et al.* (2012) presented promising results from the inspection of 60 mm thick concrete: they identified cracks, fractures and holes using C-Scan (multiple measurement) imaging. Inspection of materials with ultrasonic techniques however requires some form of coupling between the sensor and the object. The technique used by Iyer *et al.* (2012) involves the pipe being immersed in water, limiting applicability. Towlson *et al.* (2022) have investigated the use of air-coupled ultrasonic arrays for characterization of blockages and pipe wall defects. The research provided promising results, particularly for pipe wall defects where a 2 mm through hole was identified from a distance of 200 mm. For identification of blockages an area between the pipe wall and the centre of the pipe suffers from superposition of reflections cancelling the signal. Blockages were however successfully identified and useful information about the number of transducers and the aperture over which the transducers should be spread was reported. This is a developing area of research, the relatively short distance (up to 1 m) over which the ultrasonic waves transmit requires the use of some form of crawler to position the array.

Sonar is another technology that has been applied for condition assessment of sewer pipes (Selvakumar *et al.*, 2014). The principle is similar to acoustic sensing except that the sound waves pass through the fluid; thus, it is used in filled pipes (e.g., siphons and rising mains) or below the water line. Analysis of the reflections allows detection of defects such as cracks, corrosion and deflection, as well as sediment build up, although the latter of course obscures a view of the pipe wall, as can solids in the water.

A relatively new development is the application of sound to detect leaks and gas pockets in pressure mains. This allows for identifying the presence of gas/air pockets and leakages in pressure mains due to the sounds they produce (see e.g., Pure Americas Inc, 2011).

Apart from the application of passive acoustic methods, detection of leakage can, reportedly, also be achieved by active acoustic methods (see e.g., Lee *et al.*, 2023).

4.2.3.3 Sensor combinations

It has been acknowledged that single sensors each have their own limitations; thus, inspection systems incorporating multiple sensors have been developed. In the late 1990s, several multi-sensor platforms were developed, as reviewed by Wirahadikusumah *et al.* (1998) and Duran *et al.* (2002). The German prototype, KARO was a tethered device capable of operating for up to 400 m in 200 mm diameter pipes, incorporating a camera, 3D optical sensor, ultrasonic sensors, and microwave radar. Data from the multiple sensors was fused through mathematical techniques. KARO was claimed to be capable of measuring obstacles, cracks, and wall thickness as well as conditions beyond the pipe wall as well as 3D positioning. It is believed that the system was not developed beyond the prototype stage. In Australia, the PIRAT system was developed adding internal geometry measurements via laser above the waterline and sonar below the water surface, to CCTV. Automated recognition, rating and classification of pipe defects were carried out by AI software. Early tests were reported to give superior results to CCTV for concrete and vitreous clay pipes, but as with KARO it did not move beyond prototype stage. Sewer scanner and evaluation technology (SSET) was developed in Japan and incorporates an optical scanner and gyroscope alongside CCTV. An unwrapped image of the whole pipe is output; defects can be colour coded and annotated. A non-crawler-based technique is the use of a manhole zoom camera with acoustic reflectometry (Plihal *et al.*, 2016). This was also shown to provide better information than the individual techniques. Based on the available literature, SSET seems to be the combined sensor technology that has seen the most uptake. While combinations of sensors do provide better information than the individual techniques, there are increases in costs and complexity both in the hardware and data analysis.

4.3 EMERGING TECHNOLOGIES

The technologies described up to this point all focused on the interior of the pipe; however, that is clearly only a part of the pipe. The material within and on the outside of the walls can deteriorate and voids can form outside the pipe. Hao *et al.* (2012), described techniques such as ground penetrating radar, which can identify voids in the ground. They also described ultrasonic-guided waves, which are used in other fields and can identify pipe corrosion; however, this technique faces significant difficulties when applied to granular and non-homogenous materials such as concrete.

There is growing interest in developing autonomous, untethered robots for UD inspection. Autonomous robotics have the potential to inspect pipes more cost effectively due to longer deployment times, less human labour, less highway disruption. Lower unit inspection costs could therefore allow a greater proportion of the networks to be surveyed more frequently. Such robots have been predominantly developed for larger (e.g., >600 mm diameter) pipes (Kolvenbach *et al.*, 2020; Spectar, 2023) and are still mainly prototypes. Ongoing and recent research has investigated robots for smaller pipes (e.g., 200–300 mm diameter), including the Danish ASIR (2018) project and Pipebots in the UK (Shepherd *et al.*, 2021). Autonomous robotics have been developed to use a range of different sensors; key considerations for the deployment of sensors on autonomous robots are the power, data volume, and data processing requirements. Autonomous robots also have significant challenges for localization and navigation in sparse piped networks with no GPS coverage, as well as environmental challenges to overcome due to variable depths and velocities of water, sewage matter such as rags and grease and the potential for explosive gases. Regarding localization, there has been a significant amount of work which has investigated different sensing and processing algorithms, as summarized by Aitken *et al.* (2021); however, the problem is not solved. As with condition assessment, sensor fusion seems to be a promising way forward.

