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Review

Linking sewer condition assessment methods to asset managers' data-needs

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ABSTRACT

Data-driven sewer asset management uses digital sewer representations to store inspection data and to support predictive maintenance planning. This approach requires asset managers to determine what inspection data they need to collect for the assessment of the asset conditions. Existing studies review sewer inspection methods based on their technical working principles but do not explicitly address what data about condition cues these methods provide. Consequently, literature lacks structured insights that help sewer asset managers link their data-needs with appropriate condition assessment methods. To make this link, we propose a data-needs based categorization of sewer inspection methods. Specifically, we relate data output of inspection methods to condition cues using the classification of hydraulic, structural, and environmental inspection domains. This shows that few methods exist to collect data about cues in structural and environmental domains. Future research should develop methods to satisfy these needs, and eventually, contribute to holistic data-driven asset management.

1. Introduction

Sewer pipes fulfill both hydraulic and structural functions. The hydraulic function of pipes allows the transition of flow and separates pipeline content from its environment. The structural function preserves the integrity of the pipe wall such that its hydraulic function can be fulfilled [1]. Essentially, the adequacy of sewer pipeline maintenance influences the quality levels of the hydraulic and structural functions. Hence, a significant part of asset management tasks, on long-lived networks in developed countries, is devoted to the maintenance and rehabilitation of the existing sewer pipes [2].

Nowadays, managers adopt proactive and preventive maintenance to reduce disturbance to urban life and environment, and to minimize life cycle costs. In a proactive asset management strategy, sewer pipes are regularly inspected and maintained over time. They are replaced once the severity of their deterioration outweighs the benefit of doing further maintenance [3].

Proactive sewer asset management uses data-driven systems [4–7]. These systems periodically collect data – using single or multiple inspection methods – to: conduct statistical analyses; assess vulnerable infrastructures [8–10]; and, predict their likelihood of failure [11–16]. The effectiveness of data-driven systems depends on their access to accurate, sufficient, and up-to-date data about the location and condition of the sewer pipes [17–19], which requires that sewer network owners frequently collect and interpret relevant data about their assets. This, in turn, can be done by investing in the development and deployment of methods that are suitable for collecting the required data.

Several methods exist that collect sewer asset condition data. A number of inspection methods evaluate the properties of the sewage and pipes mainly on the network scale (e.g., [20,21]). These often require permanent sensor network installations inside pipes structures. In the large majority of existing sewer networks, however, such permanent data collection methods are not embedded yet. In these cases, *temporary non-destructive local* inspection methods should be deployed inside the pipe to collect data and feed sewer management systems. This study focuses on those temporary methods that support non-destructive local inspection of existing sewer pipelines.

Literature contains a range of temporary non-destructive local inspection methods. These methods all collect different types of data. They hence inform sewer asset managers about distinctive cues that, once taken together, contribute to an accurate description of the condition of a sewer pipe. Since deterioration conditions of a sewer pipe differ across various local contexts [22–25], asset managers need to collect data about those specific cues that can meaningfully assess the sewer pipe's condition. It is hence important that asset managers select appropriate inspection methods that suit their data-needs.

Existing studies categorize inspection methods mainly based on their technical working principle and the asset types in which they function

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[26–31]. These studies, however, do not address explicitly how the various methods can fulfill the data-needs of sewer asset managers. Literature thus lacks a categorization that bridges this gap between condition data-needs and inspection method capabilities. This, in turn, limits the development and deployment of inspection methods that may provide data about relevant sewer condition cues. As a result, some essential condition cues may currently be overlooked during an inspection. The aim of this study is, therefore, to categorize temporary non-destructive local inspection methods based on their link with the condition cues that they observe, and to identify areas for further research and development of these inspection methods.

The remainder of this paper is structured as follows. The next section develops the theoretical argument that a link between data-needs and sewer inspection methods is necessary. Next, we explain our research methodology. Then, we address literature about data-needs for proactive maintenance of sewer pipes, and introduce the 'composite-structure' of a sewer cross-section as a basis for classifying these data-needs. Further, we review temporary non-destructive in-pipe inspection methods for non-ferrous pipes of gravity sewer mains. We categorize these methods using the 'composite-structure', and finally elaborate how this categorization contributes to identifying inspection research areas that are relatively unexplored and have potential for further development.

2. Theoretical background: shortcomings of inspection method selection approaches

Digital asset management systems store sewers as virtual object models and add data from condition inspections to those as attributes. The increase in processing power and advances in remote in-pipe inspection methods have created opportunities to collect, and frequently update, comprehensive data input for these systems. By integrating inspection data about multiple condition aspects, asset management systems perform advanced and holistic analyses of pipe conditions. One complicating factor for assessment is that pipelines have deterioration patterns that vary across distinctive local contexts [24]. It is, therefore, essential that sewer managers decide upfront what data they need to assess the dominant deterioration patterns for their local sewer network. In practice, this frequently takes place by assessing historical statistical data from the inspection area (e.g. its traffic intensity, the types of used rehabilitation measures, and previous incident reports [32,33]).

Further, to select an appropriate method that delivers the needed data, inspectors need to be able to assess the effectiveness of that method in its local context.

