Co-UDlabs

Building Collaborative Urban Drainage research Labs communities

D07.2 Assessment of Current Pipe Condition Assessment Approaches and Proposals for Improvement

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Background: about the Co-UDlabs Project

Co-UDlabs is an EU-funded project aiming to integrate research and innovation activities in the field of Urban Drainage Systems (UDS) to address pressing public health, flood risks and environmental challenges.

Bringing together 17 unique research facilities, Co-UDlabs offers training and free access to a wide range of high-level scientific instruments, smart monitoring technologies and digital water analysis tools for advancing knowledge and innovation in UDS.

Co-UDlabs aims to create an urban drainage large-scale facilities network to provide opportunities for monitoring water quality, UDS performance and smart and open data approaches.

The main objective of the project is to provide a transnational multidisciplinary collaborative research infrastructure that will allow stakeholders, academic researchers, and innovators in the urban drainage water sector to come together, share ideas, co-produce project concepts and then benefit from access to top-class research infrastructures to develop, improve and demonstrate those concepts, thereby building a collaborative European Urban Drainage research and innovation community.

The initiative will facilitate the uptake of innovation in traditional buried pipe systems and newer green-blue infrastructure, with a focus on increasing the understanding of asset deterioration and improving system resilience.

List of acronyms

Acronym / Abbreviation	Meaning / Full text
CCTV	Close circuit television
CoF	Consequence of failure
DWA	The German Association for Water, Wastewater and Waste
FL	Fuzzy Logic
GIS	Geographical Information System
INDIGAU	Indicateurs de performance pour la gestion patrimoniale des réseaux d’assainissement urbains, - Performance indicators for the robust management of sewer networks
LoF	Likelihood of failure
ML	Machine Learning
NASSCO	National Association of Sewer Service Companies -USA
PACP	Pipeline Assessment and Certification Program
PVC	Poly-vinyl-chloride
RCP	Reinforced concrete pipe
RERAU	Rehabilitation of urban sewer networks
RF	Random Forest classifier
SRM	Sewerage Rehabilitation Manual
UDS	Urban Drainage Systems
VCP	Vitrified clay pipe
WRc	Water Research Centre, UK, Swindon, UK.

1. Executive summary

This report describes the historical use of condition grading of pipes and ancillary assets in sewer networks to inform intervention decisions and investment planning. The early condition assessment approaches, used defect data obtained from CCTV inspection to assign a condition grade to an individual pipe. Condition grades were normally integer values. The defect data was obtained by manual inspection of the CCTV images, and the use of a standard defect coding system. The earliest asset management approaches used this asset condition grading to make intervention and investment decision. These condition grading approaches developed more complexity with time, by including information on the consequences of any asset failure and the cost of any intervention.

Multi-criteria based schemes were then introduced to explicitly account for socio-economic and environmental factors as well as the physical condition of the assets. The relative weighting of these factors proved to be problematic and different approaches were developed in a number of studies and were applied in different countries. There was little consensus as to value of the relative weighting factors.

Two types of uncertainty have been identified, the first associated with the uncertainty associated with mapping uncertain defect data to condition class and the second in terms of the uncertainty in definition and values of the different criteria weighting on the final ranking for intervention and investment.

It is clear that current and even emerging inspection technologies will not be able to inspect all assets in the short to medium term. Deterioration models are therefore required to understand the physical condition of individual assets due to this lack of high quality defect data. Three different approaches are currently used, all rely on calibration/training/validation form limited collected condition data. All approaches provide a similar level of predictive performance at a network level, but Machine Learning (ML) based approaches provide more accurate asset condition predictions at an individual asset level.