While fibre optics were previously discussed for distributed temperature sensing, there has been potential shown for permanently installed fibre optic sensors to be used as distributed strain sensors which are able to carry out some structural assessment and monitor hydraulic parameters (Ainger *et al.*, 2021). This area is receiving further attention, as reviewed by Prisutova *et al.* (2022), with applications for both condition and flow measurement. There is a range of fibre optic measurement methods and installation techniques which affect cost and applicability for retrofitting. Overall, Prisutova *et al.* (2022) suggested that further research is needed on the application to partially full pipes. There is some commercial application of the technique in sewer pipes (e.g., nuron, https://www.nuron.tech/water/)

Another emerging technology entering the field of UDAM is machine learning: apart from the obvious application in processing inspection footage or defects, the quantification of some processes using cameras has been subject to the application of machine learning techniques. For example, Moreno-Rodenas *et al.* (2021) reported on the successful application of a semantic segmentation algorithm on video footages obtained in wastewater pumping stations to estimate the accumulation of FOG deposits. Overall, the use of images (i.e., photo, video) as source of information is an emerging field. From video footage, using particle image velocimetry (PIV), particle tracking velocimetry (PTV) or optical flow (OF) algorithms, footage information on velocity and vorticity fields can be obtained (see e.g., Duinmeijer, 2020) using PIV. Another emerging application is the use of spectral cameras for extracting potential on the composition of the wastewater (see e.g., Lechevallier and Rieckermann, 2020). In addition, the use of infrared cameras for detecting inflow has been reported (see e.g., Lepot *et al.*, 2017a).

4.3.1 Emerging technologies and lack of standards

Despite the fact CCTV is the most popular technology for piped network inspection, it has some serious drawbacks. During the last decades, some new monitoring techniques have been designed and tested in the field. While many of these solutions look promising since they partially or totally compensate for the disadvantages of CCTV, to the authors knowledge, there is no standard to deploy such inspections in the field and process the data. Additionally, several techniques are specific for one type or one group of defects and, therefore, could not identify all standard defects listed in the broadly accepted standards.

Section 4.3 described a plethora of emerging technologies, some of which are available commercially, while others are still in or never progressed beyond the prototype stage for various reasons. It is however clear that moving beyond the subjective data provided by human interpreted visual imagery to objective sensor measurements has many potential benefits to enhance the data collected from inspection of UD networks. Existing defect coding and classification frameworks have been developed based on the data available from the ubiquitously used CCTV surveys. Such codes and classifications are likely neither sufficient to record the detail available from alternative inspection technologies, nor to record the changes between the potentially more frequent surveys. The existing coding and classification schemes also focus on the structural attributes of the pipes; however, the hydraulic performance and remaining lifespan is generally of more concern to the responsible utilities.

An interesting development is the application of stereo imaging, LIDAR and 3D laser scanning (see Wang *et al.*, 2022). The use of stereo allows for a 3D reconstruction based on which at least some geometrical information on the inside of the construction can be obtained. A broad application of these technologies seems to be hampered by existing standards and existing workflows with managing organizations and enterprises providing inspection services.

4.3.2 Automated mapping of underground infrastructures

Despite much effort being put into obtaining accurate maps of the underground infrastructure (basically answering the fundamental AM question: 'what am I managing and where is it?') there is still a need for a system able to more or less autonomously map a network of underground pipes. In practice, one needs to open each individual manhole in order to obtain observations on invert elevation, geometrical dimensions, and so on.

In theory, one could construct a sensor platform that moves, either self-propelled or floating on the (waste)water stream and collects data on profile dimensions and keeps track of its position. The latter is the main challenge, as underground autonomous navigations is not a simple hurdle to overcome as GPS systems typically do not function when deployed subsurface. An alternative method can be the application of accelerometers, from which, after integrating twice, theoretically the relative 3D position of the device as a function of time can be reconstructed. However, due to the accumulation of the measuring uncertainties combined with the numerical integration errors such an approach can only work when a regular update on the position can be obtained from an independent source. One might, for instance, consider supplying the device with a database with the position of landmarks (e.g., manholes); such information can be used in conjunction with a distance sensor of the device that detects the presence of landmarks (e.g., manholes, see e.g., Thielemann *et al.*, 2008). This is a field under development in which combinations of methods (e.g., accelerometers, stereo vision, acoustic distance metering, etc.) are deployed to keep the uncertainty in the position within an acceptable envelope.

4.4 CONCLUSIONS AND OUTLOOK

This chapter has focused on the plethora of inspection techniques which have been and continue to be developed for the inspection of UD assets. It is clear that CCTV remains the most popular method of inspection, despite limitations as to which defects can be identified with costs often affecting the frequency of inspection and subjectivity of the footage interpretation by the operator.

Several other techniques are available (at various maturity levels) to provide objective measurements for specific defects. In order to fully understand asset condition, a range of techniques needs to be applied which requires more research and development effort for them to be widely used. The potential for robotic inspection has attracted significant interest over the years and is currently an area of research. While fully autonomous robots continuously inspecting sewer pipes seem to remain some way off, the benefits of some degree of autonomy and lack of reliance on human operators and tethers could start to bring benefits in terms of coverage, cost, and measurement techniques in the nearer future. The inspection of nature-based solution assets remains the least mature part of this field, likely due to a lack of comprehension of the ageing processes of such solutions and status criteria (e.g., infiltration).

Even if the lack of process comprehension or industrial development could be blamed for the limited use of other inspection techniques (i.e., besides CCTV), the absence of standards definitely counteracts a wider use of other techniques.

Researchers, industrialists, and legislators need to work together to deploy the presented (and coming) technologies at a larger scale. This collaboration appears mandatory to conduct numerous and accurate inspections to hold sewage and stormwater service under unavoidable and growing constraints: climate change and limited resources. The authors hope this chapter will contribute to solving this challenge we all face.

REFERENCES

AECOM (2015). Georgia Stormwater Management Manual Appendix E, September, 138 p. https://cdn.atlantaregional.org/wp-content/uploads/operation-and-maintenance-guidance-document.pdf (accessed 23 August 2023).