2.1. Existing categorizations

Although literature reviews methods for sewer inspection, it has not yet supported the process of sewer asset management that explicitly links an inspection method to the condition data that it can acquire. Two arguments support this claim:

First, the literature about inspection methods mainly classifies the existing methodologies based on their *technical working principle* [27,31,30,28]. They use, for example, acoustic, ultrasound, or vision as technological features to define inspection method categories. This conceptualization along technical working principles helps understand how physics and engineering principles are used to evaluate condition aspects. While this might merit from a technical viewpoint, it does not provide direct insight into essential data required by asset managers and inspectors: viz. the asset condition data that a method can collect to enable decision making about maintenance or rehabilitation of the asset. This is because a technology-centered categorization does not directly link the requested inspection data outputs with the suited methods for retrieving them.

Second, literature categorizes inspection methods based on the attribute *asset type*. Such categorizations review or cluster multiple methods based on their applicability to types of water and energy utilities. In such categorizations, freshwater and wastewater pipeline inspection methods are usually grouped as one type of asset. Although seminal reviews such as Costello et al. [28], Rizzo [29], Hao et al. [30], Liu and Kleiner [31] adopt this categorization, this approach neglects that freshwater and wastewater pipelines comprise different materials and have distinctive properties and maintenance needs. As a result, these categorizations do not acknowledge that each water pipeline type should be inspected by distinctive methods.

2.2. Required categorization of inspection methods based on data-needs

So, the logic behind the two existing classification approaches does not provide clarity about how specific inspection methods provide the required data that enables assessing sewer pipe conditions. We argue that this is problematic because inspection methods should be selected according to the data-needs, as it is visible in Fig. 1, which shows the sewer asset management workflow based on Shahata and Zayed [34], Ana and Bauwens [32], Ariaratnam et al. [35], Lemer [36], Younis and Knight [37], Ahmadi et al. [38], Halfawy et al. [39]. In Fig. 1, the clockwise process starts with formulating asset management goals and selecting a suitable management strategy to fulfill those goals. Next, asset managers define performance indicators and satisfactory scoring levels. They further identify required inspection data and select suitable inspection methods to collect such data. The next step is to collect and store the collected condition data in the digital model of the asset. Condition data should then be translated into condition information and compared with the performance scores. Next, possible maintenance scenarios should be examined and a decision must be made about an effective maintenance intervention that restores the pipeline into a satisfactory condition. Finally, a new iteration through the asset management workflow starts after the evaluation of the previous cycle. The trend in practice towards proactive and data-driven asset management stresses the relevance of this cycle, especially that inspection methods should be selected based on data-needs (i.e. steps 4 and 5).

When this workflow was used about forty years ago, Closed-Circuit Television (CCTV) seemed to be the only technologically developed inspection method that could collect the condition data that were sought for at that time [40]. Therefore, CCTV was selected to collect data in the first inspection rounds. To build experience with the defined scoring indicators and relevant data-needs the method was then mobilized on sites to inspect pipelines in many contexts in the decades that followed [41].

Although the steps 3–5 in Fig. 1 may be implicitly followed to select CCTV based on the strategy that existed when this method was first

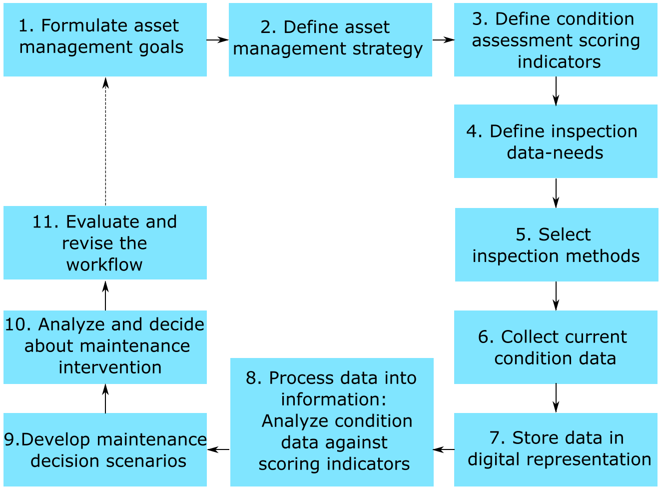

Fig. 1. Sewer asset management workflow.

selected, more inspection methods have developed since then. Ideally, every time an inspection is planned, it should be evaluated which of all available methods is able to collect the required data needed in the local inspection context. This should be done to avoid a sub-optimal inspection method selection and collection of less relevant data. In turn, supporting meaningful data collection for data-driven proactive asset management requires that literature is complemented with a framework that explicitly links inspection methods with the specific data-needs of asset managers (step 5 in Fig. 1).

Thus, because existing literature reviews and categorizations of inspection methods are based on the technical working principles, rather than taking data-needs as a point of departure, they do not yet effectively support step 5 of the outlined sewer asset management workflow. The goal of this study is, therefore, to categorize the sewer inspection methods based on their ability to fulfill specific data-needs. This categorization would ultimately allow for better alignment between inspection methods and asset managers' data-needs, and provision of better quality data in sewer asset management systems.