If there was better understanding of the processes that govern the mechanisms that create individual types of defect then the ML based approaches could be applied at a defect level on an individual asset rather than on an aggregated condition grade. This combined with existing hydraulic network modelling approaches would allow the impact of the size and likelihood of failure associated with individual assets to be simulated. This combined with higher resolution social and environmental data would allow better informed multi-criteria decision approaches to be developed and so better identify the individual assets in need of intervention. By working at an individual asset level the assignment of weighting factors to the physical, socio-economic and environmental factors should become more transparent and the only uncertainty that remains is the sensitivity of the final intervention ranking to these weighting values.

2. Current Condition Assessment Approaches

2.1. Introduction

In Deliverable 7.1 a wide range of inspection technologies were reviewed. These were grouped into existing and emerging and an assessment of near and long term developments was made. It was clear that inspection technologies based on visual inspection (e.g. Closed-circuit television CCTV) dominated the sewer inspection industry. CCTV videos provided images of the internal surface of sewers. In Europe, there is strong commonality between countries, as practically all country's defect coding system has common historical roots and these are codified in a Euro Norm, EN 13508-2 for visual inspection (EN 13508-2, 2011). Currently defects are usually coded manually by trained inspection staff to national coding structures, compliant with EN 13508-2 and these pipe inspection reports are then used to assess overall pipe condition. Given the dominance of CCTV inspection there is a strong drive to automate the analysis of CCTV images. AI based methods are being developed, but for many methods large training data sets of defects are needed and the quality of the images is an important factor in terms of the robustness of any automated analysis. Different sensing techniques are also starting to come on the market. There are emerging image based technologies that can recreate 3D surfaces but the computational resources required are limiting their application in the sewer environment. However the inherent limitation of visual methods is that only the character of the internal pipe wall can be assessed. Multi-sensor approaches are being developed where different data sources are being combined to provide more information on individual defects. This approach is not replacing CCTV inspection but can give more information on the physical characteristics of defects. Different technologies are being adapted for application in the sewer environment, for example infra-red sensors to identify infiltration/exfiltration, installed distributed fibre optic systems to locate damage/misconnections, ultrasonic sensors to better measure defects in and behind pipe walls. However, these emerging inspection technologies are hindered by the reluctance of water utilities to move from CCTV based inspection technologies even though their technological and cost limitations are well known. This means that CCTV based data are used in all current condition based assessment schemes.

This report presents a review of the classification approaches developed to systematically consider a number of factors in order to assign a sewer pipe/asset condition grading that is to be used in investment decision processes. These approaches tend to be country specific, reflecting different water utility structures and regulatory structures within particular countries. This difference between countries is reflected in the complexity of the grading schemes, with the simplest schemes just taking into account measurements of the physical condition of the sewer network infrastructure, whilst the most complex takes into account the physical condition of the infrastructure combined with the consequences of failure and the overall costs of any interventions.

The most common condition assessment schemes assess CCTV based defect inspection reports and have rule-based approaches to enable the consideration of numerous reported defects in a single pipe into a smaller number of condition classes to allow an "objective" and consistent comparison between different assets. Different condition assessment approaches are used in different countries and organisations but they all have the same aim to provide a comparative ranking so that investment decisions, into asset replacement, repair or refurbishment appear to have a quantitative basis. All the condition assessment approaches described provide a single condition score (either structural or operational) for each sewer pipe/asset. Some more complex approaches then combine information on the impact of asset failure and intervention costs to develop a final ranking for investment. Two main approaches can be identified: a criticality based and cost based approaches. For criticality based approaches, sewer condition grades are often based on the most severe defect, or the number/size of defects per asset. These condition grades are meant to map an asset onto a priority for action to prevent asset failure and significant damaging consequences. For cost-based approaches, the final condition grade is calculated based on the length of sewer that will require action. Cost based methodologies do not aim to assess the worst physical condition of a sewer but rather to rank the amount of replacement, repair and refurbishment that would be required to maintain overall asset condition in a system.

