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REPORT

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D 1.1 REVIEW OF AVAILABLE TECHNOLOGIES AND METHODOLOGIES FOR SEWER CONDITION EVALUATION

Project acronym: SEMA

by

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Abstract

Recent infrastructure studies underline the general deterioration of sewer system and the risk reversing public health, environment and increasing costs (ASCE, 2009). Since the origin of sewer systems in the 19th century, sewers have been installed at different periods using available standards and technologies. Sewer assets have limited service life and it is crucial to assess their condition throughout their life cycles to avoid potential catastrophic failure and expensive emergency rehabilitation due to their deterioration (Hao *et al.*, 2011).

This report first presents the wide panel of inspection technologies available to obtain information about sewer defects and condition. Visual inspection (e.g. Closed-circuit television CCTV, zoom camera) appears to be the industry standard for sewer inspection. It provides visual data (images and/or videos) of the internal surface of the pipe. Defects are usually coded manually by the inspection staff according to standard coding methods. In Europe, the current codification system is the normative EN 13508-2 for visual inspection (EN 13508-2, 2011) used by the CEN-Members (European Committee for Standardization). In addition, physical techniques are available that can give further information and details about pipe defects. These techniques do not replace the CCTV inspection but can give deeper insights on the type and severity of defects. Sonar and Lasers enables to analyze pipe geometry and can identify defects such as deflections, cracks, sediments or corrosion. Ultrasonic testing and magnetic flux leakage (MFL) are applied directly on the pipe wall. They enable to measure wall thickness and detect pipe defects such as corrosion, deflections and cracks. Ground Penetrating Radar (GPR) and Infrared Thermography are used from above ground and are useful to locate pipes and identify bedding conditions, voids and leaks. Finally, network wide inspection technologies like smoke testing or Distributed Temperature Sensing (DTS) can locate cross-connections and/or sewer infiltration. The purpose, inspection procedure and limitations of these methodologies are briefly presented.

On a second step, this report presents the available classification methodologies developed to interpret automatically visual CCTV inspection reports and evaluate sewer condition. These methodologies enable to transfer the extensive amount of visual inspection data from CCTV inspection into a more easily manageable number, useful to support asset management practices. Most approaches have a similar goal: they aim to rank rehabilitation priorities and support municipalities in the definition of rehabilitation programs. They do not pretend to replace the knowledge and analysis skills of a local expert but can help him to identify rehabilitation priorities. All methodologies provide an overall condition score for each sewer segment or sub-scores for different requirements (e.g. structural and operational condition) or dysfunctions. From the review of available methodologies, two main approaches can be distinguished: priority based and substance based methodologies. For priority based methodologies, the calculation of sewer condition grades is based on the most severe defects, the density of defects and/or the defects length. Condition grades express the priority of rehabilitation, i.e. the emergency of action regarding the probability of failure or collapse. For substance based methodologies, the final score is calculated based on the length of sewer that will be affected by rehabilitation actions. Substance based methodologies do not aim to assess the condition of sewers but rather to rank sewer pipes considering the amount and type of rehabilitation needs: replacement, renovation and repair.

Each methodology aggregates and combines sewer defects in a very different way making very hazardous the benchmarking of final scores from different methods. Therefore, municipalities using different evaluation system are not able to benchmark the condition of theirs networks. Finally, the accuracy of the classification results remains a key issue, crucial for the further use of inspection data to support asset management strategies.

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Chapter 1 Introduction

Asset management is an increasing concern for wastewater utilities and municipalities. According to a need survey conducted by EPA (2008), total funding needs for replacement, rehabilitation and expansion of existing collection systems for a 20 year period in the USA is 82.7 billion dollars, i.e. 28% of the total need of public agencies for wastewater treatment and collection. According to a French ministerial survey (OIEau, 2003), the total need in France for sewer rehabilitation is about 7 billion euros. Average yearly investments in the wastewater system in France are about 1.7 billion euros (including capital costs for replacement, rehabilitation or expansion of existing collection systems). In Germany, a national study estimates that about 17% of the sewers have severe defects and should be immediately or at short term rehabilitated (Berger and Falk, 2009). In the last 30 years, most municipalities have invested in sewer system expansion and treatment plant upgrade but a relatively small component has been allocated to the improvement of sewer system condition.

Part of the funds needed to upgrade the condition of sewer systems will be generated through increases of municipal taxes and user fees (Allouche *et al.*, 2002). Other efforts will focus on the reduction of overall costs through the definition of cost-effective rehabilitation plans and the optimization of inspection and maintenance programs. In this context, the condition assessment of sewers aims to evaluate the current condition of assets and support the prioritization of maintenance and rehabilitation activities. The assessment of sewer condition is crucial in implementing a successful asset management program since the cost of sewer failure may have significant economic impacts on the municipality or utility (Rahman and Vanier, 2004).

Most condition assessment methodologies aim to provide an overall grade to each inspected sewer, which represents the current condition of the asset. Input data to these classification methods are sewer defects recorded during CCTV inspections and coded according to standard coding systems. For that purpose, mobile and rotatable cameras are inserted in the sewer system to record pictures or movies from the inner side of sewer pipes. Damages, defects and other abnormalities are documented and additionally described using standard defect codes.

Besides CCTV inspection, a number of additional inspection technologies are available. They can be used complementary to CCTV to gain more precise information about in-sewer defects or to identify defects hardly visible using inspection camera such as deteriorated bedding conditions.

This report is divided in three independent parts. Chapter 2 gives a short overview on CCTV inspection and other current inspection technologies. It describes the purpose, inspection procedure and limitations of each technology. Chapter 3 introduces the historical development of coding system and describes the main coding systems applied in Europe and North America. Chapter 4 presents the main sewer condition classification methodologies. In conclusion, the different approaches are compared to highlight further research needs.

Chapter 2 Inspection Technologies

There is a wide panel of inspection technologies to obtain information about sewer defects and condition (Figure 1). The most common and comprehensive way of inspecting pipes is the visual inspection. Man-entry visual inspections can be performed in very large diameter sewers to identify and describe visible sewer defects. Camera technologies like CCTV or Zoom Camera provide a visual representation of the inner pipe condition without person-entry. Image analysis enables to identify the type and position of visible defects like offset joints, pipe cracks, leaks, sediment, debris and root accumulation. Defects can be coded according to standard defect codifications in order to store the data and allow the later evaluation of sewer condition (chapters 3 and 4).

In addition, physical techniques are available that can give further information and details about pipe defects. These techniques do not replace the CCTV inspection but can give deeper insights on the type and severity of defects. Sonar and Lasers support the detection of changes in the pipe geometry that may be caused by deflections, cracks, sediments or corrosion. Ultrasonic testing and magnetic flux leakage (MFL) can detect pipe defects such as corrosion, deflections and cracks and measure wall thickness. They require access to the sewer since the sensors need to be put in contact with the pipe wall (on-line inspection). Ground Penetrating Radar (GPR) and Infrared Thermography are used from above ground and are useful to locate pipes and identify bedding conditions, voids and leaks. Finally, network wide inspection technologies like smoke testing or Distributed Temperature Sensing (DTS) can locate cross-connections and/or sewer infiltration. Figure 1 gives an overview of current available inspection technologies.

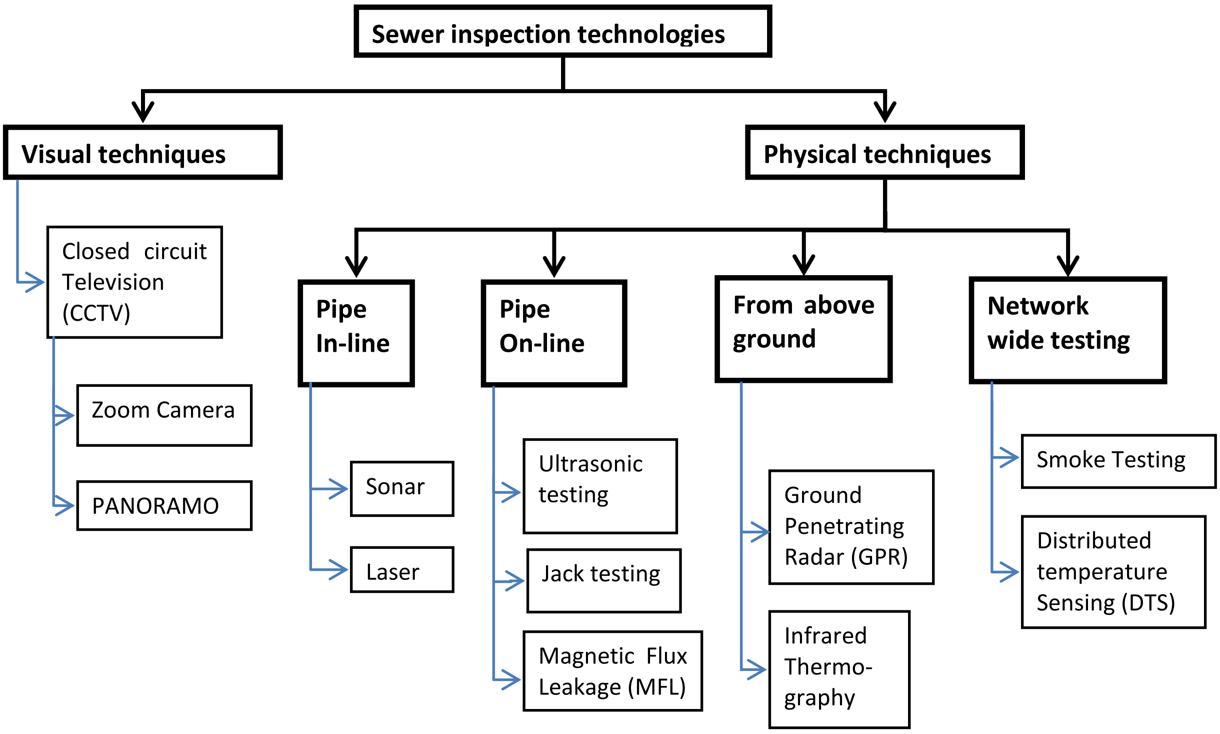


Figure 1: Overview of main sewer inspection technologies. In-line technologies are applied from inside the sewer. On-line technologies are also applied from inside the sewer but require contact with the sewer material.

The following subchapters describe shortly the purpose, application, inspection procedure and limitations of each technique. For cost-benefit analyzes and a more detailed review of inspection technologies, the reader can refer to the literature (Hao *et al.*, 2011; Marlow *et al.*, 2007; Redman, 2007 and Tuccillo *et al.*, 2010).

2.1 Visual techniques

2.1.1 CCTV

CCTV is used since decades as industry standard for sewer system inspection. CCTV is a standard technology for detecting a wide range of sewer defects without person-entry. It provides visual data (images and/or videos) of the internal surface of the pipe. The analysis of the image enables to identify the type and position of defects like offset joints, pipe cracks, leaks, sediment, debris and root accumulation (Martel and Tuccillo, 2010).

According to EN 13508-1 (2012), indirect inspection technologies like CCTV should be preferred to direct inspection with person-entry. CCTV is suited for any pipe material and for pipe diameter of 90 mm and greater (Marlow *et al*., 2007). The technology can be used with a power supply cable up to 500 m; otherwise, the image quality of the video may be downgraded. Other inspection technologies can be attached to CCTV camera to improve the quantitative analysis of defects (e.g. Laser, Sonar) (Marlow *et al.*, 2007).