3. Methodology

This study was executed in three steps: First, we defined inspection domains based on pipe's composite-structure for which condition data needs to be collected. Second, we identified temporary inspection methods that require access to the inside of sewer pipes to assess their condition locally (hereby called in-pipe methods). We reviewed the literature about these methods without limiting ourselves to methods that are used most commonly in practice or to those that assess only specific inspection domains. We focused on non-ferrous gravity sewers since these comprise a great part of existing sewer networks [42,43]. We clustered the various in-pipe sewer inspection methods based on their data output. To deduce the type of data that each method collects, we reviewed general descriptions, experimental outcomes, and the working principles behind each method. Third, we assessed the performance and degree of complexity of the inspection methods. For this, we used the staircase of Structural Health Monitoring (SHM) systems [44]. Table 1 shows the five categories in this classification of SHM evaluation systems. The complexity and functionality of systems increase by moving to higher levels on the staircase. In their simplest form, SHM systems can only detect the presence of damage (Level I). Level II systems can identify the location of damage in addition to its presence. We distinguished location into longitudinal (i.e. along the pipe), and circumferential (i.e. within the cross-section of the pipe) location. The collected data on Level III is more advanced. Such systems can indicate the presence, location, and severity of a damage. We considered a system to be capable of assessing the severity if it can quantify this during a measurement. Level IV systems can also indicate the consequence of the damage next to its presence, location, and severity. Finally, systems at Level V of the staircase can perform self-healing functions [45].

After classifying the methods based on their data output in the inspection domains and their performance and degree of data complexity, we drew preliminary conclusions about the maturity of each inspection domain and its future research needs.

Table 1
Staircase of structural health monitoring systems based on their performance and degree of complexity [44]

Level I	Detect presence of damage
Level II	Detect presence and location of damage
Level III	Detect presence, location and severity of damage
Level IV	Detect presence, location, severity, and consequence of damage
Level V	Detect presence, location, severity, consequence of damage, and self-healing

4. Proposed inspection domains and corresponding data-needs

Failures occur when hydraulic and structural loads that are applied on the sewer pipe are more than the pipe's load-carrying capacity [46,41]. The structural load-carrying capacity of sewer pipes depends on the intrinsic strength of the pipe and the strengthening effect of the ground that covers the pipe. Therefore, the condition of a sewer pipe cannot be fully assessed without inspecting its surrounding ground. In other words, sewer pipes must be perceived as systems, where “sewer is considered as a composite-structure that consists of the sewer pipe itself, the ground in which it is buried and the local environment [47]”.

Based on this more holistic perspective on pipeline conditions, we use a subsurface cross-section as a starting point to distinguish between the distinctive data-needs that exist to inspect the status of *hydraulic, structural*, and *environmental* domains and their *interfaces*. Data about the *hydraulic* domain addresses sewer conduit contents and its flow. Data about the *structural* domain describes the condition of the pipeline's fabric itself. Data about the *environmental* domain describes the condition of the ground which is adjacent to the pipe. In addition, data about the *interfaces* between these three domains plays a role in condition assessment. To acknowledge these interfaces, we define two domains specifically: the *hydraulic-structural* and the *hydraulic-structural-environmental.* Data about *hydraulic-structural* interface mainly focuses on the inner surface of the pipe wall. Data about *hydraulic-structural-environmental* interface describes pipe's degenerated hydraulic function, due to loss of structural integrity. This occurs when pipe contents are no longer separated from the environment.

This proposed subsurface cross-section enables developers, researchers, and asset managers to study the data collection range that a specific in-pipe inspection method can effectively cover. Fig. 2 visually represents these inspection domains.

Condition aspects about which inspectors collect data are often referred to as indicative factors in sewer deterioration [24,22], defects, and failures [48]. Since one damage feature (e.g. a crack) can be a causal factor for another damage feature (e.g. a tree root obstruction), the distinction between factors, defects, and failures is not clear cut. To assess the ability of inspection methods to collect data about one of these elements, it does not seem relevant to distinguish between them. In the remainder of this paper, we therefore, refer to those together by the term *condition cue*. A condition cue is any physical attribute in the composite-structure of the sewer system that indicates the condition of the system.

Table 2 summarizes the definitions and classification of the condition cues in five defined domains: Hydraulic (H), Structural (S),

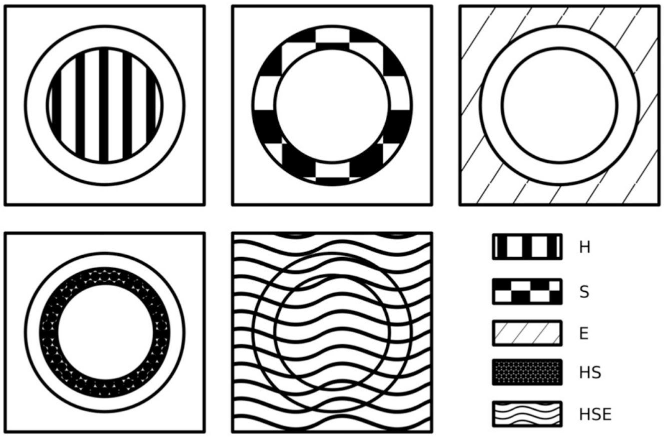

Fig. 2. Schematic illustration of the Hydraulic, Structural, Environmental domains and their interfaces about which in-pipe inspection methods provide data.