Ahmadi M., Cherqui F., de Massiac J. C., Werey C., Lagoutte S. and Le Gauffre P. (2014). Condition grading for dysfunction indicators in sewer asset management. *Structure and Infrastructure Engineering*, **10**, 346–358, https://doi.org/10.1080/15732479.2012.756916

Ahmed F., Gulliver J. S. and Nieber J. L. (2015). Field infiltration measurements in grassed roadside drainage ditches: spatial and temporal variability. *Journal of Hydrology*, **530**, 604–611, https://doi.org/10.1016/j.jhydrol.2015.10.012

Ainger M., Kingsley S., Horoshenkov K. and Tait S. (2021). Optical fibre pressure sensing apparatus employing longitudinal diaphragm. GB2567610B.

Aitken J. M., Evans M. H., Worley R., Edwards S., Zhang R., Dodd T., Mihaylova L. and Anderson S. R. (2021). Simultaneous localization and mapping for inspection robots in water and sewer pipe networks: a review. *IEEE Access*, **9**, 140173–140198, https://doi.org/10.1109/ACCESS.2021.3115981

Almeida F., Brennan M. J., Joseph P., Withfield S., Dray S. and Paschalini A. (2014). On the acoustic filtering of the pipe and sensor in a buried plastic water pipe and its effect on leak detection: an experimental investigation. *Sensors*, **14**, 5595–5610, https://doi.org/10.3390/s140305595

Arbeitshilfen A. (2018). Arbeitshilfen Abwasser – Planung, Bau und Betrieb von abwassertechnischen Anlagen in Liegenschaften des Bundes. Bundesministerium des Innern, für Bau und Heimat, Berlin, Germany.

ASIR (2018). Autonomous Sewer Inspection Robot, collaborative project funded by Innovation Fund Denmark. https://inlocrobotics.com/en/engineering/autonomous-robots/ (accessed 19 September 2022).

ASTM (2009). Standard Test Method for Infiltration Rate of In Place Pervious Concrete 1, https://cdn.standards.iteh.ai/samples/71163/3c358f91d5144ad4b082effaf2b02d27/ASTM-C1701-C1701M-09.pdf

ATV-M 143-2 (1999). Optische Inspektion -Inspektion, Instandsetzung, Sanierung und Erneuerung von Abwasserkanälen und -leitungen (Optical/visual Inspection – inspection, renovation, replacement and rehabilitation of sewers). Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e. V., Hennef, Germany.

Bahnsen C. H., Johansen A. S., Philipsen M. P., Henriksen J. W., Nasrollahi K. and Moeslund T. B. (2021). 3D sensors for sewer inspection: a quantitative review and analysis. *Sensors*, **21**, 2553, https://doi.org/10.3390/s21072553

Bean E. Z., Hunt W. F. and Bidelspach D. A. (2007). Evaluation of four permeable pavement sites in eastern North Carolina for runoff reduction and water quality impacts. *Journal of Irrigation and Drainage Engineering*, **133**, 583–592, https://doi.org/10.1061/(ASCE)0733-9437(2007)133:6(583)

Beheshti M., Sægrov S. and Ugarelli R. (2015). Infiltration/inflow assessment and detection in urban sewer system. *Vann*, **01**, 24–34.

Beheshti M. and Saegrov S. (2019). Detection of extraneous water ingress into the sewer system using tandem methods – a case study in Trondheim city. *Water Science & Technology*, **79**(2), 231–239, https://doi.org/10.2166/wst.2019.057

Bin Ali M. T., Horoshenkov K. V. and Tait S. J. (2011). Rapid detection of sewer defects and blockages using acoustic-based instrumentation. *Water Science and Technology*, **64**(8), 1700–1707, https://doi.org/10.2166/wst.2011.183

Boogaard F. C. (2015). Stormwater characteristics and new testing methods for certain sustainable urban drainage systems in The Netherlands. PhD, Delft University of Technology, https://doi.org/10.4233/UUID:D4CD80A8-41E2-49A5-8F41-F1EFC1A0EF5D

Boogaard F. C. (2022). Spatial and time Variable long term infiltration rates of green infrastructure under extreme climate conditions, drought and highly intensive rainfall. *Water*, **14**, 840, https://doi.org/10.3390/w14060840

Boogaard F. and Lucke T. (2019). Long-term infiltration performance evaluation of Dutch permeable pavements using the full-scale infiltration method. *Water*, **11**, 320, https://doi.org/10.3390/w11020320

Borgwardt S. (2006). Long-term in-situ infiltration performance of permeable concrete block pavement. Proceedings of the 8th International Conference on Concrete Block Paving, 6–8 November, San Francisco, CA, USA.

Brennan M. J., Kroll de Lima F., Almeida F., Joseph P. and Paschoalini A. T. (2016). A virtual pipe rig for testing acoustic leak detection correlators: proof of concept. *Applied Acoustics*, **102**, 137–145, https://doi.org/10.1016/j.apacoust.2015.09.015

Browne D., Godfrey M., Markwell K. and Boer S. (2017). WSUD Audit Guidelines (Version 1.0), Stormwater Victoria and E2Designlab, June, 131 p. https://musicauditor.com.au/HostedFiles/WSUD%20Audit%20Guidelines%20Draft.pdf (Access 23 August 2023).