Typical CCTV systems use a video camera with lighting to provide a visual recording of the interior pipeline condition. Generally the camera is mounted on a tractor or crawler (Figure 2), which enables the camera system to drive through the sewer pipe and record the entire pipe section. The European norm EN 13508-1 recommends cleaning and dewatering the sewer length between two manholes by means of temporary bypass or flow blockage. The camera can also be used in a non-dewatered pipe by mounting the camera on a float rig but only the surface above the water can be recorded. The camera is connected to a video monitor and a recording device through a cable, which also measures the distance of observed defects to the manhole. These video technologies often have the ability to pan, tilt, rotate and zoom, which supports the operator to gain a full circumferential view of the pipe even behind connections and obstructions.

Figure 2: Example of CCTV robot from the company IPEK (http://www.ipek.at)

Besides classical CCTV systems, digital scanning systems have been developed in order to improve the image resolution and the inspection speed (e.g. PANORAMO from the IBAK Helmut Hunger GmbH (Kiel, Germany)). The PANORAMO system uses two high-resolution digital photo cameras with 186° fisheye lenses. By travelling through the pipe it takes two images at distances of every 5 cm, one with the front and the other with the rear camera (Figure 3).

The recorded pipe sections can be combined to generate two types of images: a 3D interior view of the entire sewer pipe and unfolded views of the inner pipe surface. The unfolded view of the inner pipe surface enables computer-aided measurement of defects and objects. Furthermore, the image quality is improved since the camera does not record videos but high resolution photos (IBAK, 2013).

Figure 3: Digital scanning system PANORAMO 150 (http://www.ibak.de)

Figure 4 shows the procedure of CCTV inspection. An operator drives the camera into the pipe and can stop the process to review the video images and decide to perform closer examinations on regions of interest. Digital scanning systems allow the operator to move freely in the sewer pipe without viewing restrictions. He can stop at any position, pan around 360°, zoom, look into inlets and even look backwards. The videos and images collected by CCTV cameras can be analyzed by the operator during the inspection on site (common approach) and after the inspection at the office. Defects observed are coded according to standard coding systems (chapter 3).

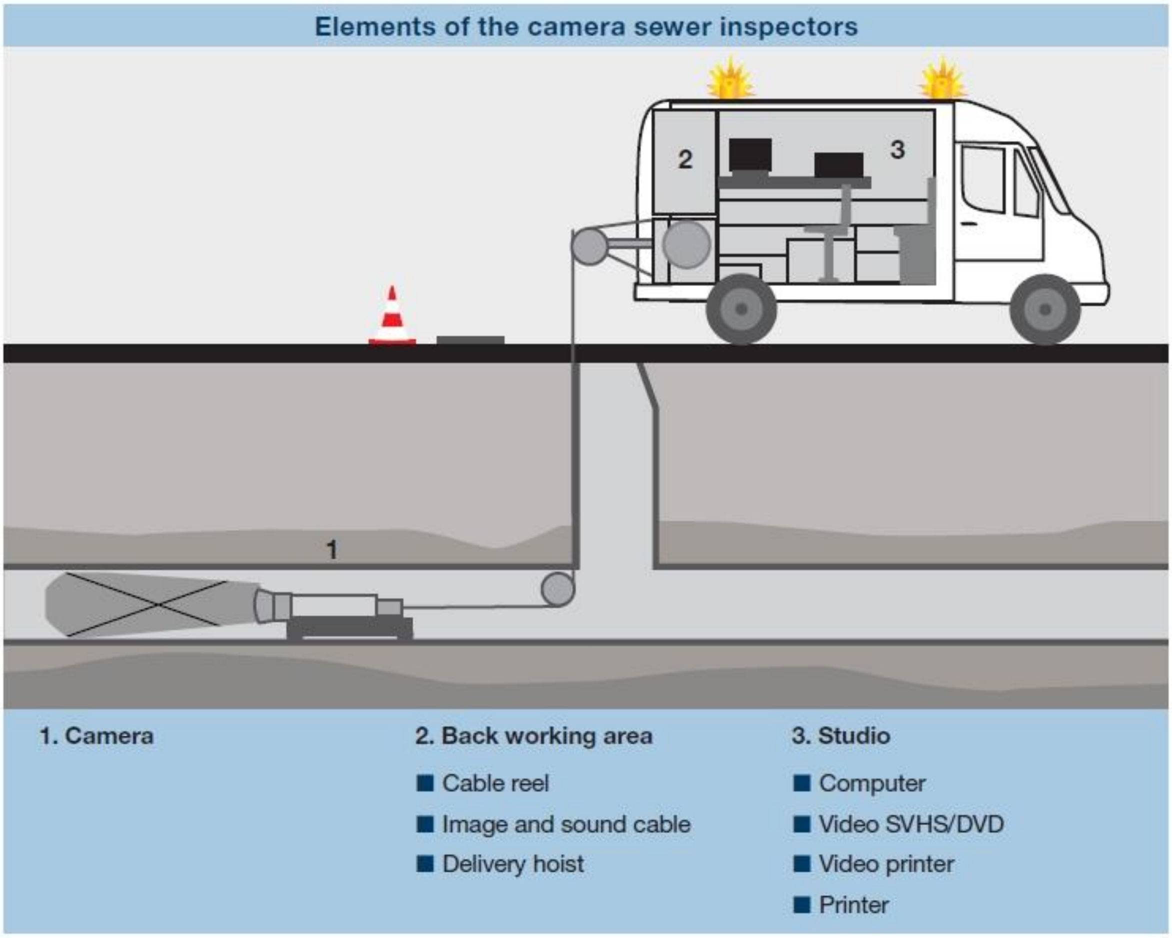


Figure 4: Elements and inspection procedure of the CCTV (from FCSM, (2009))

Traditionally, the defect codification is performed manually by the inspection staff. Due to the labour-intensive and error-prone manual detection and interpretation of pipe defects, recent research projects have intended to automate this procedure. Several methodologies have been developed, but are not commonly used by municipalities. Thus their benefits are still to be demonstrated. According to Hao (2011), existing methodologies cannot provide satisfactory confidence by identifying all sewer defects, especially under harsh conditions. A short review of existing methodologies can be found in Guo *et al.* (2009).

Limitations:

- Set-up time and cost of CCTV inspection depend highly on sewer characteristics (e.g. pipe size, slope and depth) and flow characteristics (flow velocity and water depth). Pipe dewatering can be needed to inspect the entire sewer section.
- CCTV inspection only provides a visual representation of the pipe interiors. CCTV does not detect external voids, deteriorated bedding conditions and does not provide information about pipe wall thickness. Defects under the flow line or behind obstructions cannot be identified (Hao *et al.*, 2011).
- Accuracy greatly depends on the interpretation of the operator (Salman, 2010). The procedure is work-intensive and highly subjective (Dirksen *et al.*, 2013).

2.1.2 Zoom camera

Zoom camera is a standard method to perform a quick screen of the sewer condition. It does not replace conventional CCTV inspection, but is useful to identify quickly sewers that may need cleaning or a more detailed inspection with conventional CCTV (Tuccillo *et al.*, 2010). It can detect and locate visible cracks, leaks, root intrusion and the overall surface condition of pipes and manholes.

Zoom cameras generate still images or recorded videos of the pipe interior by zooming and panning 360° down the pipe. Instead of driving through the pipe, the camera remains stationary. The camera is truck- or pole-mounted and lowered into a manhole to perform the inspection (Tuccillo *et al.*, 2010) (Figure 5).

Figure 5: left: QuickView® System ; right: an example of visual screening done with a zoom camera (Ertl, 2012)

Limitations:

- Same limitations as CCTV: information only about the interior condition of the pipe and subjectivity of the defect interpretation (Liu *et al.*, 2012).
- The visibility of defects strongly depends on the sight distance of the camera and on the flow-line level. The quality of the image depends on zooming and significant defects may be missed for long manhole to manhole distances.
- The camera gives only an axial vision of the pipe. Defects can be missed (e.g. cracks) especially in the case of bended or curved pipes.
- Uncertainties in the measurement of defect position.

2.2 Physical techniques

2.2.1 In-line inspection

Laser based system

A laser based system generates a profile of the inner surface of the pipe. It allows the detection and measurement of changes in the pipe geometry that may be caused by deflections, cracks, sediments or corrosion (Tuccillo *et al.*, 2010). Measurement of pipe diameter and ovality is especially relevant for plastic pipes in which deflections indicate stresses that can cause premature collapse of the pipe (Marlow *et al.*, 2007). The laser technology is applicable for any pipe material with a diameter between 600 and 1600 mm.

The common 2-D technique uses a laser to create a line of light on the pipe's profile. The laser draws the sewer shape and can detect changes in the pipe's shape. The recent development of 3D laser scanning enables to provide a 3D profile of the pipe. The laser technology is usually attached to a CCTV robot. The laser records automatically the shape of the pipe by creating a pipe measurement diagram. The results are evaluated by an operator after the inspection to describe the observed defects (Figure 6). Due to the possible diffraction of the laser beam under water, laser surveys can only be used reliably above the flow line (Hao *et al.*, 2011).

Limitations:

- Laser surveys can only inspect the pipe section above the water line.

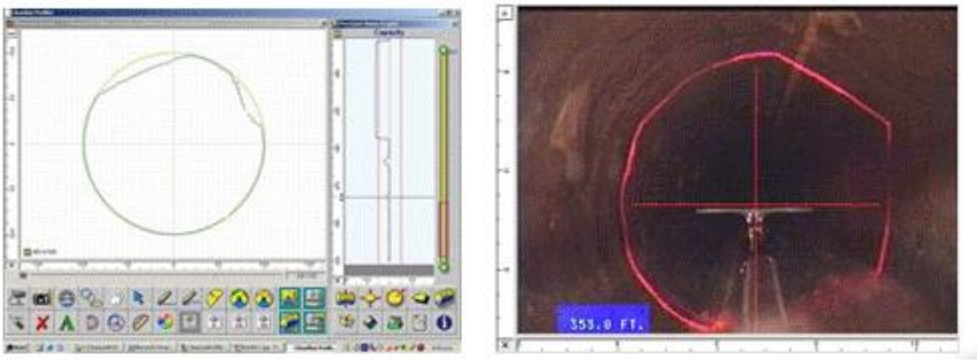


Figure 6: Example of image processing from a laser profiler (http://www.cuesinc.com)

Sonar

A sonar is an acoustic detection technology designed to operate under water (Liu *et al.*, 2012). It can also be used above the flow line but different transducers are required to operate in air and water (Marlow *et al.*, 2007). Like the laser technology, the sonar profiles the circumference of the pipe interior and records pipe geometry and pipe defects, such as pipe wall deflections, cracks and sedimentation. A sonar is applicable for gravity sewers and force mains of any pipe material with a diameter greater than 300 mm (Tuccillo *et al.*, 2010).

The sonar technology can be used individually, especially in situations where a camera system cannot be used for inspections (e.g. flooded pipe section). However, it is commonly combined with CCTV robots to inspect sewer lines below and above the water line without dewatering.

The sonar system sends out high-frequency ultrasonic signals, which are reflected by the pipe walls and then received by the sonar head. The time between signal transmission and reception determines the distance between the sonar head and the pipe wall or sediments.

Depending on the size and flow conditions of the sewer, the sonar head can be mounted on a tractor, crawler or float. By passing through the pipe, it provides a continuous series of cross-sections along the sewer. Results are analyzed by an operator after the inspection to determine the sewer shape and identify structural defects and sediment deposits (Figure 7).

Limitations:

- The accuracy of the sonar is affected by the quantity of suspended solids in the sewage and the degree of turbulence (Tuccillo *et al*., 2010).