Table 2

Condition cues related to sewer pipe condition and their classification in the five inspection domains

Name	Domain	Description
Obstacles	H	Objects inside the pipe that obstruct the cross-sectional area
Water level deviation	H	The degree by which the pipe's water or sewage level deviates from the expected value
Wire breaks	S	Can occur in the rebars of reinforced pipes
Corrosion	S	Can occur on the rebars and within the fabric of reinforced pipes
Change in wall thickness	S	Change of pipe wall thickness from its design value, which can originate from inside or outside the pipe
Cavities inside the pipe wall	S	Unsurfaced cracks and voids formed within the pipe wall
Void in the surrounding ground	E	Formed due to ground movement or in/ex-filtration
Slope deviation	E	The degree by which the slope of the pipe deviates from its designed slope gradient
Fissure	HS	Damage in the inner surface in the form of surface cracks
Loss of material	HS	Scouring, spalling, delamination, increased roughness of the surface, and extruding aggregates
Gain of material	HS	Encrustation, fat deposits, fouling, and attached sediments
Lining defect	HS	Detached, wrinkled, or blistered lining
Softening of material	HS	Porous and weak texture of the concrete mainly due to acid attack and carbonation
Deformation	HS	Deviation of the pipe's cross-sectional shape from its designed shape and diameter
Break/Collapse	HSE	Displaced or missing pieces of the pipe wall
Displaced joint	HSE	Longitudinal, radial, or angular displacement of pipe joints
Root intrusion	HSE	Intrusion of roots of trees and other plants inside the pipelines
Infiltration	HSE	Water leaking from the surroundings to inside the pipe, e.g., when the water table level is higher than the water level inside the pipe
Exfiltration	HSE	Sewage leaking from the pipe to the surroundings, e.g., when the water table level does not reach the water level inside the pipe

Environmental (E), Hydraulic-Structural (HS), and Hydraulic-Structural-Environmental (HSE). The table does not prioritize which condition cues are most relevant to be detected because research on the most influential factors in sewer structural deterioration is inconclusive. The main reason for this is that sewer deterioration mechanisms vary in different areas, and thus are very local phenomena [24,22].

5. In-pipe sewer inspection methods

We discuss below the temporary in-pipe methods that locally inspect non-ferrous gravity-based sewer main lines. The discussed methods have a wide range of Technology Readiness Levels (TRLs): from widely-used camera-based methods to methods of which their potential has been tested only in the research laboratories. For each method, we briefly explain the underlying working principle and its limitations to eventually define the data-needs that it can fulfill and its performance level.

5.1. Camera-based methods

Camera inspection exists for decades and remains the main inspection method for sewer pipes. There are various camera-based methods for sewer inspection. The general working principle and goal of these methods are the same: a camera is sent inside a sewer pipe to retrieve visual data in the form of video and images from the pipe segments [28]. Camera-based methods can hence indicate the presence and longitudinal and circumferential location of the visible condition cues, and provide qualitative data about their severity. Despite this similarity, camera-based methods have been named differently in the literature. Distinctions are made based on the number and features of cameras (e.g., wide lens digital scanning, panorama [29–31]), the use of additional sensors, e.g., Sewer Scanner Evaluation Technology (SSET) [27,28,49]), and data visualization and processing method. All methods collect the same kind of data about sewer pipes. We provide two examples to explain the most prevalent methods:

5.1.1. Closed-Circuit television (CCTV)

This method often requires pre-cleaning of the pipes [30]. The camera is usually mounted on a carrier that a human operator steers along the pipe. This makes the practice of the method labor-intensive and time-consuming [50]. However, CCTV data is often the primary source of information for making rehabilitation decisions [41].

5.1.2. Zoom camera

Images of pipe interior are taken while a camera is mounted on a pole and lowered from a manhole [51]. Operating a zoom camera does not require pre-cleaning of the pipe. This prevents that cleaning jet-water damages the inspected pipe. Compared to CCTV, the operation of zoom camera requires fewer skills and it has a lower set-up and run time which results in less traffic disruption. These factors result in cost-savings [52]. However, the images collected by the zoom camera contain much fewer details about the severity and location of the damages. Therefore, this method is mostly used for screening and prioritizing the pipes for further inspections [53]. In addition, zoom camera's sight distance depends on the type of camera, illumination conditions, and pipe configuration. Best results can be achieved when the distance between manholes is less than 40 meters and when there is no sharp bend or slope in the pipe [51].

Despite the extensive list of condition cues detected by the camera-based methods, these methods have few disadvantages. Cameras are prone to condensation on the lens. They cannot provide data about the presence of defects under the water or when the pipe surface is covered with mud. Moreover, pipeline joint defects can be identified easier when tree roots are intruding inside the pipe. Therefore, when there are no trees in the vicinity of the pipe or when the roots have been removed by jet-water during the pre-cleaning of the pipes, joint defects are most probably not identified [54]. Another disadvantage of camera-based methods is that they cannot identify voids in the supporting ground, cracks that have not surfaced in the inside of the pipe yet, and deterioration of the pipe's exterior [54]. These are the main factors that can cause lack of structural integrity and lead to the most capital-intensive failures such as pipe breakdowns and sinkholes. Moreover, even when such structural defects leave visual traces at the interior of the pipe, such as by-products of corrosion, the presence and location of these condition cues can be identified but their severity cannot be evaluated.