2.2. UK: Sewerage Rehabilitation Manual

The Sewerage Rehabilitation Manual (SRM) has been developed since 2001 by WRc. It was developed in the U.K to meet the UK's water sectors sewerage rehabilitation needs. A methodology to assess sewer condition relied on information on individual defects based on sewer defects coded according to the Manual of Sewer Condition Classification MSCC (WRc, 2004) which has now been updated (WRc, 2013) and is used in the revised online Sewerage Risk Management (2013) approach – which supersedes the SRM, see below for details.

The SRM prioritized investigations on those parts of any sewer system with the most expected severe defects and highest consequences of failure in order to limit investigation costs and limit future replacement, repair and refurbishment costs. This decision is made using tools and limited data incorporated in the SRM. The SRM approach then evaluates the operational and structural condition of each sewer pipe considering its most severe defects and/or the defect density and the consequences of failure. Defects are identified and coded following the 4th edition MSSC (WRc, 2004). Defects are classified in two categories: structural and operational defects. Structural defects reflect the physical condition of the pipe, e.g. cracks, collapses and structural defect interventions focus on replacement and repair needs. Operational defects impact of the hydraulic capacity of the pipe. Operational defects include obstructions such as roots and in-pipe debris (blockages). Operational interventions include refurbishment options such as cleaning.

Structural and operational weighting values are assigned based on the results of the MSCC (2004) defect codification. The weighting value of each defect estimates the potential impact of any defect on the service life and performance of a sewer pipe length. Using these weightings three approaches are used to calculate a single integrated condition grade for a single sewer pipe length from the structural and operational defect weightings. The first approach is just the sum of the weighting values, the second takes the maximum weighting value, so the poorest defect and a mean weighting value is considered as representing a defect density. Overall pipe structural and operational condition grades are then assigned based on the approach selected. The structural condition grade assesses the likelihood of structural failure of the pipe and the operational condition grade assesses the ability of that pipe to meet its functional requirements, i.e. its serviceability. There are numerical 5 condition grades (1-5) for both structural and operational condition. Condition grades 4 and 5 represent assets in very poor/poor condition, or unable to meet their required function and for which timely intervention is essential.

In the SRM once the structural and operational condition grade of a pipe has been determined then sewers are grouped into three categories (A, B, and C) based on the consequence of failure which is taken to be the balance between the costs of a failure versus the proactive replacement, repair or refurbishment costs that need to be incurred to eliminate the likelihood of a failure. The SRM provides a structured pathway to gather information about the environmental context. For example, the assigned category can depend on the sewer size, depth and soil conditions, the importance of the highway above the sewer in terms of local connectivity and traffic volumes. For category A sewers the cost of failure could be extremely high and/or the loss of this asset would cause significant third-party disruption. Category C are located on low traffic routes so the cost of disruption caused by failure/repair would be much less (Rahman and Vanier, 2004). This information combined with the condition grade is used to prioritize assets for intervention.

The SRM has been significantly revised and was replaced in 2013, by the new Sewerage Risk Management approach, it added complexity and to combat this new tools to carry out lighter touch assessments before a final ranking list for interventions was produced. The Sewerage Risk Management approach and the tools and data for its implementation is hosted online (WRc, 2013). The website was developed by the UK water sector, including financial support from water utilities, regulators and hosts information and tools for the update of WRc's Sewerage Rehabilitation Manual. It provides an expanded approach that integrates a broader range of factors with a strong focus on the economic justification of any intervention. The Sewerage Risk Management toolbox has new planning tools and assessment protocols. It has initial screening tools to limit the resources needed when assessing assets in sewerage systems for rehabilitation, repair or replacement. Performance requirements, planning horizons and spatial extent all need to be explicitly defined. A broader range of information is now required, for example historical asset and performance data is now combined with newly commission inspection data to better estimate the likelihood of asset failure. Simpler tools are used at first, to focus efforts in particular areas to limit the resources needed to produce an intervention priority list therefore there are a range of tools with different complexities. Multi-criteria analysis is used to balance asset, social, environmental and economic factors, with weighting obtained from expert advice and analysis of historical data. A broader range of economic assessment tools are available: cost-benefit, cost effectiveness analysis, risk-cost-benefit analysis and whole life cost analysis. In summary the new Sewerage Risk Management approach is more complex, but has simpler initial planning tools to focus resources early in any study. It still follows the critically approach in which the assets with the largest consequence of failure are identified and prioritized for interventions.