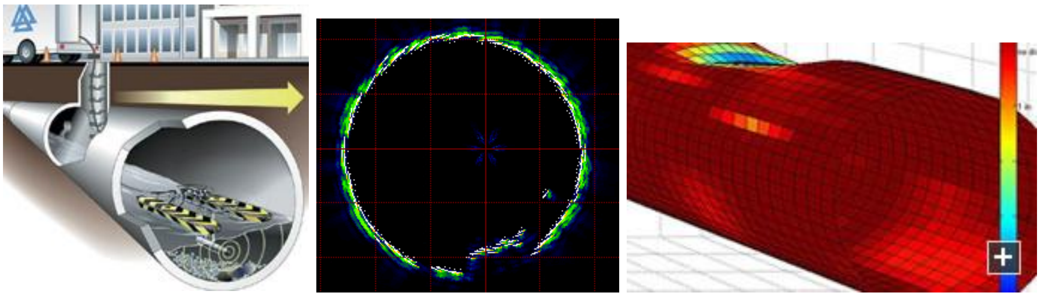


Figure 7: left: inspection process of a combined CCTV and Sonar survey from the Andrews Infrastructure Company (http://andrewsinfrastructure.com); middle: selected sonar profile of a cross section; right: continuous series of closely spaced cross-sections along a sewer (http://www.aquacoustic.com)

2.2.2 On-line inspection

Ultrasonic testing

Ultrasonic testing is a material testing method that analyses changes in the sewer material. It can detect pipe defects such as corrosion, deflections and cracks and measure the wall thickness. The method is suitable for all pipe materials but performs better for iron and steel pipes (Tuccillo *et al*., 2010).

Ultrasonic devices send high frequency sound waves towards the inner surface of the pipe. The pulse passes through the material until it reaches the other side or a change in material density. The signal echo is reflected and received on the inner surface of the sewer. The duration and velocity of the pulse are analyzed to determine the distance from the inner surface to the outer side (i.e. the wall thickness).

The sewer must be previously cleaned and debris and roots should be removed. A gel is then injected on the pipe surface to ensure an optimal contact between pipe wall and sensor (Redmann, 2007). The device can perform several measurements along the sewer line and results are analyzed by the operator.

Limitation:

- The technique performs better for iron and steel pipes.
- Access to the sewer is required (man-entry sewers). The sensor needs to be put in contact with the pipe wall or at least very close since the precision of the measurement decreases with the distance to the wall.
- The method is relatively slow due to the required point-by-point measurements (Tucillo *et al*., 2010)
- The pipe has to be dewatered and cleaned before the inspection.

Magnetic Flux Leakage (MFL)

The MFL technique is used for the detection and characterization of metal loss defects such as corrosion and cracks on the interior wall of metallic pipes. The MFL has good detection capabilities even for small defects: even under extremely poor conditions, a magnetic response is still obtained (Hao *et al*., 2011). Hence, wall thickness reductions can be detected with a high degree of accuracy (Marlow *et al*., 2007).

The MFL tool consists of two or more bodies. One body is the magnetizer with the magnets and sensors and the other bodies contain the electronics and batteries (see Figure 8). The MFL magnet sends magnetic flux into the material whereas the sensor head measures the axial, radial and circumferential signals with three integrated sensors. Damaged areas cannot support as much magnetic flux as undamaged homogeneous areas, resulting in an increase in the flux field.

The pipe needs to be off-line, dry and cleaned prior to the inspection. The MFL device is inserted into the sewer and moved along the pipe by an operator.

Limitations:

- The technique is only suitable for metallic pipes.
- Access to the sewer is required (man-entry sewers) since the sensor needs to be put in contact with the pipe wall.
- The pipe has to be dewatered and cleaned before the inspection.
- The accurate interpretation of the results requires a skilled operator.

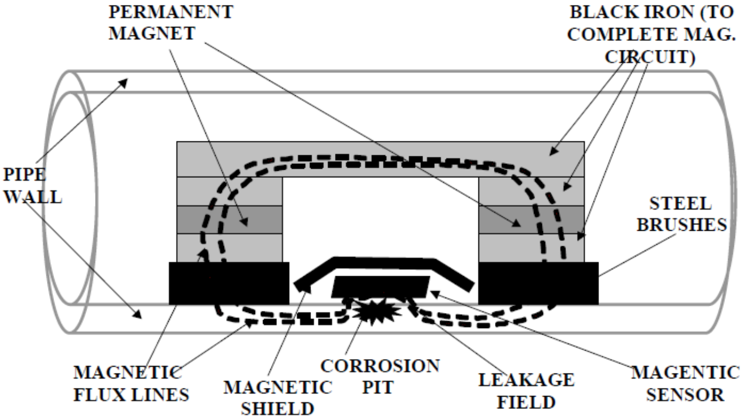


Figure 8: Schematic representation of the Magnetic Flux Leakage (MFL) device (Marlow *et al*., 2007)

Jack testing

The jack testing can be used to assess the structural condition of sewer pipes, the presence of voids and the quality of the interface between the pipe and the surrounding soil. The test has been developed and patented by the water utility of Paris “Eau de Paris” (vérinage interne, tool MAC).

The test consists in applying two forces on both sides of a sewer and measuring the resulting deformation (Thepot, 2004). The analysis of the deformation enables to describe the characteristics of the sewer-soil interface and identify the presence of voids. This technology is often used to assess the quality of rehabilitation construction works.

Limitations:

- Access to the sewer is required (man-entry sewers).
- The accurate interpretation of the results requires a skilled operator.

2.2.3 Above ground inspections

Ground Penetrating Radar (GPR)

Ground Penetration Radar (GPR) systems are usually used to locate underground utilities such as tunnels, mines or concrete structures (Hao *et al*., 2011). GPR can also determine the soil condition by detecting voids, rocks and areas of water saturation around the sewers. GPR can be used for all pipe diameters.

A GPR transmits high frequency radio waves into the ground. By travelling through the ground, the radiation hits objects with differing conductivity and dielectric constant (Tuccillo *et al*., 2010). A reception antenna records the amplitude of each reflected pulse. The return time can be analyzed to determine the position and depth of features below the ground surface (Figure 9).

The traditional GPR inspection is performed from the ground surface by an operator (look-down mode). Recent GPR systems have been developed for in-pipe inspection (Hao *et al*., 2011). The transmitter is mounted on a robot inside the pipe and the receiver can be installed either in the pipe on the robot (look-in mode) or outside on the ground (look-through mode).

Limitations:

- The quality of results depends strongly on the local soil conditions.
- The accurate interpretation of the results requires a skilled operator.

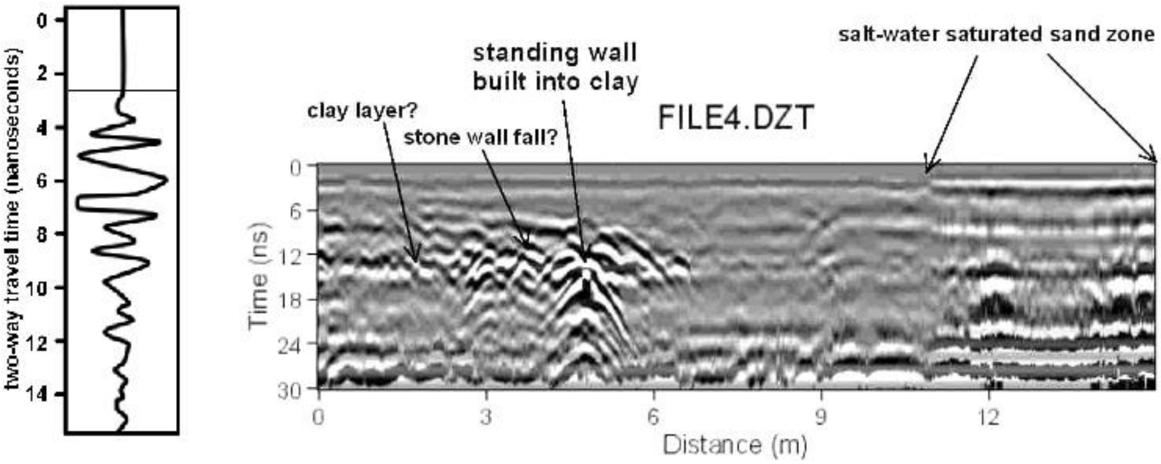


Figure 9: left: one reflection trace with the amplitudes of a reflected pulse; right: an example of a GPR reflection 2D profile (http://www.avalonus.com)

Infrared thermography (IRT)

The Infrared Thermography (IRT) can be used to detect leaks, voids, and variations in pipe wall thickness.

IRT uses an infrared camera to measure infrared radiation across the surface of sewers. Different temperatures on the pipe surface can indicate the presence of defects (e.g. leaks or voids outside the sewer) and emit different infrared radiations. These radiations are recorded by sensors and analyzed by an operator to identify and evaluate defects and voids.

The IRT can be used from above ground or inside the pipe. There are two basic IRT methods: the passive IRT, which requires no external heat source, and the active IRT, which requires a heat source in the pipe such as an infrared tube light (Tuccillo *et al*., 2010). With a passive IRT, the sun serves as the energy source by warming the ground.

Limitations:

- A trained operator is needed for IRT inspection and interpretation of the results.
- The sensitivity of temperature changes received by the device and its resolution can be reduced with distance to the object and angle of view.

2.2.4 Network-wide inspections

Smoke Testing

Smoke testing is a quick and relatively inexpensive method usually used to locate illegal or faulty connections to sewers. It can also be used to locate leaks or broken pipes (Marlow *et al*., 2007). The application to large pipes is limited due to the capacity of blowers (Salman, 2010).

Smoke is created using either a non-toxic smoke bomb or liquid smoke. The blower injects the smoke through a manhole into the system. After several minutes improper connections can be located by the smoke filtering out of the pipe.

Before pipe inspections, the residents and emergency services of the inspection area have to be informed and traps need to be properly placed in the sewer to prevent the smoke from entering houses and to keep the smoke in the test area.

Further surveys can be used to determine infiltration issues. Existing flow records (e.g. treatment plant influent data, pump run time data) and additional flow monitoring stations can be analyzed in order to identify differences between the measured downstream and upstream flows in the several catchment subsystems.

Limitations:

- The technique requires access to property.
- A partially blocked pipe can lead the smoke away from the test area to areas not being inspected.
- The smoke may cause alarm to residents.
- The application to large pipes is limited due to the capacity of blowers (Salman, 2010).

Distributed temperature Sensing (DTS)

DTS is a useful tool for locating illicit connections and detecting sewer infiltration (Hoes *et al*., 2009).

The technique uses a fiber-optic cable connected to a laser/computer instrument which measures temperature simultaneously at many locations along the cable. Typical spatial and temporal resolutions are 1-2 meters and 1 minute, respectively (de Haan *et al*., 2011). The accuracy of temperature measurement is about 1 °C.

The fiber-optic cable is installed temporarily (several days or weeks) inside a sewer over a length of several kilometers. Once the cable is laid, the system records automatically the temperature provides a detailed representation of in-sewer temperatures in both time and space (an example is shown in Figure 10). Results are analyzed by an operator to identify illicit connections and/or infiltration.

Limitations:

- The technology has high initial costs (newly developed and expensive equipment)
- Long duration of equipment installation
- The efficient detection of wrong connections and/or leaks depends on the temperature gradient of sewage and infiltration water.