Caradot N., Rouault P., Clemens F. and Cherqui F. (2018). Evaluation of uncertainties in sewer condition assessment. *Structure and Infrastructure Engineering*, **14**, 264–273, https://doi.org/10.1080/15732479.2017.1356858

Chandler D. M. and Lerner D. N. (2015). A low cost method to detect polluted surface water outfalls and misconnected drainage. *Water and Environment Journal*, **29**, 202–206, https://doi.org/10.1111/wej.12112

Chughtai F. and Zayed T. (2011). Integrating WRc and CERIU condition assessment models and classification protocols for sewer pipelines. *Journal of Infrastructure Systems*, **17**, 129–136, https://doi.org/10.1061/(ASCE)IS.1943-555X.0000052

Clemens F., Stanić N., Van der Schoot W., Langeveld J. and Lepot M. (2015). Uncertainties associated with laser profiling of concrete sewer pipes for the quantification of the interior geometry. *Structure and Infrastructure Engineering*, **11**, 1218–1239, https://doi.org/10.1080/15732479.2014.945466

Clemens-Meyer F. H. L. R., Lepot M., Blumensaat F., Leutnant D. and Gruber G. (2021). Data validation and data quality assessment. In: Metrology in Urban Drainage and Stormwater Management: Plug and Pray, J.-L. Bertrand-Krajewski, F. Clemens-Meyer and M. Lepot (eds), IWA Publishing, London, UK, 327–390, https://doi.org/10.2166/9781789060119_0327

de Bénédittis J. and Bertrand-Krajewski J. L. (2005). Infiltration in sewer systems: comparison of measurement methods. *Water Science and Technology*, **52**(3), 219–227, https://doi.org/10.2166/wst.2005.0079

DiBT (2012). Zulassungsgrundsätze Niederschlagswasserbehandlungsanlagen Teil 2: Wasserdurchlässige Beläge für Kfz-Verkehrsflächen für die Behandlung des Abwassers zur anschließenden Versickerung in Boden und Grundwasser (Abwasserbehandelnde Flächenbeläge), Fassung April 2012.

Dirksen J., Clemens F. H. L. R., Korving H., Cherqui F., Le Gauffre P., Ertl T., Plihal H., Muller K. and Snaterse C. T. M. (2013). The consistency of visual sewer inspection data. *Structure and Infrastructure Engineering*, **9**(3), 214–228, https://doi.org/10.1080/15732479.2010.541265

Dirksen J., Pothof I. W. M., Langeveld J. G. and Clemens F. H. L. R. (2014). Slope profile measurement of sewer inverts. *Automation in Construction*, **37**, 122–130, https://doi.org/10.1016/j.autcon.2013.10.014

Duan W., Kirby R., Prisutova J. and Horoshenkov K. V. (2015). On the use of power reflection ratio and phase change to determine the geometry of a blockage in a pipe. *Applied Acoustics*, **87**, 190–197, https://doi.org/10.1016/j.apacoust.2014.07.002

Duinmeijer S. P. A. (2020). On the free-surface driven motion of buoyant particles. PhD thesis, Delft University of Technology, ISBN 978-94-6366-271-0. https://repository.tudelft.nl/islandora/object/uuid%3Aa33fa2a9-f347-40a3-96be-51e880018974

Duran O., Althoefer K. and Seneviratne L. D. (2002). State of the art in sensor technologies for sewer inspection. *IEEE Sensors Journal*, **2**, 73–81, https://doi.org/10.1109/JSEN.2002.1000245

DWA-A 138 (2005). Arbeitsblatt DWA-A 138, Planung, Bau und Betrieb von Anlagen zur Versickerung von Niederschlagswasser. Planning, construction and operation of facilities for the infiltration of precipitation water. ISBN Print: 978-3-937758-66-4, ISBN E-Book: 978-3-96862-062-6.

DWA-M 149-7 (2016). Zustandserfassung und -beurteilung von Entwässerungssystemen außerhalb von Gebäuden – Teil 7: Beurteilung der Umweltrelevanz des baulichen/betrieblichen Zustands (Condition assessment and classification of urban drainage systems outside of buildings). Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e. V., Hennef, Germany.

DWA-Themen T4 (2012). Leitfaden zur strategischen Sanierungsplanung von Entwässerungssystemen außerhalb von Gebäuden (Guideline on strategical rehabilitation planning of urban drainage systems outside of buildings). Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e. V., Hennef, Germany.

Eiswirth M. and Heske C. (2000). Pipe Defect Characterisation by Multi-Sensor Systems (pp.1–12). No-dig 2000.

Ékes C. and Mahmood S. (2019). Looking into the Void: Condition Assessment with Pipe Penetrating Radar 198–204, https://doi.org/10.1061/9780784482490.021

Ellis J. B. and Bertrand-Krajewski J. L. (eds) (2010). Assessing Infiltration and Exfiltration on the Performance of Urban Sewer Systems (APUSS). IWA Publishing, London, UK.

Ellis J. B. and Butler D. (2015). Surface water sewer misconnections in England and Wales: pollution sources and impacts. *Science of the Total Environment*, **526**, 98–109, https://doi.org/10.1016/j.scitotenv.2015.04.042

EN 13508-2 (2011). Condition of Drain and Sewer Systems Outside Buildings – Part 2: Visual Inspection Coding System. European Commitee for Standardization, Brussels, Belgium.

EN 752 (2017). Drain and Sewer Systems Outside Buildings. European Commitee for Standardization, Brussels, Belgium.

Enquête Eau (2008). CGDD, SOeS/SSP – Ministère du Développement Durable. Enquête C.I.EAU, 2006/Source: L'eau du robinet dans notre quotidien, C.I.EAU, 2006.