2.3. RERAU, France

Concepts for structured sewer asset condition assessment were developed during the French RERAU program (Rehabilitation of urban sewer networks) (Le Gauffre et al., 2007). The project developed rules to support sewer asset management decisions using several assessment criteria. The overall principle was to take use assessments of defects, performance/failure types, and the level of the impacts (consequences) of any asset failure and combine these to obtain an overall ranking/assessment to inform investment choices. Based on these concepts there are several stages.

Defects are normally assessed via direct observations during CCTV inspection and then coding of defects using EN13508-2. Failure types are identified, for example those at a pipe scale such as infiltration, exfiltration, silting/blockage and those failures remote from the system, e.g. property flooding. Finally, typical impacts also have to be identified, for example damage to buildings, excessive treatment plant costs, damage to the natural environment and traffic disruption. This multi-criteria approach allowed information on the system state, the type of failures and external impacts to be accounted for in the final ranking for sewer asset management decisions.

Each type of defect is assessed against the 10 failure type indicators: infiltration, exfiltration, a reduction in sewer hydraulic capacity, sand intrusion and deposition, blockage, destabilization of soil-pipe system, pipe wall corrosion, pipe degradation from roots intrusion, pipe degradation from abrasion and structural collapse. The contribution of each defect to a loss in sewer performance is evaluated using tables developed within the RERAU project. For each defect, interim weightings are calculated for each particular failure pathway/mode. These interim weightings are then aggregated for each failure type within a system. These aggregated weighting scores can be obtained dependent on the density of defects or by examining critical defects. The aggregated scores are then reported on a four-grade scale G1-G4. The threshold levels to define the four grades are based on expert judgement (Ahmadi et al., 2014; Cherqui et al., 2008).

Finally, the asset condition grades can be combined with vulnerability factors to obtain an overall composite condition grade that can be used for asset investment prioritisation. For example, to obtain the condition grade (G1-G4) of the failure type “exfiltration” which has impacts on groundwater and soil quality, firstly, the defect weighting is obtained of the assets water tightness condition by visual inspection, this is combined with an estimate of the likelihood for exfiltration at that location to estimate an overall likelihood of infiltration. In the next step, this risk estimate is combined with the estimate of the local vulnerability of soils and groundwater to pollution to provide an overall condition grade (Debères et al., 2011). This process ensures that many relevant parameters are taken into account in the final condition grading of any system. In the INDIGAU project several software based condition assessment tools have been developed (i) *indigau-conversion*, (ii) *indigau-inspection*, and (iii) *indigaucriter*ia following the RESEAU concepts (Le Gauffre et al., 2010). These tools aimed to firstly provide better interpretation of visual inspections, then to better prioritise the rehabilitation needs of individual pipes using multi criteria analysis and then to better understand potential hydraulic failure pathways and likelihood by considering external environmental factors such as rainfall. Better techniques to understand system vulnerabilities and their economic impact were also developed. More focus was given to accepting the uncertainty in data and earlier analysis and an inference system, based on Fuzzy Logic (FL) principles was used to develop new performance indicators that take into account the imprecise data and nuanced reasoning common in earlier RERAU decisions.

2.4. U.S.A. - Pipeline Assessment and Certification Program

The National Association of Sewer Service Companies developed the Pipeline Assessment and Certification Program (PACP) (NASSCO, 2007) to standardise sewer inspection and condition grading in the US. The US is a diverse market, in which water utilities, often controlled by municipalities range vastly in size. Size normally reflects the technical capability of the utility so NASSCO wanted to develop standards for inspection and condition assessment that have a level of complexity that could be applied nationwide by a wide range of organisations. The PACP standards have become the standard used by hundreds of municipalities and utilities, and their consultants and contractors in the US and Canada (Opila and Attoh-Okine, 2011; Thornhill and Wildbore, 2005).