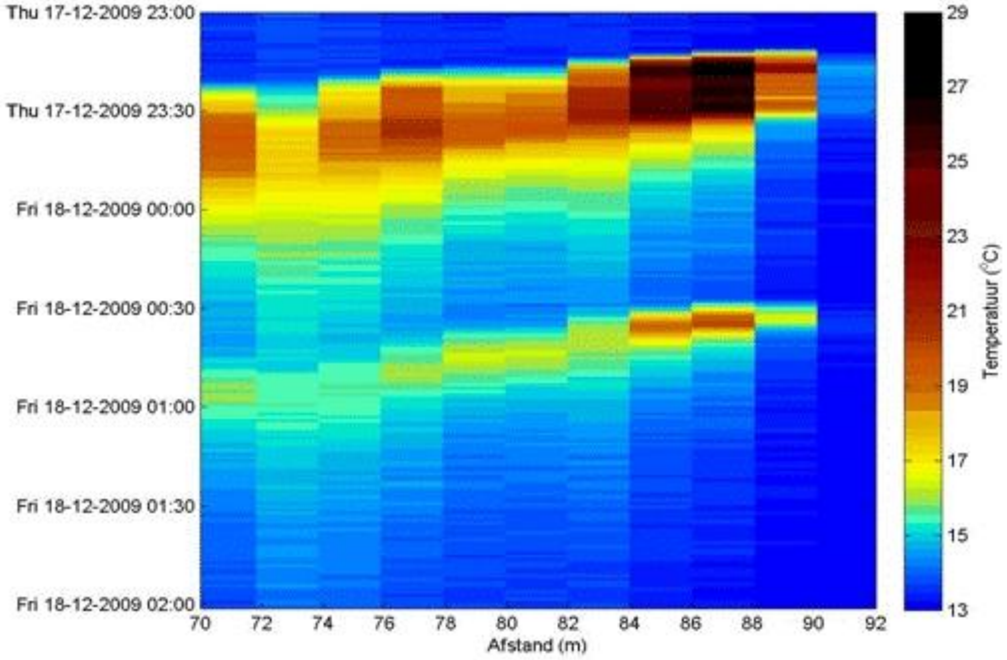


Figure 10: Representation of the temperature changes over time and cable length using the DTS technology of the company Royal Haskoning (http://www.waterindestad.nl)

Chapter 3 Defect coding

3.1 General presentation

The coding method is the documentation of the CCTV inspected sewer condition (chapter 2). It describes the inspected sewer defects with standard codes together with asset information. The transformation of visual information into standard codes by the inspection staff is a crucial step to ensure a reliable data processing for the further use of inspection data. It can be done either on site or after the inspection at the office. The procedure is very subjective, depends highly on the experiences and qualifications of the operating staff and is hardly automatable (Schmidt, 2009). Therefore, the defect coding system needs to be simple and consistent as far as possible (Dirksen *et al*., 2013). Based on the documented codes the condition of inspected sewer can be evaluated (chapter 4).

The first coding method was released in 1980 in the Manual of Sewer Condition Classification MSCC by the Water Research Centre (WRc). These codes are the basis of numerous condition classification protocols developed throughout the world during the past 35 years (U.S.A., Canada, etc.); Figure 11 shows an overview of the historical development of national coding systems based of MSCC. The latest version of the Manual of Sewer Condition Classification MSCC4 (WRc, 2004) has been published in 2004 and became the UK standard in 2005.

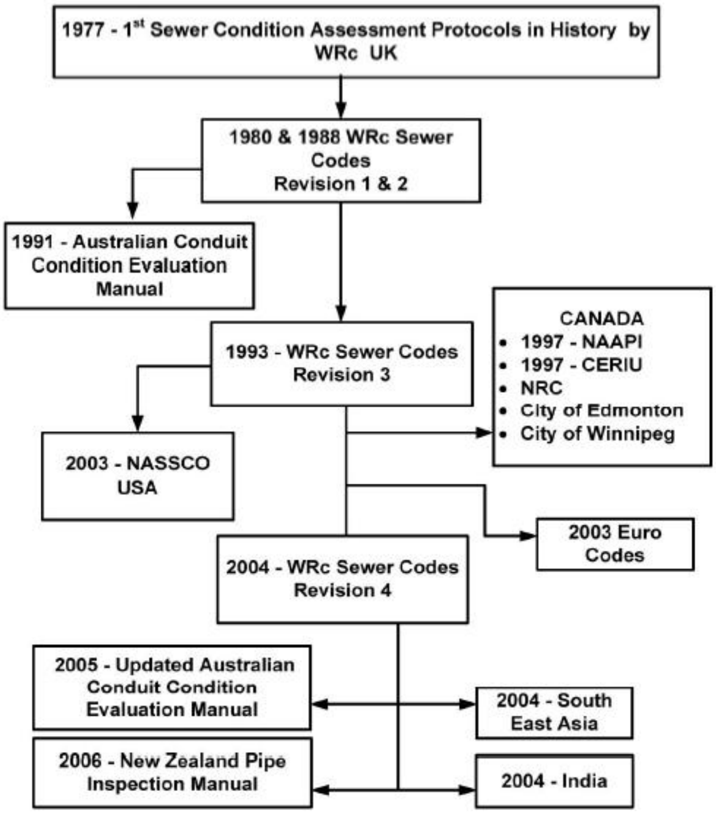


Figure 11: Historical background of sewer condition assessment protocols based on the first assessment protocol from WRc (Chughtai and Zayed, 2011)

In Europe, the current codification system is the normative EN 13508-2 for visual inspection (EN 13508-2, 2011) used by the CEN-Members (European Committee for Standardization). The European standard has been (or has to be) transferred and translated completely into national standards. For example in Italy, the national association for sewer maintenance (ASPI Associazione nazionale delle imprese per la manutenzione e lo spurgo delle reti fognarie e idriche) released in 2008 a guideline (LGN Linee Guida Nazionali) for sewer defect codification based on a simplification of the normative EN 13508-2.

In the European coding system, observed defects are coded with letters on three positions.

- Position 1: a main code (up to three letters) describes the observed defect (e.g. BAB for crack and BBF for infiltration).
- Position 2 and 3: letters can be used to indicate the defect characterization (e.g. open crack in longitudinal direction).

A numerical value can be added to quantify the defect. The circumferential position of the defect is described by the clock reference method. An example of defect coding is shown in Table 1.

Table 1: Example of defect coding according to EN 13508-2 (2011)

<table>
<tr><th>Main code</th><th>Characterization</th><th>Quantification</th><th>Position</th><th>Defect on connection</th><th>Longitudinal position</th><th>Photo reference</th><th>Video reference</th><th>Remarks</th></tr>
<tr><td>BAB</td><td>C,A</td><td>06</td><td>3</td><td>-</td><td>5,50</td><td>F16</td><td>12:23</td><td>-</td></tr>
<tr><td>BBF</td><td>B</td><td>-</td><td>3</td><td>-</td><td>5,50</td><td>F16</td><td>12:23</td><td>-</td></tr>
<tr><td colspan="9">Crack(BAB); visible open (C); longitudinal direction (A); 6 mm wide; 3 o’clock,
5,50 m after the starting position; on photo 16; in the video from 12:23
Infiltration (BBF); drippy (B); 3 o’clock, 5,50 m after the starting position;
on photo 16; in the video from 12:23</td></tr>
</table>

If the European standard has already been converted in the different national versions, it has not been fully implemented by all member countries. Indeed, further existing national standard systems are still in use in many countries.

For example, in France, many utilities still use the former recommendations of the AGHTM for the inspection reports (AGHTM, 1999). Using this guideline, defects are not coded but described as observations by the operator.

In Germany, many utilities still use the German coding system according to ATV-M 143-2 (1999) or company-specific coding systems. A translation procedure has been proposed by the DWA (German Association for Water, Wastewater and Waste) to transfer German inspection data into the European codes (Advisory Leaflet ATV-DVWK-M 152). This procedure can be implemented to translate old inspection data in the European coding system and enable comparison with new inspections.

The procedures of the German and European coding systems are similar: the defects are documented with letter codes together with further general and defect specific information. The difference lies in the specific letters for defects. In the German coding system, defects are coded with letters on 4 positions and additional defect quantification.

- Position 1: a letter names the main group of the defect (e.g. R for crack),
- Position 2: a letter indicates the characterization of the defect (e.g. L for longitudinal),
- Position 3: a letter gives details about infiltration (e.g. E for water entry),
- Position 4: a letter localizes the defect (R for right or 3 o’clock).

3.2 Uncertainty and subjectivity in the coding procedure

The uncertainty of condition grading is a main issue for the further use of coded data, especially for decision making and for the development of deterioration models. Dirksen *et al*. (2013) analyze findings from several European case studies related to the accuracy and reliability of data obtained from CCTV inspection. Uncertainties originate mainly from the subjectivity in the (i) recognition and (ii) description of defects as well as in the (iii) interpretation of CCTV inspection reports. The probability that an inspector fails to recognize the presence of a defect were found to be about 25%. They also found out that the probability of an incorrect observation (defect recognition and description) for all defects was higher than 50%. Finally, Hüben (2002) analyzed the changes in condition scores between repeated inspections using data of a German municipality. Results indicate that over 50% of the sewers changed in condition scores between the several inspections. In the future, further studies are needed to assess these uncertainties and their influence on the decision making processes.

Chapter 4 Condition Classification methods

4.1 Overview

A wide panel of condition classification methodologies has been developed during the last decades. These methodologies typically use algorithms to weight, combine and aggregate sewer defects recorded during CCTV inspection of sewer pipes and coded according to a specific coding system (chapter 3). They provide for each sewer segment (from manhole to manhole) an overall condition score or sub-scores for different requirements (e.g. structural and operational condition). Most methodologies have been developed by national research centers in collaboration with municipalities.

As far as known to the authors, only few legal requirements exist regarding their implementation. In several regions of Germany, local regulations commit sewer operators to inspect their network regularly. Inspection frequency is defined in the self-monitoring ordinance of each Land (Selbstüberwachungsverordnung). For example, operators in North Rhine-Westphalia have to inspect their entire network within 10 years and at least 10% of the network each year. In Saxony, the entire network must be inspected once until 2019. In some regions, further legal requirements commit sewer operators to evaluate and report sewer condition based on the recorded defects.

The primary interest of condition classification methodologies is to transfer the extensive amount of visual inspection data and single defect codes into an easily manageable number, useful to support asset management. Most approaches have a similar goal: they aim to rank rehabilitation priorities and support the definition of rehabilitation programs. However, depending on the classification method used, the scores have very different meaning and should be interpreted carefully. The survey of available methodologies highlights two main approaches: priority and substance based methodologies.

4.1.1 Priority-based methodologies

These methods assign a final mark to each inspected sewer (from manhole to manhole) that represents the priority of rehabilitation, i.e. the emergency of action regarding the probability of failure or collapse. The first approach developed to assess the current condition of sewer pipes was proposed in 1986 by the Water Research Centre (WRc) in the UK. Based on or parallel to this original scheme, several approaches have been developed especially in Canada, U.S.A., Australia, France and Germany. These methods focus on the structural condition of the sewers but consider also operational and environmental factors (e.g. vulnerability of groundwater to pollution).

Grades are calculated according to (i) the most severe damage within the sewer and/or (ii) the density of defects along the sewer line. Factors of vulnerability or failure consequences are often integrated (e.g. traffic flow above the sewer, location of services such as industry or highways) to evaluate the risk of failure or collapse (Le Gauffre *et al*., 2004; WRc, 2001). Thornhill (2008) indicates that data about failure consequences need to be considered in the condition assessment since they are primary in the rehabilitation decision process. However, only few utilities managed to implement full risk-based sewer condition evaluation, mainly because of the lack of standards and high costs associated with the collection of such critical data (Thornhill, 2008).