Fassman E. A. and Blackbourn S. (2010). Urban runoff mitigation by a permeable pavement system over impermeable soils. *Journal of Hydrologic Engineering*, **15**(6), 475–485, https://doi.org/10.1061/(ASCE)HE.1943-5584.0000238

Fatemi Aghda S. M., Ganjalipour K. and Nabiollahi (2018). Assessing the accuracy of TDR-based water leak detection system. *Results in Physics*, **8**, 939–948, https://doi.org/10.1016/j.rinp.2018.01.026

Feeney C. S., Thayer S., Bonomo M. and Martel K. (2009). Condition Assessment of Wastewater Collection Systems, US Environment Protection Agency Report EPA/600/R-09/049, nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P1003ZQY.TXT (Accessed 6 April 2023).

Flyability (2023). Sewer Inspections by Drone: How Suez RV Osis Uses the Elios 2 to Ensure 100% Coverage When Inspecting Wastewater Infrastructure [WWW Document]. URL https://www.flyability.com/casestudies/suez-rv-osis-drone-sewer-inspections (Accessed 13 April 2023).

García-Serrana M., Gulliver J. S. and Nieber J. L. (2017). Infiltration capacity of roadside filter strips with non-uniform over-land flow. *Journal of Hydrology*, **545**, 451–462, https://doi.org/10.1016/j.jhydrol.2016.12.031

Ghozzi R., Lahouar S., Besbes K. and Souani C. (2018). Mapping of sewer lines using GPR: a case study in Tunisia. *Data*, **3**(4), 40, https://doi.org/10.3390/data3040040

Hao T., Rogers C. D. F., Metje N., Chapman D. N., Muggleton J. M., Foo K. Y., Wang P., Pennock S. R., Atkins P. R., Swingler S. G., Parker J., Costello S. B., Burrow M. P. N., Anspach J. H., Armitage R. J., Cohn A. G., Goddard K., Lewin P. L., Orlando G., Redfern M. A., Royal A. C. D. and Saul A. J. (2012). Condition assessment of the buried utility service infrastructure. *Tunnelling and Underground Space Technology*, **28**, 331–344, https://doi.org/10.1016/j.tust.2011.10.011

Hoes O., Schilperoort R. P. S., Luxemburg W. M. J., Clemens F. H. L. R. and van de Giessen N. C. (2009). Locating illicit connections in storm water sewers using fibre optic distributed temperature sensing. *Water Research*, **43**, 5187–5197, https://doi.org/10.1016/j.watres.2009.08.020

Horoshenkov K. (2012). Acoustical monitoring of water infrastructure. Société Fraņcaise d'Acoustique. Acoustics 2012, Apr 2012, Nantes, France. https://hal.science/hal-00811121

Iyer S., Sinha S. K., Pedrick M. K. and Tittmann B. R. (2012). Evaluation of ultrasonic inspection and imaging systems for concrete pipes. *Automation in Construction*, **22**, 149–164, https://doi.org/10.1016/j.autcon.2011.06.013

Japanese Sewerage Works Association (1998). Japan Defect Classification System for Sewer Pipe Inspection. Japanese Sewerage Works Association, Tokyo.

Khazraeializadeh S., Gay L. F. and Bayat A. (2014). Comparative analysis of sewer physical condition grading protocols for the City of Edmonton. *Canadian Journal of Civil Engineering*, **41**, 811–818, https://doi.org/10.1139/cjce-2014-0077

Kley G., Kropp I., Schmidt T. and Caradot N. (2013). SEMA D1.1 – Review of Available Technologies and Methodologies for Sewer Condition Evaluation. Kompetenzzentrum Wasser Berlin, Berlin, Germany.

Kolvenbach H., Wisth D., Buchanan R., Valsecchi G., Grandia R., Fallon M. and Hutter M. (2020). Towards autonomous inspection of concrete deterioration in sewers with legged robots. *Journal of Field Robotics*, **37**, 1314–1327, https://doi.org/10.1002/rob.21964

Kracht O., Gresch M., de Benedittis J., Progiobbe V. and Gujer W. (2003). Stable isotopes of water as a natural tracer for infiltration into urban sewer systems. *Geophysical Research Abstracts*, **5**, 07852. http://www.cosis.net/abstracts/EAE03/07852/EAE03-J-07852-1.pdf

Lechevallier P. and Rieckermann J. (2020). Data and codes: towards non-contact pollution 624 monitoring in sewers with hyperspectral imaging, https://doi.org/10.25678/0007WY

Lee J. C., Choi Y. R. and Cho J. W. (2023). Pipe leakage detection using ultrasonic acoustic signals. *Sensors and Actuators A: Physical*, **349**, 114061, https://doi.org/10.1016/j.sna.2022.114061

Le Gauffre P., Joannis C., Vasconcelos E., Breysse D., Gibello C. and Desmulliez J. J. (2007). Performance indicators and multicriteria decision support for sewer asset management. *Journal of Infrastructure Systems*, **13**, 105–114, https://doi.org/10.1061/(ASCE)1076-0342(2007)13:2(105)

Lepot M., Hernandez B., Cedillo S., Goes B. H., Schellart A., Verlinden J. C. and Clemens F. H. (2016). 3D printed pills to investigate mis-connections. 8th International Conference on Sewer Processes and Networks.