The NASSCO grading system assesses the structural and operational condition of the sewer pipes. It does not take any additional factors such as soil type or groundwater condition into consideration as part of the condition classification. Therefore, this system is considerably simpler to apply than other national approaches which take into account the consequences of any failure.

The PACP 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). The approach also counts the most severe defects in a pipe and the frequency of defects. To communicate this information the PACP produces a 4-digit index for each sewer pipe. 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. This allows operators to quickly identify pipes with the most severe defects. Based on this information a sewer length likelihood of failure (LoF) can be determined using the Overall Pipe Rating and prioritisation of intervention can start to be identified. The PACP provides general guidance on determining the consequences of failure (CoF) and any pipe's is risk of failure is then determined by multiplying the LoF with the CoF.

Recent work in the USA has started to examined the consequences of the failures of pipe defects as well as just the severity of any pipe defect. Vladeanu and Mathews (2018) provided a comprehensive review of various method being used to determine the consequences of sewer failure. Vladeanu and Matthews (2018a) then reported on the development of a methodology to assess the consequences of sewer pipe failure based on analytical hierarchy-based approaches, which expressed the importance of one group pf factors over another informed by expert knowledge. They used a weighted multi-criteria based method that took into account the economic, social and environmental consequences of individual pipe defect failure. The criteria weighting was mainly informed by expert opinion. This triple bottom line approach (TBL) used both direct and indirect costs to assess economic impact, social cost included proximity to other infrastructure, traffic loads, property types and number and environmental cost considered distance to water bodies and land use. Expert advice was checked for consistency, and advice found not to be consistent was not used. The model was applied in a case study and demonstrated that the most important factor was the social cost associated with disruption to traffic and the least important factors were associated with the physical condition of the sewer. The authors highlighted that their results were sensitive to the resolution of the scale used to weight the different factors (economic/social/environmental) and the potential for their model not containing all the factors that might influence the final ranking. They also highlighted that engaging more experts may change the relative importance weights for the studied factors.

2.5. Germany – DWA and private sector approaches

German seems to have developed both critical and cost-based approaches. Several German studies for example, DWA T4, (2012) reported that existing critical-based condition classification approaches do not allow for a pragmatic viewpoint in terms of asset management costs. For this reason, more cost-based condition assessment approaches have been developed in German. According to Baur et al. (2005), cost-based condition classifications approaches evaluate the "intrinsic value of the sewer as cost based approaches do not aim to be driven by the structural and operational condition of sewers but rather rank sewer pipes in terms of their asset management costs. These approaches define a cost class for each sewer type based on the repair length. Depending on the type of defect, different replacement/repair/refurbishment solutions need to be considered. Different defects affect a specific sewer length, If there are several defects are very close to each other, they may be dealt with at one time thus reducing the intervention costs.

Germany has also developed priority based approaches. The German (DWA-M 149-3, 2011) approach is thought to be the most used methodology among German utilities. It uses defect codes from EN 13508-2. Single defects are evaluated according to their relevance in respect to three fundamental requirements: Leak tightness (L), Stability (S) and Operational safety (O) separately. They are rated according to 5 interim condition classes from 0 (very severe deficit with danger of failure if intervention is delayed) to 4 (minor/no defect) for each of the three fundamental requirements. If a defect quantification is unknown, the worst case can be assumed. The approach examines the operational and structural condition of a sewer pipe considering the most severe defects, the defect density and also the influence of boundary conditions (e.g. groundwater level, sewer depth). For each sewer and each requirement, a condition score is calculated based on the most severe interim condition class and the density of defects. External environmental conditions can be considered by the addition of an additional weighting factor. If information the external environmental conditions (e.g. soil type) is unknown, a high weight factor can be used to indicate a worst case scenario. For each criteria, a value between 0 (best case) and 1 (worst case) is chosen, and then this are combined. The purpose of this approach is to develop intervention programs by ranking individual sewer pipes according to their need for timely intervention. This approach therefore uses assessments of the operational and structural condition of a sewer pipe considering the most severe defects, the defect density and also the influence of external environmental conditions (e.g. groundwater level, soil type), it does not include an assessment of the consequences of any failure. Finally, assessments for physical condition and the external environmental factors are combined for each requirement into a single condition grade that is used to rank the recommended timing for intervention. The approach has been implemented in several software tools, which can be purchased from DWA or private consultancies, open source tools to carry out this type of assessment do not appear to be available.