4.1.2 Substance-based methodologies

Several German projects (DWA T4, 2012; Hochstrate, 1999) stated that existing priority-based classifications do not allow for a pragmatic and accurate estimation of renewal needs. For that purpose, substance-based models have been developed. There is currently no clear definition of the meaning of the term “substance”. According to Baur *et al*. (2005), substance based classifications evaluate the “intrinsic value of the sewer”. Indeed, substance based methodologies do not aim to assess the condition of sewers but rather to rank sewer pipes considering the amount and type of rehabilitation needs (replacement, renovation and repair).

These methods define a substance class for each sewer based on the repair length, i.e. the length of sewers that will be affected by rehabilitation actions. Depending on the type of defect, no-dig or open trench solutions will be required. Rehabilitation interventions will affect a specific sewer length, longer than the defect itself. If defects are very close to each other, they may be rehabilitated together using few rehabilitation technologies and thus reducing the intervention costs. If a major part of the sewer is affected by rehabilitation interventions (e.g. many severe defects spread over the sewer length), the substance of the sewer is considered to be very low since an expensive replacement will be the most cost effective solution. If only a small part of the sewer is affected (e.g. only one severe point defect), the sewer has a better substance value since repair or renovation technologies will be appropriate and the expensive replacement of the sewer is not necessary.

The next chapters describe in detail the available methodologies for sewer condition classification.

4.2 Priority based methodologies

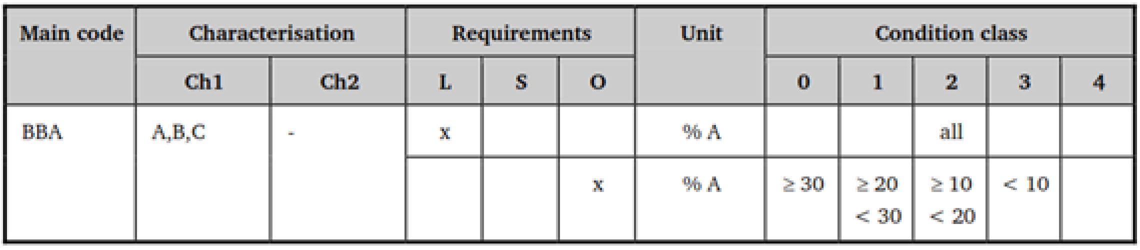
4.2.1 DWA-M 149-3, Germany

The German methodology DWA-M 149-3 is described in the advisory leaflet M 149-3 from the DWA (DWA-M 149-3, 2011). It is probably the most used methodology among German utilities since it represents the generally accepted rules of technology ("allgemein anerkannte Regeln der Technik" in German). The leaflet is available in English and German language and has been developed to replace its predecessor ATV-M 149 in order to meet the new requirements from EN 13508-2. Thus, it is only applicable for standard defect codes according to EN 13508-2 (2011) which underlines the need to translate old coding systems in EN 13508-2 (Chapter 3).

The methodology is implemented in several software tools, for example in “Kanalinspektions-Expert Professional” (DWA, 2013), which can be purchased from DWA, or in an additional add-on for “IKAS 32” from IBAK Helmut Hunger GmbH. Open source tools are not available to our knowledge.

Goal of the methodology is to support rehabilitation strategies by ranking sewer pipes according to their urgency of rehabilitation. The methodology evaluates the operational and structural condition of a sewer pipe considering the most severe defects, the defect density and the influence of boundary conditions (e.g. groundwater level, sewer depth).

Single defects are evaluated according to their relevance in respect to three fundamental requirements: Leaktightness (L), Stability (S) and Operational safety (O) separately. They are rated according to 5 interim condition classes from 0 (very severe deficit with danger in delay) to 4 (minor deficit) for each requirement. If a defect quantification is unknown, the worst case can be assumed. Figure 12 shows an example of condition class attribution: defect 1 (intruding roots that cover 25% of the pipe cross-section) is classified into condition class 1 for operational safety (O) and into condition class 2 for leaktightness (L) and is not relevant for the requirement stability.



Main code	Characterisation		Requirements			Unit	Condition class				
	Ch1	Ch2	L	S	O		0	1	2	3	4
BBA	A,B,C	-	x			% A			all		
					x	% A	≥ 30	≥ 20 < 30	≥ 10 < 20	< 10	

Figure 12: Example of classification of individual defects (roots) according to DWA-M 149-3 (2011)

For each sewer and each requirement, a condition score is calculated based on the most severe interim condition class and on the density of defects. Boundary conditions can be considered by adding an extra factor for each requirement (Table 2). If a boundary condition is unknown, the worst case can be assumed. For each criteria, a value R between 0 (best case) and 1 (worst case) is chosen.

Table 2: Boundary condition values for sewer pipelines according to DWA-M 149-3 (2011)

Requirement	Criteria	Characteristics	R
Leaktightness	Type of joint	built until 1965	1
		built after 1965	0
	Hydraulic load	requirements of DWA-A 118 met	0
		requirements of DWA-A 118 not met	1
	Position to groundwater	within groundwater	1
		transition zone	0.5
		above groundwater	0
Stability	Depth of cover	≤ 2.5 m	1
		>2.5 m and ≤ 4.0 m	0.5
		> 4.0 m	0
	Soil group (ATV-A 127)	non-cohesive soil (G1)	0
		slightly cohesive soil (G2)	0
		cohesive mixed soil, silt (G3)	0.5
		cohesive soil (G4)	1
Operational safety	Hydraulic load	see requirement leaktightness	
	Depth of cover	see requirement stability	

Finally, the individual evaluations for each requirement are merged into a coefficient of rehabilitation need based on the most severe requirement. The coefficient of rehabilitation need can be transformed into a sewer condition class that defines the time-horizon for rehabilitation actions (Table 3).

Table 3: Evaluation of the coefficient of rehabilitation need according to DWA-M 149-3 (2011)

Coefficient of rehabilitation SZ	Need for action	Condition evaluation	Condition class
SZ >= 9,000	immediate	very severe deficit	0
8,000 <= SZ < 9,000	short-term	severe deficit	1
7,000 <= SZ < 8,000	medium-term	medium deficit	2
6,000 <= SZ < 7,000	long-term	slight deficit	3
5,000 <= SZ < 6,000	no need for action	minor deficit	4
SZ = 0	defect-free	no deficit	5

4.2.2 Arbeitshilfen Abwasser (Waste Water Guide), Germany

The Waste Water Guide was established as a guideline for planning, building and operating the wastewater facilities of all German federal real estates (Arbeitshilfen Abwasser, 2013). It is published by the Federal Ministry for Transport, Construction and Urban Development (BMVBS) and the Federal Ministry of Defense and regularly updated by the regional tax office of Lower Saxony. The latest German version has been published in July 2013 and an English version is available since 2004. The procedure considers the general principles for condition evaluation as stated in DWA-M 149-3, but differs in the order of the several evaluation steps. The classification of single defects uses similar condition-specific tables as DWA-M 149-3 based on the European defect codification EN 13508-2 (2011). Publicly available software solutions for the methodology are not available.

The aim of the methodology is to identify priorities for sewer rehabilitation. The condition evaluation considers the most severe single defect, the influence of boundary conditions and the defect density.

As for DWA-M 149-3, the codes of single defects are evaluated according to their relevance for the three fundamental requirements Leaktightness (L), Stability (S) and Operational safety (O) separately. For each defect, an interim condition class from 1 (best) to 5 (worse) is attributed according to the defect's severity for each requirement. Additionally, an extra factor is summed considering the boundary conditions (Table 4).

Table 4: Extra factor for considering the boundary conditions according to Arbeitshilfen Abwasser (2012)

Boundary condition	**Criteria**	**Extra factor**		
		Leak-tightness	**Stability**	**Operational safety**
Type of waste water network	channelized stream	-50	irrelevant	0
	storm water	-30		0
	combined wastewater	+30		+40
	sewage	+30		+40
Type of sewage	hazardous to water	+150	irrelevant	irrelevant
Water protection area	outside	0	irrelevant	irrelevant
	protection area IIIb	+20		
	protection area IIIa	+40		
	protection area II	+250		
	protection area I	+400		
Position to groundwater	within groundwater	0	0	irrelevant
	transition zone	+10	+10	
	above groundwater	+10	+10	
Soil type	clay, silt, loam	0	+40	irrelevant
	sandy loam, loess, loamy sand, fine sand	+15	+20	
	medium sand, coarse sand, gravel	+30	0	
Circumferential position (clock reference)	3 – 9 (invert)	+10	0	+20
	9 – 3 (soffit)	0	+10	0
	whole circumference	+10	+20	+20
Position on joint	yes	+10	irrelevant	irrelevant
	no	0		

Lastly, the sewer condition is evaluated considering the most severe defect evaluation and adding up a factor calculated from the defect density and defects length. The assessment leads to a condition at least as bad as the worst single condition.

4.2.3 RERAU, France

A methodological approach for the assessment of sewer condition was developed in the framework of the French RERAU program (Rehabilitation of urban sewer networks) (Le Gauffre *et al*., 2004; Le Gauffre *et al*., 2007). Based on the RERAU concept, several condition assessment tools have been developed: e.g. the software developed by the company G2C within the INDIGAU research program or the software OCTAVE proposed by Veolia Eau. In this sub-chapter, the methodology RERAU is presented following the workflow of the INDIGAU methodology.

The methodology INDIGAU aims to support rehabilitation strategies by ranking sewer pipes according to the severity and density of defects for a list of dysfunction indicators.

The defects are assessed according to 10 dysfunction indicators: infiltration (INF), exfiltration (EXF), decrease of hydraulic capacity (HYD), sand silting (SAN), blockage (BLO), destabilization of ground-pipe system (SPD), ongoing corrosion (COR), ongoing degradation from roots intrusion (ROO), ongoing degradation from abrasion (ABR) and risk of collapse (COL). The contribution of each defect to sewer dysfunctions is evaluated using tables developed within the RERAU project (Le Gauffre *et al*., 2004). For each defect, interim scores are calculated for the affected dysfunctions. In a second step, interim scores are aggregated for each dysfunction. This can be done either by calculating condition scores focusing on the density of defects or by detecting a critical concentration of defects.

Dysfunction indicators are then assessed on a four-grade scale (G1-G4, G4 being the highest gravity) according to three calibrated thresholds. The choice of thresholds is based and calibrated on expert's propositions (Ahmadi *et al*., 2013; Cherqui *et al*., 2008). Results from the calculation procedure were compared with expert judgments of the codes of CCTV inspections. The thresholds have been fixed in to minimize the consequences of assignment errors (Figure 13).