Lepot M., Makris K. F. and Clemens F. H. (2017a). Detection and quantification of lateral, illicit connections and infiltration in sewers with infra-red camera: conclusions after a wide experimental plan. *Water Research*, **122**, 678–691, https://doi.org/10.1016/j.watres.2017.06.030

Lepot M., Stanić N. and Clemens F. H. (2017b). A technology for sewer pipe inspection (part 2): experimental assessment of a new laser profiler for sewer defect detection and quantification. *Automation in Construction*, **73**, 1–11, https://doi.org/10.1016/j.autcon.2016.10.010

Lepot M., Pouzol T., Aldea Borruel X., Suner D. and Bertrand-Krajewski J. L. (2017c). Measurement of sewer sediments with acoustic technology: from laboratory to field experiments. *Urban Water Journal*, **14**(4), 369–377, https://doi.org/10.1080/1573062X.2016.1148181

Li H., Kayhanian M. and Harvey J. T. (2013). Comparative field permeability measurement of permeable pavements using ASTM C 1701 and NCAT permeameter methods. *Journal of Environmental Management*, **118**, 144–152, https://doi.org/10.1016/j.jenvman.2013.01.016

Li Y., Wang H., Dang L. M., Song H.-K. and Moon H. (2022). Vision-based defect inspection and condition assessment for sewer pipes: a comprehensive survey. *Sensors*, **22**, 2722, https://doi.org/10.3390/s22072722

Luimes R. A., Scheperboer I. C., Suiker A. S. J., Bosco E. and Clemens F. H. L. R. (2023). Assessment of chemo-mechanical degradation of concrete sewer pipes through an integrated experimental approach. *Engineering Structures*, **293**(2023), 116590, https://doi.org/10.1016/j.engstruct.2023.116590

Makris K., Langeveld J., Clemens-Meyer F., Watts J., Begun H. and Horoshenkov K. (2023). Sonic assessment of physical ageing of plastic pipes. *Journal of Sound and Vibration*, **544**, https://doi.org/10.106/j.jjsv2022.1177393

Martins L. L., do Almeida M. C. and Ribeiro ÁS (2020). Optical metrology applied in CCTV inspection in drain and sewer systems. *ACTA IMEKO*, **9**, 18–24, https://doi.org/10.21014/acta_imeko.v9i1.744

Meijer D. W., Luimes R. A., Knobbe A. J. and Back T. H. W. (2022). RADIUS: robust anomaly detection in urban drainage with stereovision. *Automation in Construction*, **139**, 104285, https://doi.org/10.1016/j.autcon.2022.104285

Micevski T., Kuczera G. and Coombes P. (2002). Markov model for storm water pipe deterioration. *Journal of Infrastructure Systems*, **8**, 49–56, https://doi.org/10.1061/(ASCE)1076-0342(2002)8:2(49)

Moradi S., Zayed T. and Golkhoo F. (2019). Review on computer aided sewer pipeline defect detection and condition assessment. *Infrastructures*, **4**, 10, https://doi.org/10.3390/infrastructures4010010

Moreno-Rodenas A. M., Duinmeijer S. P. A. and Clemens-Meyer F. H. L. R. (2021). Deep learning monitoring of FOG layers in wastewater pumping stations. *Water Research*, **202**, 117482, https://doi.org/10.1016/j.watres.2021.117482

Morgan E. S. and Crosse P. A. E. (1978). The acoustic ranger, a new instrument for tube and pipe inspection. *NDT International*, **11**(4), 179–183, https://doi.org/10.1016/0308-9126(78)90052-4

NASSCO (2016). Pipeline Assessment Certification Program (PACP). National Association of Sewer Service Companies.

ÖWAV-RB 22 (2015). Betrieb von Kanalisationsanlagen (Operation of Urban Drainage Systems). Österreichischer Wasser- und Abfallwirtschaftsverband, Vienna, Austria, Vienna, Austria.

Palhegyi G. E. (2010). Designing storm-water controls to promote sustainable ecosystems: science and application. *Journal of Hydrologic Engineering*, **15**, 504–511, https://doi.org/10.1061/(ASCE)HE.1943-5584.0000130

Panasiuk O., Hedström A., Langeveld J. and Viklander M. (2022). Identifying sources of infiltration and inflow in sanitary sewers in a northern community: comparative assessment of selected methods. *Water Science and Technology*, **86**, 1–16, https://doi.org/10.2166/wst.2022.151

Park S., Lim H., Tamang B., Jin J., Lee S., Park S. and Kim Y. (2020). A preliminary study on leakage detection of deteriorated underground sewer pipes using aerial thermal imaging. *International Journal of Civil Engineering*, **18**(10), 1167–1178, https://doi.org/10.1007/s40999-020-00521-8

Pezzaniti D., Beecham S. and Kandasamy J. (2009). Influence of clogging on the effective life of permeable pavements. *Proceedings of the Institution of Civil Engineers – Water Management*, **162**(3), 211–220, https://doi.org/10.1680/wama.2009.00034

Plihal H., Kretschmer F., Schwarz D. and Ertl T. (2014). Innovative sewer inspection as a basis for an optimised condition-based maintenance strategy. *Water Practice and Technology*, **9**, 88–94, https://doi.org/10.2166/wpt.2014.010

Plihal H., Kretschmer F., Bin Ali M. T., See C. H., Romanova A., Horoshenkov K. V. and Ertl T. (2016). A novel method for rapid inspection of sewer networks: combining acoustic and optical means. *Urban Water Journal*, **13**, 3–14, https://doi.org/10.1080/1573062X.2015.1076857

Prisutova J., Krynkin A., Tait S. and Horoshenkov K. (2022). Use of fibre-optic sensors for pipe condition and hydraulics measurements: a review. *CivilEng*, **3**, 85–113, https://doi.org/10.3390/civileng3010006

Pure Americas Inc. (2011). SmartBall Inspection Report of North Beach Force Main, August 2011. https://your.kingcounty.gov/dnrp/library/wastewater/wtd/construction/NorthBeachFM/1108_NorthBeachForceMainInspectionReport.pdf (visited on 25 August 2023).