Another limitation of camera-based methods is that interpretation of the results by human operators is laborious and subjective and it can lead to highly variable conclusions [55]. Automatic and objective detection of the defects from camera data is the subject of investigations through machine learning and pattern recognition but cannot completely take away the human judgment yet [56,50,57–60].

5.2. Laser profiling

In this method, a compact laser scanner device is placed on an in-pipe crawler robot and sent along the sewer pipe. Laser profiling aims at providing an accurate, objective, and quantitative assessment of the inner geometry of sewer pipes [61–63]. The goal of laser profiling is to present a graph of internal diameter along the pipe's length. In this way, the size and location of changes in the pipe's inner diameter are recorded, which yields to the detection of condition cues such as loss/gain of the material, sediment and fat deposits, cracks, wall erosion, displaced joints, pipe deformation, intruding roots and sewer laterals, and objects inside the pipe [54,61].

Similar to the cameras, laser profilers can only inspect parts of the pipes above the waterline.

5.3. Sonar

Sonar surveys can provide quantitative data about the pipe geometry such as wall deflection, sediment buildup, and cracks [54,61]. Sonar can be used to inspect below and above the waterline, but not simultaneously. Therefore, when there is water flow in the sewer pipes, sonar is usually used in conjunction with other methods such as CCTV to collect data about the entire circumference of the pipe. In this way, the camera provides information from above the waterline while sonar determines the pipe profile under the waterline [27].

Limitations are that sonar has a low resolution and low survey speed. The method cannot ‘see through’ turbulent water flows and water with high concentrations of suspended particles [53]. The latter problem can be solved by lowering the sonar's wave frequency but at the expense of losing accuracy and resolution [31]. Recent studies are attempting to elevate some of these issues [64].

5.4. Transmissive acoustic profiling methods

Acoustic inspection equipment consists of audio speakers that transmit acoustic signals and an array of microphones that record the reflected signals. Together, these are mounted on a telescopic pole and then lowered from sewer manholes while the sewer is in operation. The recorded signals are then processed immediately to obtain quantitative results [65,66].

This method can detect changes in a pipe's cross-section such as blockages, cracks, intruding sewer laterals, and encrustation. Transmissive Acoustic profiling methods have a high inspection range. Depending on the pipeline condition, they can inspect up to 2000 meters of a straight pipeline in one signal acquisition period of less than a minute [51].

The presence of condition cues cannot be recognized if they are located under the waterline, within a few meters of the manhole, or within a wavelength distance behind a change in a pipe's cross-section [51].

5.5. Tilt measurement

This method is used to derive the slope profile of the pipe. In-pipe Tilt measurement can be done by mounting an inclinometer on a crawler and running the crawler through the sewer pipe [67]. An internal inclinometer is usually embedded in a CCTV tool to attain slope data while doing the visual inspection.

The method can quantify the pipe's gradient to verify whether it is correctly aligned [67]. It can additionally be used to interpret the differential settlement of the ground on pipe level [68].

Similar to all methods that require traversing through the sewer pipes, in-pipe tilt measurement cannot be performed if a section of pipe is obstructed and the crawler robot cannot pass through it.

5.6. Electroscanning

Electroscanning is used to derive the longitudinal location and to quantify the severity of potential leaks and sources of infiltration and exfiltration in non-ferrous pipes. In this method, first, the pipe segment needs to be filled with water. Then one probe is submerged in the water and it is moved along the sewer pipe. Another probe is placed on the ground surface outside the pipe to measure the electrical potential difference between the two. An intact and watertight pipe will not allow the electrical circuit between the two probes to be closed. Once the in-pipe probe passes by a potential leak, the electricity will flow through the defect. The severity of the defect can be evaluated by measuring the electric current [69,53].

A limiting factor in using the electroscanning method is that it is usually not possible to derive the type of leaks and their circumferential location directly from the electroscan results. This information can only be extracted after superimposing the results with a map of pipe features marked with the location of joints and sewer laterals [53] which might not always be available.

5.7. Pressure testing

This method is used to identify faulty pipe sections and joints that are not intact and are potential source of leakages in the sewer pipe [69].

In this method, a pipe section is isolated from the rest of the pipeline using inflatable sealing devices. Next, pressurized air or water is applied to the sealed section. If the pressure decreases over time this indicates that the section is not intact and it is leaking [70,71].

Pressure testing has a few limitations: the method cannot be used in the vicinity of the sewer laterals [69], and specifying the exact longitudinal location of the leakage can be a cumbersome and time-consuming task [72] while the method cannot identify the circumferential location of the leak.

5.8. Smoke testing

Smoke testing is a basic method that detects inflow and infiltration in the sewer pipes [73,74]. Similar to the pressure testing, smoke testing requires isolating a section of the pipe using sealing devices. Next, highly visible smoke mixed with a large volume of air is blown inside the isolated part. The appearance of smoke from the areas adjacent to the ground surface above the pipe indicates leaks in the pipe section [69,20].

Smoke testing does not allow localization of a cue, since smoke that is blown into a pipeline is likely to travel through porous subsoil and cavities to eventually exit the subsurface at a location remotely located from the leakage in the pipe. Smoke testing cannot quantitatively indicate the severity and type of the defects [69]. Furthermore, testing large pipes with this method can be difficult due to the limited capacity of the blowers [75].