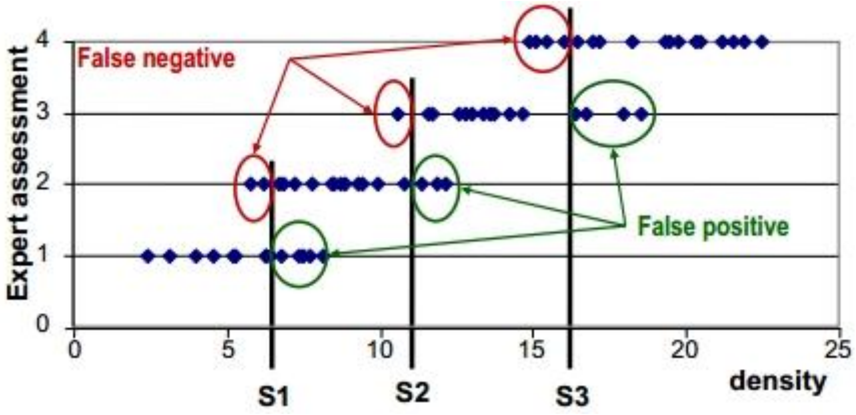
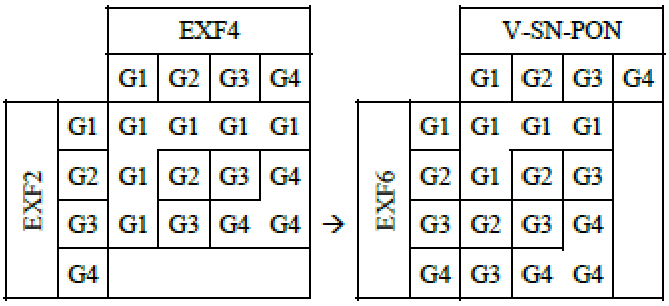


Figure 13: Definition of thresholds using the comparison of experts opinion and calculated condition grades using the INDIGAU methodology

Finally, the condition grades can be combined with each other and with vulnerability factors to obtain the overall grade regarding a list of decision criterion. For example, to obtain the condition grade (G1-G4) of the dysfunction "exfiltration" (consequences of exfiltration on groundwater and soil quality, EXF) two steps are needed (Table 5).

Table 5: Evaluation matrix to gain the ordinal grade of the dysfunction EXF (Debères *et al*., 2011)



		EXF4			
		G1	G2	G3	G4
EXF2	G1	G1	G1	G1	G1
	G2	G1	G2	G3	G4
	G3	G1	G3	G4	G4
	G4				

→

		V-SN-PON			
		G1	G2	G3	G4
EXF6	G1	G1	G1	G1	
	G2	G1	G2	G3	
	G3	G2	G3	G4	
	G4	G3	G4	G4	

Firstly, the condition grade of the indicator "water tightness deficiency for exfiltration, estimated by visual inspection (EXF4)" combined with the condition grade of the indicator "risk factor for exfiltration (EXF2)" leads to the condition grade of the indicator "Risk of exfiltration (EXF6)". In the next step, the indicator EXF6 is combined with the grade of the "vulnerability of soils and groundwater to pollution (V-SN-PON)" indicator (Debères *et al.*, 2011).

4.2.4 NEN3399, Netherlands

In the Netherlands and Belgium, utilities commonly use the NEN3399 (1992), which is the Dutch sewer classification system for visual inspection of sewers.

This condition classification model supports the identification of rehabilitation needs according to the most severe observed defects.

Pipe defects are categorized into three main groups: defects related to water tightness (group A), to structural stability (group B) and to hydraulic performance (group C). Depending on the type and extent of a defect, the system classifies each defect into five discrete condition classes. If a sewer segment has several defects, the classification of the whole sewer segment only considers the worst defect. Sewer pipes in condition classes 1, 2 and 3 are considered to be in acceptable condition, while pipes in classes 4 and 5 are considered in unacceptable condition.

The interpretation of the condition classes is done by classifying the observed defect according to its required action. The different kinds of actions are categorized into 3 groups: additional maintenance, further observations needs and rehabilitation is required (Table 6).

Table 6: Assignment of required actions depending on type and severity class of defect in the Netherlands (adapted from Schmidt (2009))

Additional Maintenance		**Further Observation Needs**		**Rehabilitation is Required**	
Defect	Threshold CC	Defect	Threshold CC	Defect	Threshold CC
Roots	2	Corrosion	4	Corrosion	5
Obstructions	3	Cross-Crack	4	Cross-Crack	5
Encrustations	3	Infiltration	4	Infiltration	5
		Deformation	5	Longitudinal Crack	4

4.2.5 NorVar report 150, Norway

The NorVar report 150 (NV150, 2007) is the current condition classification method in use in Norway. The methodology was developed by Rørinspeksjon-Norge (RIN, Pipe Inspection Norway), an interest group for municipalities and private firms in the wastewater community, and the Norwegian Water and Wastewater BA. The condition classification uses the Norwegian coding system.

The methodology assigned condition grades to sewers according to the severity and density of defects.

A damage grade from 1 to 4 (4 is a severe damage) is assigned to each defect based on the severity and extent of the defect using tables provided by NV150 (2007). A condition score is then calculated based on the density of defects within the sewer segment. An additional score can be calculated according to the difference in water level along the pipe during the inspection. Differences in water level may originate from surcharges due to depressions within the pipe, downstream pipes or sedimentation (Hauge, 2012). Thus, the additional score gives an indication of potential hydraulic weaknesses. The total condition score is calculated by adding the condition score and the additional score. However, in the case that at least one defect is evaluated with the damage grade 4, the pipe segment will be automatically classified in the worst condition.

4.2.6 SRM (Water Research Centre), U.K.

The Sewerage Rehabilitation Manual SRM (latest edition: WRc, 2001) published by the Water Research Centre (WRc) was developed in the U.K to meet the sewerage rehabilitation needs. A methodology to assess sewer condition is proposed based on sewer defects coded according to the Manual of Sewer Condition Classification (WRc, 2004).

SRM aims to schedule investigations on parts of the system with the severest problem in order to save costs of rehabilitation work, limit future rehabilitation costs and justify financial requirements (WRc, 2001). The methodology evaluates the operational and structural condition of a sewer pipe considering the most severe defects and/or the defect density and the consequences of failure.

Defect codes are divided in two categories: structural and operational defects. Structural defects affect the structural condition of the pipe, i.e. the physical strength of the pipe, and can give information about rehabilitation and replacement needs. Operational defects depict the capability of a sewer pipe to meet its service requirements. Major operational defects include obstructions, debris, encrustations and roots. They give information about cleaning and maintenance needs of the pipe segment.

Structural and operational deduct values are assigned from the defect codification. The deduct value of each defect is a weight that determines the impact of the defect on the service life and performance of the sewer segment. From the deduct values, three approaches are proposed to calculate the structural and operational scores of a pipe segment. The “Total Score” represents the summations of all deduct values in the pipe segment, whereas the “Peak Score” is the highest deduct value. The “Mean Score” of the defect scores per meter of pipeline represents the defect density. Structural and operational condition grades are calculated from the selected scores. A high condition grade (CG 4 and CG 5) represents an asset in poor condition with high probability of failure. The operational condition grade describes the serviceability of the pipe segment whereas the structural condition grade assesses the likelihood of failure and is used to determine the risk of failure.

Sewers are then classified into three categories (A, B, and C) based on the consequence of failure, i.e. the costs of failure versus the pre-emptive repair or rehabilitation costs prior its failure. The category depends on the size of the sewer, traffic flow above the sewer, depth of the sewer, soil conditions and location of services (e.g. hospital zone, industrial zone or beneath highways). For sewers in category A the cost of failure would be extremely expensive and the loss of the asset would be critical for the municipality or the utility. On the other hand, sewers in category C are laid e.g. in good ground conditions or in a low traffic route failure so the failure cost would be less expensive (Rahman and Vanier, 2004). The three categories are presented in Table 7.

Table 7: Consequences of failure and sewer category according to Sewerage Rehabilitation Manual SRM

Sewer Category	Consequence of failure
Category A	Post-failure rehabilitation cost is greater than 6 times planned repair cost
Category B	Post-failure cost is between 3 and 6 times the planned repair cost
Category C	Post-failure cost is less than 3 times planned repair cost

To assess the risk of structural failure, the structural performance grade (SPG) is calculated based on the structural condition grade and the category of the consequence of failure. A common approach consists in multiplying the structural condition grade by the consequence of failure score (a numerical score derived from the three categories, e.g. A=3, B=2, C=1) to determine the associated risk of failure (Opila and Attoh-Okine, 2011).

4.2.7 PACP (NASSCO), U.S.A.

To standardize the evaluation of sewer pipes conditions, the National Association of Sewer Service Companies NASSCO has developed the Pipeline Assessment and Certification Program (PACP) (NASSCO, 2007). The PACP standards hence successfully became the industry standard used by more than 200 municipalities and utilities in the US and Canada (Opila, 2011; Thornhill and Wildbore, 2005).

The focus of the NASSCO grading system is to assess the structural and operational condition of sewers; environmental factors such as soil type or groundwater condition are not considered as part of the condition classification. The methodology evaluates sewer condition considering the most severe defects or the average severity of defects.

A condition grade from 1 to 5 is assigned to each defect depending on its severity. The Overall Pipe Rating is calculated by adding all condition grades per pipeline. Additionally, the Pipe Ratings Index can be calculated by dividing the Overall Pipe Rating by the number of defects. It represents the average severity of the defects in the pipe (Feeney *et al*., 2009; Opila and Attoh-Okine, 2011).

Furthermore, PACP proposes the Quick Rating system that produces a 4-digit index for each sewer. The first and third digits of the 4-digit index provide the severity code of the most severe defects coded. The second and fourth digits of the 4-digit index provide the frequency of these defects. For instance, a pipe with one defect code of condition class 5, two defect codes of 4, and three defect codes of 3 would receive the quick rating index of 5142.

4.2.8 CERIU classification, Canada

In the province of Quebec (Canada) the Centre for Expertise & Research on Infrastructure in Urban Areas (CERIU) in collaboration with the Bureau de normalisation du Québec (BNQ) developed the CERIU condition classification (CERIU, 2004). The classification has been adopted by most municipalities in the province of Quebec (Chughtai, 2007).

CERIU evaluates the structural and operational defects of sewers as well as the infiltration and connections condition. The method does not provide an overall sewer condition grade but assigns to each defect a condition grade from 1 to 5 considering the severity of defects (Table 8).

The methodology assigns condition grades to structural defects (e.g. crack, deformation) and operational defects (or hydraulic conditions like roots, deposits and water level) depending on the defect type and its severity following tables provided by CERIU (2004). In addition, CERIU evaluates three defects regarding sewer connections that may cause loss of hydraulic capacity: connection penetration, clogged connection and flow from connection. Infiltration defects are ranked separately from hydraulic defects: an infiltration grade is given according to the infiltration rate.

Table 8: Severity Condition Grades of the CERIU condition classification method (CERIU, 2004)

CERIU Condition Grade	Description
1	No Intervention or action required
2	Action required but not major
3	Action required but not urgent
4	Action required and urgent
5	Immediate Action required

4.2.9 LSCCR (NRC), Canada

The Institute for Research in Construction (IRC) of the National Research council of Canada (NRC) in collaboration with several municipal partners from Canada developed the Large Sewer Condition Coding and Rating (LSCCR) (Zhao *et al*. 2001). The condition classification method is limited to large sewers (900 mm in diameter and larger) and uses the defect coding from the Water Research Centre.

The methodology evaluates the operational and structural condition of sewers considering the most severe defects and/or the defect density and the consequences of failure.

A weight from 0 to 20 for structural defects and from 1 to 10 for operational defects is assigned to each defect using tables provided by the guideline (Zhao *et al*., 2001). The scores for structural defects represent the degree of risk for the structural integrity of the sewer and the scores for operational defects are based on the consequence of defects on sewer serviceability. A condition score is calculated for both structural and operational defects using either the Peak Score, the Total Score or the Mean Score (see also SRM). The condition score can be calculated either for a one-meter unit or for the pipe segment unit following different evaluation strategies: the score can be used to identify worst-case localized problems or to identify sewers in overall poor condition.

The LSCCR also defines failure impact scores considering failure impact factors like sewer location, soil type, pipe size, depth and function. Failure impact scores represent the consequences of sewer failures. When the impact of a factor is negligible or low, a value of 1 is assigned, and when the impact is medium or high, values of 1.5 and 3.0 respectively are assigned. The combination of the failure impact scores with the structural condition scores determines the priority for future inspections and potential rehabilitations (Table 9).