Rahman S. and Vanier D. J. (2004). An evaluation of condition assessment protocols for sewer management. Report B-5123.6. Ottawa (Canada): CNRC-NRC. Available online at: http://irc.nrc-cnrc.gc.ca/pubs/fulltext/b5123, 6, b5123.

Rieckermann J., Bareš V., Kracht O., Braun D. and Gujer W. (2007). Estimating sewer leakage from continuous tracer experiments. *Water Research*, **41**, 1960–1972. 10.1016/j.watres.2007.01.024

Roghani B., Cherqui F., Ahmadi M., Le Gauffre P. and Tabesh M. (2019). Dealing with uncertainty in sewer condition assessment: impact on inspection programs. *Automation in Construction*, **103**, 117–126, https://doi.org/10.1016/j.autcon.2019.03.012

Romanova A., Horoshenkov K. V., Tait S. J. and Ertl T. (2013). Sewer inspection and comparison of acoustic and CCTV methods. *Proceedings of the Institution of Civil Engineers – Water Management*, **166**, 70–80, https://doi.org/10.1680/wama.11.00039

Sadeghikhah A., Ahmed E. and Krebs P. (2022). Towards a decentralized solution for leakage detection-a review. *Water Science and Technology*, **86**(5), 1034–1054, https://doi.org/10.2166/wst.2022.263

Schilperoort R. P. S. (2004). Natural water isotopes for the quantification of infiltration and inflow in sewer systems. M.Sc. thesis, Delft University of Technology.

Schmitt T. G., Welker A., Illgen M., Bosseler B., Harting K. and Brüggemann T. (2007). Untersuchung des Abfluss und Versickerungsverhaltens. wasserdurchlässiger Flächenbeläge (Abschlussbericht No. IV-9-042 236 0020). Ministerium für Umwelt und Naturschutz, Landwirtschaft und Verbraucherschutz des Landes Nordrhein-Westfalen (MUNLV), Düsseldorf, Germany.

Schönberger O., Harting K., Gabryl P. and Nolting B. (2005). Prüfung wasserdurchlässiger Flächenbeläge nach mehrjähriger Betriebsdauer. IKT – Institut für Unterirdische Infrastruktur, Düsseldorf, Germany.

Seattle Public Utilities (2009) Green Stormwater Operations and Maintenance Manual, August, 25 p. https://www.seattle.gov/util/cs/groups/public/@spu/@usm/documents/webcontent/spu02_020023.pdf (last access 23.08.2023).

Selvakumar A., Tuccillo M. E., Martel K. D., Matthews J. C. and Feeney C. (2014). Demonstration and evaluation of state-of-the-art wastewater collection systems condition assessment technologies. *Journal of Pipeline Systems Engineering and Practice*, **5**, 04013018, https://doi.org/10.1061/(ASCE)PS.1949-1204.0000161

Shepherd W., Schellart A., Boxall J., Evans M. H., Yu Y. and Tait S. (2021). Passive sensing for buried wastewater collection and drainage networks. Proc 15th Int. Conf. on Urban Drainage, Melbourne, Australia.

Sinha S. and Fieguth P. (2006). Neuro-fuzzy network for the classification of buried pipe defects. *Automation in Construction*, **15**(1), 73–83, https://doi.org/10.1016/j.autcon.2005.02.005

SLG (2020). Merkblatt für versickerungsfähige Pflasterbefestigungen aus Beton: Grundlagen, Planung, Ausführung, Erhaltung. Betonverband Straße, Landschaft, Garten e. V., Bonn, Germany.

Sonkamble S. and Chandra S. (2021). GPR for earth and environmental applications: case studies from India. *Journal of Applied Geophysics*, **193**, 104422, https://doi.org/10.1016/j.jappgeo.2021.104422

Spectar (2023). Spectar Technologies – a Belgium-based startup with a clear mission to half the cost of sewer management in Europe [WWW Document]. https://spectar-technologies.com/ (accessed 14 April 2023)

Stajanca P., Chruscicki S., Homann T., Seifert S., Schmidt D. and Habib A. (2019). Detection of leak-induced pipeline vibrations using fiber optic distributed acoustic sensing. *Sensors*, **18**, 2842, https://doi.org/10.3390/s18092842

Stanić N., de Haan C., Tirion M., Langeveld J. and Clemens F. (2013). Comparison of core sampling and visual inspection for assessment of concrete sewer pipe condition. *Water Science and Technology*, **67**, 2458–2466, https://doi.org/10.2166/wst.2013.138

Stanić N., Langeveld J., Salet T. and Clemens F. (2016). Relating the structural strength of concrete sewer pipes and material properties retrieved from core samples. *Structure and Infrastructure Engineering*, **13**(5), 637–651, https://doi.org/10.1080/15732479.2016.1187631

Stanić N., Lepot M., Catieau M., Langeveld J. and Clemens F. H. (2017). A technology for sewer pipe inspection (part 1): design, calibration, corrections and potential application of a laser profiler. *Automation in Construction*, **75**, 91–107, https://doi.org/10.1016/j.autcon.2016.12.005

Stegeman B., Hoffmann R., Hopman V., Langeveld J. and Clemens-Meyer F. (2022). The assessment of a mobile geo-electrical measurement system: a study on the validity and contributing factors to quantify leakage in sewer systems. *Urban Water Journal*, **19**, 374–387, https://doi.org/10.1080/1573062X.2021.2020298

Tait S. and Kazemi E. (2022). D7.1. Report on methodologies used to identify in-pipe defects (1.0). Zenodo, https://doi.org/10.5281/zenodo.7266706

Tait S. and Kazemi E. (2023). Open Access Coding/Images for Automated detection of in-pipe defects in CCTV sewer surveys (1.0). Zenodo, https://doi.org/10.5281/zenodo.8193032

Thielemann J. T., Breivik G. M. and Berge A. (2010). Robot navigation and obstacle detection in pipelines using time-of-flght imagery. *Proc of The International Society for Optical Engineering*, https://doi.org/10111/12.838979

Thornhill R. and Wildbore P. (2005). Sewer defect codes: origin and destination. Underground Construction.