5.9. In-pipe Ground Penetrating Radar

Ground Penetrating Radar (GPR) surveys from the ground surface are used for locating buried utilities [28] and for detecting damages that cause noticeable changes in the composition of the ground such as wet areas due to water pipe breaks [30]. To reach the higher depths, the GPR antenna frequency should be reduced, leading to loss of resolution (c.f. [76] and [77]). High-frequency GPR antennas can then be placed closer to the pipe; for example, when access to the outer surface of the pipes is possible [78]. When this is not possible, the GPR can be operated from inside the pipes.

The GPR units used for in-pipe inspection have high frequencies and high resolution and are suitable for scanning pipe walls and the surroundings behind it. High-frequency GPR antennas are smaller and can be mounted on crawler robots and sent to small-diameter pipes or be carried as hand-held devices in the larger pipes where operator entry is possible. Ultra Wide Band (UWB) antennas can be used in case a broad frequency range is required for the inspection [79–81].

In-pipe GPR can be used to locate and quantify the severity of condition cues related to the structural integrity of the non-reinforced pipes [82] such as cracks, fractures, delamination, softening, loss or change of material, variations in pipe wall thickness, and presence of voids in the pipe bedding [83,78]. However, studies about the effectiveness of in-pipe GPR in the inspection of sewer pipes are limited to a few cases. In one case, the compressive strengths of core samples from an inspected PVC-lined sewer pipe were identified and matched with marked corroded areas from GPR inspections [84]. Another research showed that in their case-study there was no correlation between the interpreted condition cues of infiltration, clay and Calcite deposits from radargrams and the observed features from camera inspection and it concluded that GPR is better in detecting these condition cues [85].

One of the main difficulties in using GPR-based methods is the complexity of interpretation of the radargrams. The most common approach for data interpretation at the moment is to rely on an expert's opinion; this is subjective, inconsistent, timely, and expensive. Studies have tried to make data interpretation automatic by applying signal processing and machine learning techniques on the radargrams [86,87].

5.10. *Impact-echo*

Stress-wave-based condition assessment methods of the concrete structures such as Impact-echo are widely used in civil engineering [88]. In this method, the surface of the structure is excited by an impactor and the resulting stress-waves are recorded and analyzed to locate and quantify the severity of defects in the medium.

Sack and Olson [89] assessed a 2 meter diameter pre-stressed concrete cylinder pipe with an impact echo method and found that it effectively measures the pipe wall thickness, locates delamination and wire breaks, and recognizes reduced strength of the pipe. Kang et al. [90] refined the method for detecting cavities around the sewer pipes using an impactor inside the pipe. Field tests demonstrated successful cavity detection in the wet soil. In a more recent study, Jaganathan [91] extended the multi-channel surface wave (MASW) analysis method to extract elastic properties of medium to large diameter reinforced concrete pipe segments.

The application of this method is still limited to large-diameter pipes where human entry to the pipe is possible [29].

5.11. *Ultrasonic Pulse Velocity*

Ultrasonic Pulse Velocity (UPV) test has been widely used in civil engineering applications such as non-destructive condition assessment of concrete structures like bridges. This method can provide data about the surface of the test object and its internal condition [88]. When used for pipes, UPV can provide quantitative data about crack depth, pipe wall thickness, delamination, corrosion, wire break, and changes in material quality [92].

This method is based on analyzing the propagation of mechanical ultrasonic stress-waves between a few transducers. Since conventional UPV transducers require coupling agents, this measurement manner is effort- and time-demanding. Although alternative coupling methods have been developed to overcome this problem, their use in practice is still limited [92].

While the use of UPV in ferrous and above-ground pipes is common, its application for concrete sewer pipes poses some challenges. Concrete highly attenuates the waves because of its heterogeneous structure. As a result, even when low-frequency waves are used, the effective range is small. Another difficulty in using UPV for sewer pipe inspection is that the operation of the method requires access to the outer surface of the in-service pipe or inner surface of a dewatered pipe which is large enough for human entry [29]. In both cases proper cleaning of the surface and removing debris is necessary. Another limitation is that interpretation of UPV measurements of thick concrete slabs (a few hundred centimeters) is much easier than the interpretation of measurements from sewer pipes. The reason for this is that the signal echoes are not well separated in time when measuring in sewer pipes with a few centimeter wall thickness. The research efforts on adapting the UPV method for assessment of sewer pipes are still in development.

6. Classification of inspection methods

Sewer inspection methods can be systematically organized based on the data that they present about condition cues in the five inspection domains (see Fig. 2). This results in the classification of the methods as

Table 3
Inspection methods and the condition cues that they can evaluate within the five inspection domains – *Electroscanning method can evaluate presence and severity but not the location of the condition cue.