Table 9: Rehabilitation Priority based on structural condition grade and failure impact rating

Structural condition Grade	Implication	Failure Impact Rating	Rehabilitation Priority
5	Failed or failure imminent	1 to 5	Immediate
4	Very poor condition	5	Immediate
	High structural risk	1 to 4	High
3	Poor condition	4 to 5	Medium
	Moderate structural risk	1 to 3	Low
2	Fair condition	1 to 5	Low
	Minimal structural risk		
1	Good or excellent condition	1 to 5	Not required

4.3 Substance based methodologies

4.3.1 DWA T4, Germany

This classification model, developed by a DWA working group and published by DWA as “Guidelines for strategic rehabilitation of Drain and Sewer Systems outside Buildings” (DWA T4, 2012), presents an example for the substance classification of sewers. This methodology is relatively new and doesn’t constitute the current state of the art for sewer condition evaluation among German utilities. The model was developed by M. Hippe (Franz Fischer Ingenieurbüro GmbH) and is based on a classification system that has been already used to evaluate the substance of roads (DWA T4, 2012).

Goal of the methodology is to rank sewer pipes considering the type of rehabilitation needs: replacement, renovation and repair. The method defines a substance class for each sewer based on the repair length, i.e. the length of sewer that will be affected by rehabilitation actions. Depending on the type of defect, no-dig or open trenchs solutions will be required. Rehabilitation interventions will affect a specific sewer length assumed to be 1 m using no-dig technologies and 4 m using open trench technologies. If defects are closed, they may be rehabilitated together using few rehabilitation technologies and thus reducing the intervention costs. If a major part of the sewer is affected by rehabilitation interventions (e.g. many sever defects spread over the sewer length), the substance of the sewer is considered to be very low since an expensive replacement will be the most cost effective solution. If only a small part of the sewer is affected (e.g. only one severe point defect or several small defects spread over the sewer length), the sewer has a better substance value since repair or renovation technologies will be appropriate.

Interim condition classes are calculated for each single defect according to their relevance for the three requirements following DWA-M 149-3 (Chapter 4.2.1). A specific repair length is then attributed to each defect. As described above, the repair length is different by using open trench or no-dig technologies. A repair length of 1 m is assigned to defects that can be repaired using no-dig technologies and a repair length of 4 m is assigned to defects that require open trench technologies. The recommendation for 1 m impact length can be illustrated with the use of short liner as repair technology. The repair length is represented symmetrically around each defect on a profile view of the sewer (Figure 14). Overlapping repair lengths are considered only once with the worse condition class providing the opportunity to use only one rehabilitation action for several defects.

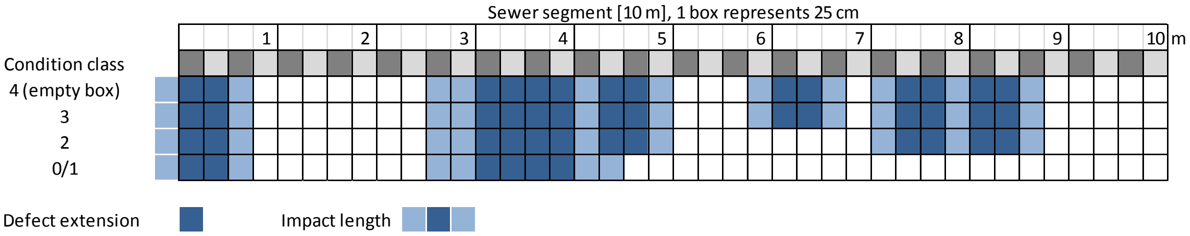


Figure 14: Example of attribution of repair lengths along a sewer

The total repair lengths are reported for each condition. The repair density is calculated doing the ratio between repair lengths and sewer length assigning a weight of 1 for reparation of defects in the worst interim condition class and smaller weights for better conditions. Finally the substance class is calculated using threshold values: if the repair density is higher than 30% of the sewer length it is assumed that repair actions are not cost effective anymore and that the entire sewer needs to be replaced. For lower values, repair or renovation actions can be envisaged.

4.3.2 Bietigheimer model, Germany

The Bietigheimer model was established by Dr. Hochstrate in the late 1990s for the sewer network of the municipality Bietigheim-Bissingen (Hochstrate, 1999). The substance-based model was developed for the rehabilitation planning activities of Bietigheim-Bissingen since priority-based classifications did not allow for an appropriate estimation of renewal needs.

The Bietigheimer model consists of two classifications for one sewer: a priority class PC and a substance class SC. A combined assessment of these two classifications allows for an appropriate determination of urgent priorities as well as mid- to long-term investment needs.

The priority class PC is determined by the most severe single defect, e.g. using DWA-M 149-3 (Chapter 4.2.1). For the evaluation of the substance class SC interim condition classes are first calculated for each single defect. The sewer segment is patterned into 1 m sections. Point defects are assigned to 1 m sections and range defects are assigned to several 1 m sections in respect to the defect extension.

A repair length of 5 m is then attributed to each defect as the minimum repair length. There is no distinction between no-dig or open trench technologies. The repair lengths of each defect are set up by combining adjacent repair lengths. For example, if two defects are separated of 5 m, the minimum repair length of 5 m will be sufficient to handle the two defects. The most severe defect class is used, if defects overlap in repair sections (Figure 15).

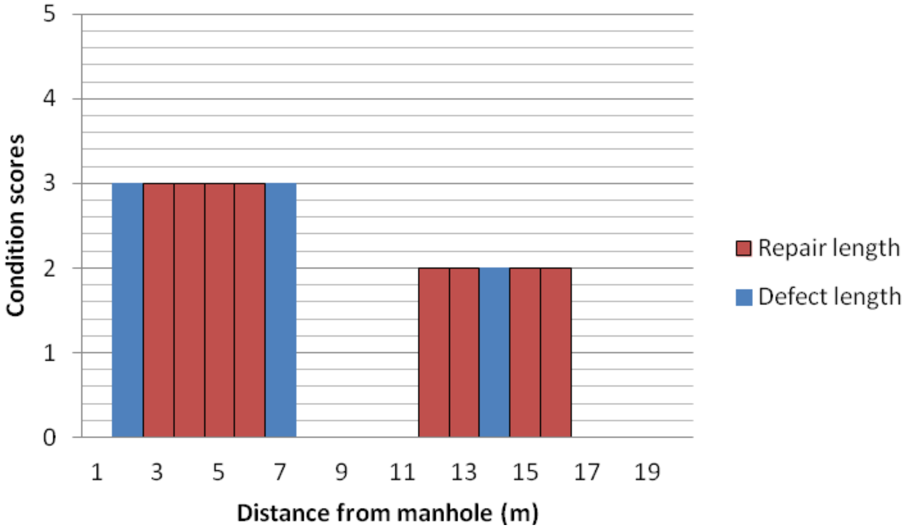
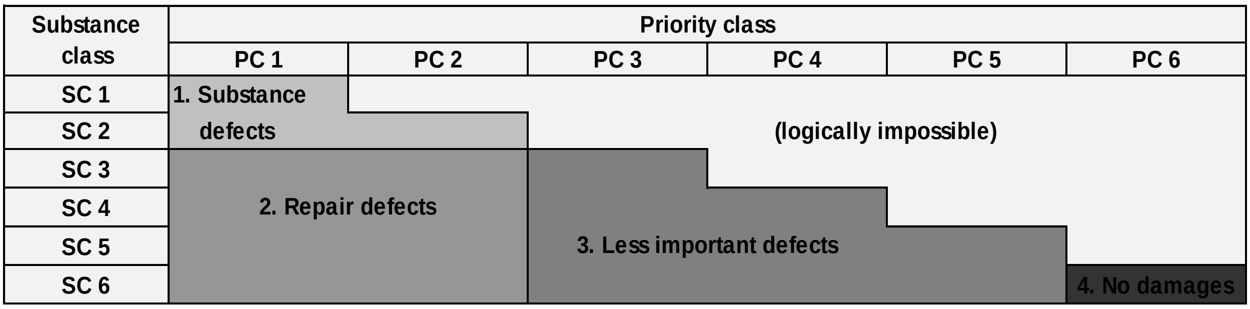


Figure 15: Example of attribution of repair lengths along a sewer line in the Bietigheimer Model

The cumulative repair length is assessed according to a threshold value (30%) that estimates whether local repair of defects is more cost effective than the entire replacement of the sewer. The cumulative length of repair lengths for each condition class is computed beginning with the worst condition class and adding up better condition classes. The substance class is defined as the condition class in which the cumulative repair length reaches the 30% threshold. In the example in Figure 15 a repair length of 5 m is in condition 3 and a repair length of 5 m is in condition 2. The cumulative repair length of the sewer in the worst condition (condition 2) reaches 25% of the sewer length: repair length of condition 2 is 5 m and the sewer length is 20 m. The cumulative repair length will reach the 30% threshold by adding up the repair length in condition 3 so the substance class of the sewer will be 3. The substance class 3 means that rehabilitation of defects in condition 3 and worse will affect 30% of the sewer length.

The combined assessment of priority class and substance class leads to 4 condition groups with different rehabilitation needs (Figure 16): replacement (1), repair (2), no urgent action needed (3), no action at all (4). If more than 30% of the sewer is in poor condition (SC 1 or SC 2), the entire sewer should be replaced. However, even if the sewer has one major defect (PC 1) but the substance is still high, repair actions could be considered to increase the service life of the sewer.



Substance class	Priority class					
	PC 1	PC 2	PC 3	PC 4	PC 5	PC 6
SC 1	1. Substance defects	(logically impossible)				
SC 2						
SC 3	2. Repair defects		3. Less important defects			
SC 4						
SC 5						
SC 6						4. No damages

Figure 16: Condition groups in the Bietigheimer classification model

4.3.3 Status sewer, Germany

Status sewer is a classification tool developed by the German engineering company Stein and Partner (S&P) Consult GmbH (Stein *et al*., 2004: Stein *et al*., 2006). Details of the methodology haven't been entirely published since the tool is available only as a proprietary engineering service.

The methodology evaluates the sewer condition based on the most severe defects using fuzzy rules. Additionally, the sewer substance is calculated based on the defect density and the damage concentration, i.e. the cumulative defects length, independent of the defects severity. This cumulative defect length could be assimilated to a repair length since it indicates the length of sewer that will be affected by rehabilitation actions.

The classification of single conditions uses fuzzy logic to consider the haziness of inspection data. The condition classes are not assigned using discrete values, but with the help of fuzzy sets and their membership functions. For example, the assignment of condition classes for longitudinal cracks follows the functions shown in Figure 17. A crack width of 4 mm is sorted into condition class 3 according to the Waste Water Guide (Chapter 4.2.2). Using the fuzzy set shown in Figure 17, the crack would be assigned a membership vector:

[ZK1, ZK2, ZK3, ZK4, ZK5] = [0; 0; 0.38; 0.62; 0].

From this vector, a continuous condition class of 3.62 (calculated from 0.38 x 3 + 0.62 x 4) is retrieved.