The Federal Ministry for Transport, Construction and Urban Development (BMVBS) have published a sewer asset condition assessment approach that follows the general principles for condition evaluation as described in DWA-M 149-3, but detail of the individual evaluation steps differs and it does not appear to consider external environmental factors so strongly and does not consider the consequence of failures implicitly. It does aim like DWA-M 149-3, 2011 to give higher importance to the most severe defects and produce a ranking listed based on the urgency of an intervention

As well as public bodies producing sewer asset condition assessment approaches, German seems unusual in a number of independent consultancies developing assessment schemes that are applied in practice. This difference in approach may be a reflection of a more fragmented water sector, in terms of size of utility and diversity in regulation at the federal and state levels.

An example of this approach is the "Status Sewer" sewer condition assessment tool developed by Stein and Partner (S&P) Consult GmbH (Stein et al., 2006). This approach evaluates an overall sewer condition mainly based on the most severe defect in an observed pipe section plus taking into consideration the cost of any intervention. The cost of intervention is based on the defect density and the cumulative length of pipe with defects independent of the defects severity. This cumulative length of defects is used to estimate a repair length since it indicates the length of sewer that will need to have an intervention. The final condition classification is estimated uses a fuzzy logic based algorithm to try an account for the uncertainty in any inspection data. The final pipe condition class is therefore determined using fuzzy sets and their membership functions which remain unpublished.

2.6. Netherlands/Belgium – NE3399 based approach

Water utilities in the Netherlands and Belgium, use the NEN3399 (1992) to classify and code in-pipe defects. Schmidt (2009) described how information on individual defects was used to define an overall condition class. Pipe defects were assigned three functional groups: defects related to water tightness (Group A), to structural stability (Group B) and to hydraulic capacity (Group C). Depending on the type and size of each identified defect, the assessment approach assigns an integer condition class between the values 1-5. If a sewer pipe has several defects, the condition class assignment 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 to require intervention. Interventions are categorized into 3 groups: additional refurbishment, further observation and replacement/repair is required. In more recent studies by van Riel et al, (2016) little appears to have changed with the authors stating that the majority of sewer replacement projects studied, that CCTV based defect inspection data was primarily used to inform replacement interventions, with information on pipe age and urban redevelopment also impacting on investment decisions.

2.7. Other Countries

Kley et al. (2013) provides a summary of sewer condition assessment approaches in other countries (Canada and Norway). In both these priority based methodologies are used. In Norway sewer condition grades are derived from a weighted assessment of the severity and number of defects observed within individual pipe section. However if a pipe contains the most severe defect it is automatically assigned the worst condition grade A bespoke Norwegian defect coding scheme (NV150, 2007) is used to identify defect type and severity.