Domain	H		S				E		HS					HSE					
	Obstacles	Water level deviation	Wire break	Corrosion	Change in the wall thickness	Cavities inside the pipe wall	Void in the supporting ground	Slope deviation	Fissure	Gain/ loss of material	Lining defect	Softening of the material	Deformation	Break/ collapse	Displaced joint	Root intrusion	Exfiltration	Infiltration	Need for pipe preparation
CCTV	II	II		II					II	II	II	II	II	II	II	II		II	Y
Zoom camera	II	II		II					II	II	II	II	II	II	II	II		II	N
Laser profiling	III	III							III	III	III		III	III	III	III			Y
Sonar	III	III							III	III	III		III	III	III	III			Y
Transmissive acoustic profiling	III	III							III	III	III		III	III	III	III			N
Tilt measurement								III											N
Electroscanning														III*	III*	III*	III*	III*	Y
Pressure testing														III*	III*	III*	III*	III*	Y
Smoke testing														I	I	I	I	I	Y
In-pipe GPR			III	III	III	III	III		III	III	III	III		III					Y
Impact echo			III	III	III	III	III		III	III	III	III		III					Y
Ultrasonic Pulse Velocity			III	III	III	III			III	III	III	III		III					Y

shown by Table 3. A cell in a specific row and column of Table 3 is marked with the degree of complexity of the collected data by the method in the corresponding row about the condition cue in the corresponding column. Empty cells indicate that the cue cannot be observed. Table 3 shows that the reviewed inspection methods can be classified into performance levels I, II, and III of SHM staircase [45]. None of the local in-pipe inspection methods yet achieves the other two higher levels. The last column in this table indicates whether preparation such as cleaning or blocking sections of the pipeline is required before the method can be applied.

We address the categorization of all methods below. Camera-based methods, CCTV and Zoom camera, are capable of identifying and locating most of the condition cues in the H, HS, and HSE domains. Since they cannot quantify the severity of problems, we classify them as level II. The details that the Zoom camera observes are lower than CCTV. Zoom camera can provide data with the same degree of complexity as CCTV only if the condition cues are close to the manhole where the Zoom camera is deployed.

Next, pipe profiling methods based on Laser, Sonar, and Transmittive acoustic provide quantitative data about the location and severity of most of the condition cues in H, HS and HSE domains. Hence, we classify them as level III. These methods, however, cannot detect in- or exfiltration directly because these cues do not necessarily occur with a change in the cross-section of the pipe.

The location (in this case only longitudinal location is relevant) and magnitude (severity) of deviations from the intended slope of a pipe segment can be quantified by Tilt measurement, resulting in a slope profile. This corresponds with performance level III.

Further, Smoke testing can identify presence of condition cues in the HSE domain but cannot indicate their circumferential location. It can also not quantify the severity of the cue (level I). Pressure testing and Electroscanning can indicate the presence of potential leakages and quantify the severity of a leak by recording differences in the pressure and current, respectively. However, while these methods can specify the longitudinal location of a condition cue, they cannot specify the circumferential location. To show this, cells related to Pressure testing and Electroscanning are marked with level III*. Finally, displaced joints and root intrusions can only be identified by the Smoke and Pressure testing and Electroscanning if they are potential leakage points.

In-pipe GPR, Impact-echo, and UPV methods indicate the presence and location and quantify the severity of most of the condition cues in S, E, and HS domains. Hence, we classify them as level III.

7. Discussion

Existing literature on sewer inspection methods does not explicitly link data-needs of sewer asset management systems with methods that can collect such needed data. This study hence developed a data-needs based classification that links inspection methods to the condition cues that they provide data about. Specifically, we proposed five inspection domains and used three inspection performance levels that indicate the degree of complexity of the data that each method can provide.

This classification scheme contributes to sewer asset management practice and has implications for future research. For one, Table 3 provides a means for asset managers to select their inspection methods. The proactive asset management workflow suggests that the data-needs for condition assessment should be defined before the appropriate inspection method can be selected (step 5 in Fig. 1). Our categorization supports this step in a structured way and may, eventually, lead to better decision making during the employment of inspection methods. In turn, this facilitates the development of asset management information systems that incorporate a wider range of data types, and that translate these into holistic sets of information for the assessment of local sewer system conditions.

Second, this study contributes to existing reviews of sewer inspection methods (e.g., [28–31]) by defining the ability of inspection methods to collect data about condition cues in different composite-structure domains and at various complexity levels. This could prevent the adverse consequences of using inspection methods that do not match data-needs for inspection activities. An example of such an adverse consequence relates to CCTV. Reviewed papers indicate that CCTV can partially assess the H, HS, and HSE inspection domains (level II in SHM table) but do not provide any evidence that CCTV can obtain data of a sufficient level for S and E domains. Thus, a corroded pipe that has lost structural load-carrying capacity, might not show this cue from CCTV footage. If digital asset management systems are developed only based on CCTV data, sewer asset managers may be inclined to overlook structural capacity problems and the need for rehabilitation or replacement of a pipe [93]. The categorization that we present in this study shows to asset managers and asset management system developers what other methods would be needed in addition to CCTV to detect such structural condition cues.

A third contribution lies in the identification of mature domains of inspection research and the niches that require further attention to grow. Although a bibliometric study is required to determine more precisely how many studies exist that have covered an inspection method, Table 3 provides a first insight about the focus points of existing studies. Specifically, it seems to indicate that an imbalance exists in the distribution of inspection methods across the various inspection domains. We found that the majority of the methods provide data about the condition cues related to the HSE category (i.e., visual inspection, profiling methods, Electroscanning, Pressure, and Smoke testing). Cues in this domain often appear after the loss of structural integrity and impairment of its hydraulic function. In addition, HS inspection domain is well-researched. Many studies are about visual inspection and pipe profiling methods. These inspect the condition cues that stem from the interface between the sewer pipe wall and sewer contents. In contrast, fewer methods assess the S domain. The same holds for the methods related to the E domain that can detect early stages of void generation around the sewer pipes that can later cause sinkholes and ground subsidence [94].