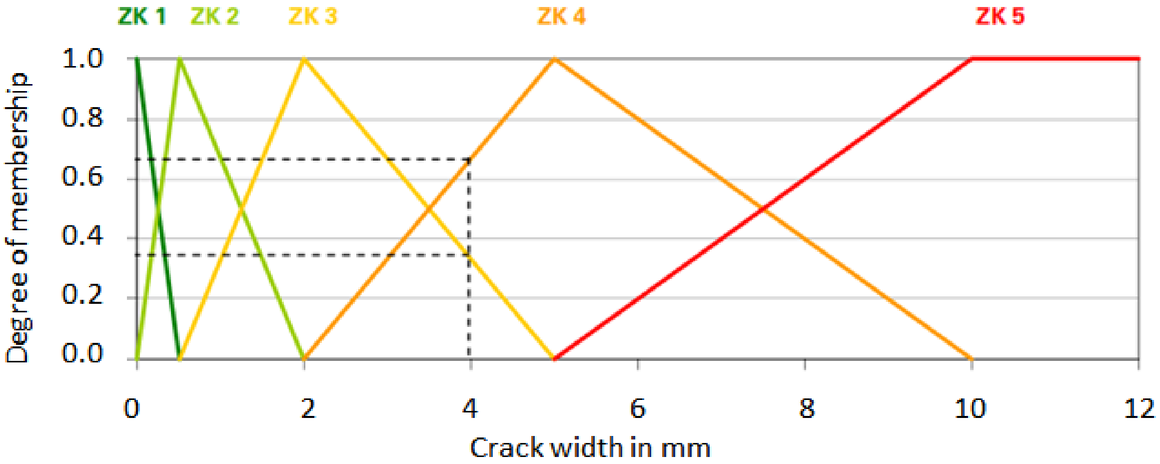


Figure 17: Condition classification of longitudinal cracks using fuzzy logic according to Stein *et al*. (2006)

Fuzzy sets for each single condition consider the individual boundary conditions of the pipe. By creating fuzzy sets for each boundary condition and linking them as shown in Figure 18, the final condition classification of single conditions can be found. The general processing for other defects is similar, but details have not been published for all fuzzy sets.

The damage concentration is then calculated considering the cumulative defect length. For this value, the condition class of single defects is not relevant, only position and extension are considered in the calculation.

The weighted defect density value is calculated by dividing (i) the sum of the products of single condition classes of defect with its length extension by (ii) the whole defect length of the object.

Finally, the substance of the sewer is determined by linking the weighted defect density and the defect concentration using an inference table. This procedure can be visualised in a three-dimensional way (Figure 19).

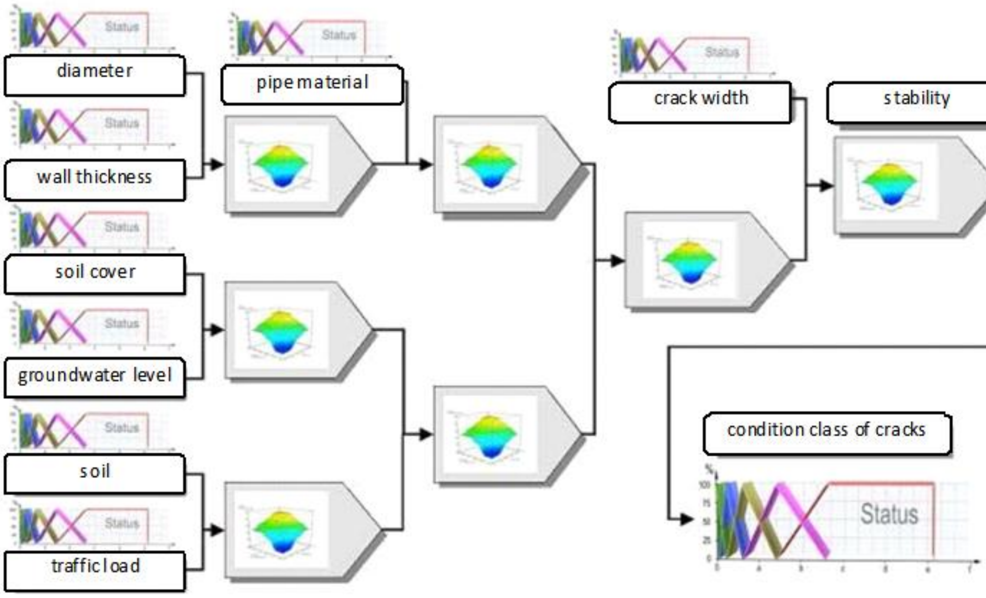


Figure 18: Condition classification of longitudinal cracks using fuzzy logic according to Stein *et al.* (2004)

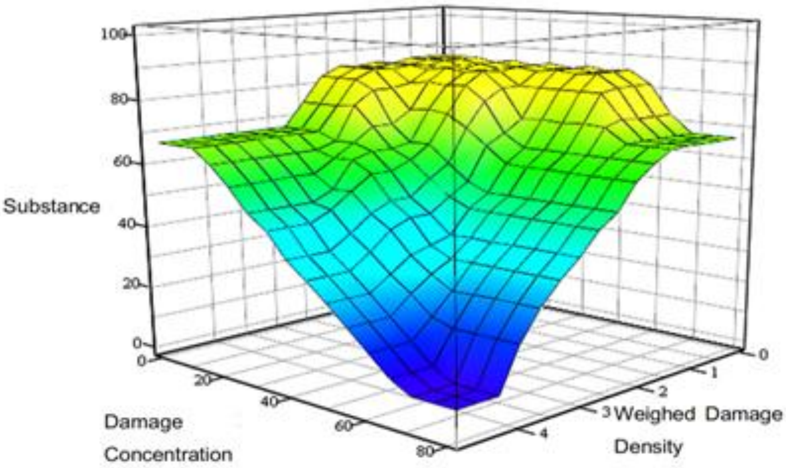


Figure 19: “Substance” determined from defect concentration and weighted defect density according to Stein *et al.* (2006)

4.4 Summary of condition classification methodologies

The type of method and scores are summarized in Table 10 for the available condition classification methodologies.

The complexity is rather similar for each presented classification methodology. All classifications rely on standard defect coding systems. Since coding systems describe all visible defects, the classification methodologies have to deal with a high number of defect codes and combinations. However, the calculation and aggregation rules that lead to the final score remain rather straightforward.

Each methodology aggregates and combines sewer defects in a very different way making very hazardous the benchmarking of final scores from different methods. Furthermore, the input data differ between methodologies: English and North American methodologies rely mostly on defect coding from WRc whereas European methodologies are based either on European coding or old national coding systems. Currently, no conversion system is available to combine and compare sewer condition assessment from different classification methodologies (Chughtai and Zayed, 2011).

Table 10: Summary of the survey from condition classification methodologies

Classification name	Country	Type of method		Classification based on				Type of score			
		Priority	Substance	Most severe defect	Density of defects	Failure impact	Repair length	Overall condition	Defects only	Structural and operational	Dysfunc-tions
DWA-M 149-3	Germany	X		X	X	X		X		X	
Arbeitshilfen Abwasser	Germany	X		X	X	X		X		X	
RERAU	France	X		X	X	X		X			X
NEN3399	Nether-lands	X		X				X		X	
NorVar 150	Norway	X		X	X			X		X	
SRM	U.K.	X		X	X	X		X		X	
PACP	U.S.A.	X		X				X		X	
CERIU	Canada	X		X					X	X	
LSCCR	Canada	X		X	X	X		X		X	
DWA T4	Germany		X	X	X	X	X	X		X	
Bietigheimer model	Germany		X	X	X	X	X	X		X	
Status sewer	Germany		X	X	X	X	X	X		X	

Therefore, municipalities using different evaluation system are not able to benchmark the condition of theirs networks. As far as we know, no comprehensive study has been undertaken to compare the results of different classification methodologies and analyze their influence on asset management decisions. Since the methodologies haven’t been compared, it is not possible to conclude about the most appropriate methodology.

The accuracy of the classification results remains another key issue. Since investments are based on the interpretation of the evaluation results, the decision makers expect the methodologies to reflect accurately the rehabilitation needs. However, most methods assign condition grades using subjective scales of numerical values. Further research is needed to calibrate these methodologies and identify the most accurate ones. For example, Ahmadi *et al*. (2013) developed a methodology to calibrate classification thresholds using the confrontation of expert opinions and classification results.

Uncertainties of the classification results originate also from the subjectivity in the recognition and description of defects (Dirksen *et al*., 2013). During the codification of the visual CCTV report, inspectors may fail to recognize the presence of a defect or to describe the defect accurately using the appropriate codes (e.g. wrong characterization or quantification). Lastly, the condition classification methodology itself contains uncertainties. Even if the defects are perfectly coded, the classification results may still differ from the opinion of an expert or the municipality. In the future these uncertainties and their influence on the decision making processes must be carefully assessed.

Chapter 5 Conclusion

This report has first presented the wide panel of inspection technologies available to obtain information about sewer defects and general condition. CCTV is the industry standard for sewer inspection. It provides visual data (images and/or videos) of the internal surface of the pipe. The analysis of the images enables to identify the type and position of visible defects like offset joints, pipe cracks, leaks, sediment, debris and root accumulation. Defects are usually coded according to standard coding methods. Based on the documented codes the condition of inspected sewers can be evaluated using classification methodologies. In Europe, the current codification system is the normative EN 13508-2 for visual inspection (EN 13508-2, 2011) used by the CEN-Members (European Committee for Standardization).

A quicker and less expensive screen of the sewer condition can be achieved using zoom cameras. However, this technology cannot replace the CCTV inspection since the visibility of defects and thus the precision of the defect description depend strongly on the sight distance of the camera. This method may be useful to identify sewers that may need cleaning or a more detailed inspection with conventional CCTV. Physical techniques are available that can give further information and details about pipe defects. These techniques do not replace neither the CCTV inspection but can give deeper insights on the type and severity of defects. Sonar and Lasers support the detection of changes in the pipe geometry that may be caused by deflections, cracks, sediments or corrosion. Ultrasonic testing and magnetic flux leakage (MFL) can detect pipe defects such as corrosion, deflections and cracks and measure wall thickness. Ground Penetrating Radar (GPR) and Infrared Thermography are used from above ground and are useful to locate pipes and identify bedding conditions, voids and leaks. Finally, network wide inspection technologies like smoke testing or Distributed Temperature Sensing (DTS) can locate cross-connections and/or sewer infiltration.

On a second step, this report has presented the current condition classification methodologies in use in Europe and North-America. These methodologies are all based on the interpretation of visual CCTV inspection reports. Defects observed during CCTV inspection are coded using standard coding systems and used as input data for the evaluation. Classification methodologies transfer the extensive amount of visual inspection data into a more easily manageable number, useful to support asset management practices.

Most approaches have a similar goal: they aim to rank rehabilitation priorities and support the definition of rehabilitation programs. All methodologies provide an overall condition score for each sewer segment or sub-scores for different requirements (e.g. structural and operational condition) or dysfunctions. From the review of available methodologies, two main approaches can be distinguished: priority based and substance based methodologies.

For priority based methodologies, the calculation of sewer condition grades is based on the most severe defects, the density of defects and/or the defects length. Condition grades express the priority of rehabilitation, i.e. the emergency of action regarding the probability of failure or collapse.

For substance based methodologies, the final score is calculated based on the length of sewer that will be affected by rehabilitation actions. Substance based methodologies do not aim to assess the condition of sewers but rather to rank sewer pipes considering the amount and type of rehabilitation needs: replacement, renovation and repair.

The complexity is rather similar for each presented classification methodology. However, the benchmarking of the methodologies remains hazardous since (i) each methodology aggregates and combines sewer defects in a very different way and (ii) input data differ between methodologies. Since the methodologies haven’t been compared, it is not possible to conclude about the best appropriate methodology. Finally, the accuracy of the classification results remains a key issue, crucial for the further use of inspection data to support asset management strategies.

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