Towlson A. R. K., Croxford A. J. and Drinkwater B. W. (2022). Ultrasonic non-destructive characterization of blockages and defects in underground pipes. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, **69**, 2540–2554, https://doi.org/10.1109/TUFFC.2022.3183339

Tscheikner-Gratl F., Caradot N., Cherqui F., Leitão J. P., Ahmadi M., Langeveld J. G., Gat Y. L., Scholten L., Roghani B., Rodríguez J. P., Lepot M., Stegeman B., Heinrichsen A., Kropp I., Kerres K., do Almeida M. C., Bach P. M., de Vitry M. M., Marques A. S., Simões N. E., Rouault P., Hernandez N., Torres A., Werey C., Rulleau B. and Clemens F. (2019). Sewer asset management – state of the art and research needs. *Urban Water Journal*, **16**, 662–675, https://doi.org/10.1080/1573062X.2020.1713382

Van der Steen A., Dirksen J. and Clemens F. (2014). Visual sewer inspection: detail of coding system versus data quality? *Structure and Infrastructure Engineering*, **10**(11), 1385–1393, https://doi.org/10.1080/15732479.2013.816974

Veldkamp T. I. E., Boogaard F. C. and Kluck J. (2022). Unlocking the potential of permeable pavements in practice: a large-scale field study of performance factors of permeable pavements in The Netherlands. *Water*, **14**, 2080, https://doi.org/10.3390/w14132080

Vermeulen D. (2022). Detection of leaks: next-generation pipe inspection: Testing the FELL system under controlled field conditions. MSc Thesis, Available at http://resolver.tudelft.nl/uuid:b062ca56-d5aa-4bf2-9fa2-e20503545dd5 (accessed 14 September 2023).

Vollertsen J. and Hvitved-Jacobsen T. (2003). Exfiltration from gravity sewers: a pilot scale study. *Water Science and Technology*, **47**(4), 69–76, https://doi.org/10.2166/wst.2003.0223

Vosse M., Schilperoort R., de Haan C., Nienhuis J., Tirion M. and Langeveld J. (2013). Processing of DTS monitoring results: automated detection of illicit connections. *Water Practice and Technology*, **8**(3–4), 375–381, https://doi.org/10.2166/wpt.2013.037

Wang Y., Li P. and Li J. (2022). The monitoring approaches and non-destructive testing technologies for sewer pipelines. *Water Science and Technology*, **85**(10), 3107–3121, https://doi.org/10.2166/wst.2022.120

Weiß G., Brombach H. and Haller B. (2002). Infiltration and inflow in combined sewer systems: long-term analysis. *Water Science and Technology*, **45**(7), 11–19, https://doi.org/10.2166/wst.2002.0112

Wilmut C. G., Dsouza B. J. and Guidry B. A. (2005). Electro-scan technology – is it the "silver bullet" for rainfall dependent infiltration (Rdi) and exfiltration? *Proceedings of the Water Environment Federation*, **2005**(4), 697–706, https://doi.org/10.2175/193864705784291529

Winston R. J., Hunt W. F., Kennedy S. G., Wright J. D. and Lauffer M. S. (2012). Field evaluation of stormwater control measures for highway runoff treatment. *Journal of Environmental Engineering*, **138**, 101–111, https://doi.org/10.1061/(ASCE)EE.1943-7870.0000454

Wirahadikusumah R., Abraham D. M., Iseley T. and Prasanth R. K. (1998). Assessment technologies for sewer system rehabilitation. *Automation in Construction*, **7**, 259–270, https://doi.org/10.1016/S0926-5805(97)00071-X

Wolf L. (2003). Anwendung einer segmentierten geoelektrischen Sonde zur Leckagendetektion in Abwasserkanälen. (Application of a segmented geo electrical sensor for leakage detection in sewers). *Technisches Messen*, **70**(7–8), 346–351, https://doi.org/10.1524/teme.70.7.346.22647

WRc (2013). Manual of Sewer Condition Classification. WRc plc, Wiltshire, U.K.

WRc (2022). Sewerage Risk Management manual. Available at: https://srm.wrcplc.co.uk/

Yu Y., Worley R., Anderson S. and Horoshenkov K. (2023). Microphone array analysis for simultaneous condition detection, localization, and classification in a pipe. *The Journal of the Acoustical Society of America*, **153**, 367–383, https://doi.org/10.1121/10.0016856

Zhang S., Liu B. and He J. (2019). Pipeline deformation monitoring using distributed fiber optical sensor. *Measurement*, **133**, 208–213, https://doi.org/10.1016/j.measurement.2018.10.021

Zhao J. Q., McDonald S. E. and Kleiner Y. (2001). Guidelines for Condition Assessment and Rehabilitation of Large Sewers. Institute for Research in Construction, National Research Council Canada, Ottawa, Canada.