In Canada a number of sewer condition grading schemes are used reflecting the federal structure of the country, for example CERIU, 2004 and Zhao et al. 2001. Both schemes assess both structural and operational defects against their own scoring system. CERIU evaluates structural and operational defects. It also includes consideration of infiltration and defects that may cause a loss of hydraulic capacity such as blockages and intrusion. The approach assigns a grade based on the severity of a defect, this single value is then used to allocate a proposed response that ranges from no intervention needed to immediate action required. The approach of Zhao et al (2001) uses a similar approach to the earlier versions of the UK's SRM, in that condition grades are assigned base on using the total score, peak score or mean score of graded structural and operational defects in a particular pipe. The approach also takes into account the consequences of a particular failure, by combining the condition grades from structural and operational defects with failure impact ratings. Again similar to the CERIU approach the defect grading impact rating information are used to define a suitable response ranging from intervention should be immediate to intervention not required at all. Recent work by Baah et al. (2015) has developed a weighted multi-criteria decision approach assessing both the risk and consequences of the failure of sewer pipes. This is a similar approach to that currently used in the UK and France, via the SRM and RERAU frameworks. It used the SRM condition grading approach for example. For pipes that had not been inspected a RF classifier developed by Harvey and McBean (2014) was used trained with a small number of pipe condition records, with a claimed accuracy of 72%. The consequence of failure (CoF) was estimated from a range of socio-economic and environmental factors that have significant commonality with the SRM and RERAU frameworks and the work of Vladeanu and Mathews (2018). This multi-criteria approach was demonstrated by application on a mid-sized city in Canada, this used an approach proposed by Salman and Salem, (2011) that focussed on pipes with the two highest physical condition grades and high COF values. The results of the application of this approach to a mid-size city indicated that around 5-6% of pipes had a high CoF and around 3.5% had a high failure risk and so required more consideration for intervention. The authors noted that the methods used to define the CoF were imprecise and were sensitive to the weightings of the socio-economic and environmental factors which was informed by expert opinion.

Cardoso et al. (2016) describe an approach that has been developed in Portugal to support decisions on investment for interventions in sewer networks. It describes the AWARE-P approach, it claims to provide outputs at three levels: strategic, tactical and operation, mapping on to long-term, medium-term and short-term interventions. The approach utilised a series of software tools many GIS based. The approach used a risk (probability-consequence) matrix. The probability was based on the UK's SRM approach. The papers reports that CCTV inspection images were coded based on EN 13508-2:2003, however little detail is given as to how the structural condition grades were assigned to individual pipes. The degradation of the assets was estimated as a proxy for age. These tools attempted to identify sub-systems where performance against set performance indicators would be poorest – this involved the development of network simulation models to assess system performance. Pipe condition grades were not incorporated in the network modelling. The AWRE-P tool kit seemed to be an approach to integrate information from different sources in a rule-based approach. It was applied by fourteen water utilities, with two case studies presented and seemed to highlight types of interventions rather than rank individual assets that needed intervention. The authors did comment that the implementation of the approach required considerable effort and resources.

2.8. Data availability and grading uncertainty

The accuracy of the final asset grade condition classification remains an issue. Most water utilities recognise that the uncertainty they have found in sewer condition grading has its origins in the defect data that is used. All condition grading approaches require data, either inspection data, and to lesser extent historical data to estimate consequences or data on local environmental factors. It has long been recognised that there are significant biases and resulting uncertainties from visually inspected CCTV data (Dirksen et al., 2013; Caradot et al., 2018; Ahmadi et al., 2019). Biases can take the form of inspectors failing to recognise the presence of a defect and failing to accurately code defects. The lessons from these studies is that condition assessment based on the manual processing of CCTV images tends to underestimate the level of deterioration and so overestimate the condition grade. Cherqui et al. (2017) stated that these errors were caused by the characteristics of individual defects, the difficult inspection environment and the condition grading procedure used. Caradot et al. (2018) reported on a study that determined the probability of under/over estimating the real condition of a pipe using a CCTV dataset that contained repeat inspections of individual pipes. Their analysis indicated the probability of inspecting a poor condition pipe was high, around 80%, whereas for pipes in a good condition the estimate of condition was much poorer. Typically, for pipes in a good condition CCTV operators would over-estimate the number and severity of defects in 20% of observations and under estimate the severity of defects in 15 % of observations. Sousa et al. (2014) used a similar approach in using periodic CCTV inspection reports for s mall number of trunk sewers and for the 25km of sewer pipes in their study, around 25% of pipes did have different condition grades, but there was closer match with the most severe defects. Both studies therefore were in agreement with the conclusions of Dirksen et al. (2013).