On balance, it seems that most inspection methods focus on HSE and HS inspection domains, while neglecting other domains of sewer pipe's condition. Since no single inspection method exists that can capture all condition cues in a sewer system, it is likely that multiple methods need to be integrated to obtain data that provides a holistic view of pipeline conditions. To support this, future research could focus on developing automation and enhancing data quality for methods in the S and E domain. This could lead to the maturing of methods that have higher performance and data quality levels and that can support the assessment of conditions cues in the domains besides HS and HSE.

Like any other, this study is not without limitations. The first one is that the categorization that we provide assesses the *technical ability* of methods to collect particular condition cues. Technical ability is, however, just one of the selection criteria for inspectors that choose a condition assessment method. Other practical adoption factors such as training requirements, availability of national certificates, equipment operation complexity and data analysis, operational costs, and extensiveness of fieldwork are relevant too. Existing studies address the relevance of those factors for a limited number of methods (CCTV, Zoom camera, and Electroscanning) [54].

The second limitation is that the scientific and grey literature underlying this review, could not fully provide a balanced, comparable, and deep insight into the nature and application context of each method. The main reason for this is that the reviewed sewer inspection methods have different technology readiness levels. Methods such as CCTV, for example, are more widely researched and have a mature research practice, while methods such as In-pipe GPR, Impact-echo, and UPV have a lower readiness level. This was shown generally by the fewer studies that were published about these developing niches.

Once those methods have further developed in the future, more insights into the practical aspects of the selection and implementation of them can be considered. When, for example, the developing inspection methods in the S and E domains – such as Impact Echo and In-pipe GPR – have achieved higher TRLs, we recommend that a wider range of practical adoption factors are considered in the study of inspection method selection processes.

The third limitation is that this study did not prioritize in its categorization whether a method detects multiple cues at once. It also did not prioritize methods that could inspect the most common cues that are used by practitioners nowadays. This limitation follows from the goal of this study to assess the *possibility* of a method to identify a cue based on proactively defined data-needs, and not to identify all other factors that influence the *current selection process*. Subsequent research could assess the impact that such attributes have on the selection of an inspection method in practice.

Fourth, although this study aims to be comprehensive, the list of possible condition cues and inspection methods in this study is not exhaustive. For example, this study focuses on in-pipe inspection of main sewer lines. Sewer inspection is, however, not limited to temporary in-pipe methods and inspection of the main line. Also remote methods (e.g. geophysical techniques [95]) may be required to determine pipe's x,y,z-location and assess additional cues such as condition of the sewer laterals. Consecutive research could therefore focus on such condition cues and methods.

Finally, the practical contribution of this study is that it provides a knowledge basis for decision-making methods for asset managers that assess local sewer contexts, define asset management strategies (Fig. 1), and select appropriate inspection methods. Since there are no universal set of cues of which data could be collected to gain insights into the condition of sewer pipes [23–25], we advise sewer asset managers to try and understand what local conditions exist, and then select whether cues can be adequately detected by the inspection methods available to them [22].

8. Conclusions

This paper proposes categorization of temporary and non-destructive in-pipe inspection methods for the condition assessment of sewer pipes. This categorization provides the missing explicit link in the literature between the data-needs for condition assessment and the inspection methods that can satisfy such data-needs.

In our categorization, we considered sewer pipes as composite-structures which consist of five domains, namely, Hydraulic, Structural, Environmental, Hydraulic-Structural, and Hydraulic-Structural-Environmental. We reviewed the data-needs specified by the literature and focused on the condition cues that can be inspected by in-pipe inspection methods. Next, we listed the kinds of condition cues that each method can inspect. Specifically, we assigned the degree of complexity of the data (based on the staircase of structural health monitoring systems) that inspection methods collect about each condition cue in the introduced five inspection domains (Table 3).

The proposed categorization shows that condition cues that can be inspected by the sewer inspection methods are not evenly distributed across the different inspection domains. The majority of methods evaluate the condition of the sewer pipe with respect to the condition cues in the Hydraulic-Structural and the Hydraulic-Structural-Environmental domains, while cues in the Structural and Environmental domains can be inspected by fewer methods.

This provides suggestions for future research. Literature is abundant with studies that focus on utilizing and improving visual inspection and pipe profiling methods. These, however, can only inspect condition cues related to Hydraulic, Hydraulic-Structural, and Hydraulic-Structural-Environmental domains. We, therefore, suggest that other methods are further developed and utilized to be able to assess a pipe's Structural and Environmental domains. We also suggest that future studies are then needed to assess the developed methods based on practical assessment criteria such as costs and operational complexity.

All in all, the presented categorization helps to identify focuses in previous research and to direct future research towards the still developing niche areas in inspection method research. This may ultimately help develop more mature methods that provide the required data-needs for proactive asset management. The proposed categorization eventually contributes to a practice of more informed selection of inspection methods by asset managers, and may steer towards a targeted collection of inspection data, and the emergence of holistic sewer asset management information systems containing various new types of inspection data types. These data are critical for developing the digital sewer asset management systems that help the contemporary management of sewer system life-cycles.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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