Even when accepting the uncertainty the uncertainty within the condition classification approach has been less studied. Even pipe defects are coded accurately the condition classification may still differ. Caradot et al. (2018) studied around 1800 km of sewer pipes which were inspected at between 8 to 10 year intervals. After a data validation exercise 1784 km of inspection records were available. This data was used to estimate a sewer pie condition grading following the RERAU concept so that the final condition grade would reflect the urgency of intervention, taking into account the physical condition of the pipe, the potential failure mechanism and consequences. There were three reasons that a pipe condition grade should transition (i) physical degradation, (ii) intervention between the two inspections and (iii) uncertainties in the grading approach. In order to isolate the uncertainties, pipes in which there had been interventions were removed, pipes with an inspection interval greater than 3 years were also removed from the analysis (assumption being no significant physical deterioration in 3 years). This left any differences due to uncertainty in the condition grading process. This indicated that around 35% of pipes had a different condition grade between the repeated inspections. Analysis of individual pipe grades indicated that the probability of correct assigning was slightly higher for pipes in a good condition rather than for pipes in a poor condition. The intermediate grades had a higher uncertainty, this pattern meant that the distribution of condition grades at a network level was quite accurate, though at an individual pipe level, grading accuracy could be poor especially for pipes with an intermediate grade.

2.9. Deterioration Modelling

There has been an appreciation that current levels of asset inspection data means that in order to allocate condition grades then some type of deterioration modelling is currently desirable. Deterioration models can only be successful if decision makers believe in their outputs and can accept their inherent uncertainties. A range of deterioration modelling approaches have been used in sewer networks ranging from purely statistical cohort-based models, to Markov chain random process type models (Ana and Bauwens, 2010) and more recently ML based data-driven models (Caradot et al, 2018a). Work by Malek Mohammadi et al. (2019) proposed a binary logistic regression deterioration model to predict the condition of sewer pipes. They used two groups of parameters one associated with the pipe (age, material, size, depth, condition) and others associated with the pipe environment (soil type, water table level) in their analysis. They developed this model using data from a single case study sewer network with PVC/VCP/RCP pipes were able to predict different deterioration curves for pipe with a different material and demonstrated an overall correct prediction percentage of around 80% when it came to examining forecasting the condition of pipes. Wirahadikusumah et al., (1999); and Ward and Savic (2014) both demonstrated the application of Markov-chain type deterioration models using existing condition data for calibration and validation. A number of studies have attempted to compare the performance of statistical and ML approaches (e.g. Rokstad et al., 2015; Sousa et al., 2014) but these studies have lacked sufficiently large asset inspection datasets and there has not been a consensus on the metrics capable of objectively assessing model performance. The metrics used often assess overall model performance without exploring performance for specific condition classes and at an individual asset level. This is important as the distribution of condition in a sewer network is highly skewed with the vast majority of pipes in a good condition and only a small number of pipes are in a condition that requires intervention. Caradot et al. (2018a) attempted to address these concerns by using a large sewer asset inspection database (>9000km of sewers) to compare condition grading performance using a Markov-chain based deterioration model and a ML based Random Forest (RF) classifier type deterioration model that used a range of pipe and environment parameters. They used both network wide and individual pipe evaluation metrics. Both the Markov-chain and the RF provided good predictions at a network level, with only a few percent difference across all the condition grades for both models. However, the performance at an individual pipe level was considerably different. The Markov-chain and RF models were compared against a random assignment model, the Markov-chain model had a similar performance to the random assignment, whilst the RF model performed significantly better particularly for pipes in a poor condition. The RF model did struggle for pipes with moderate condition grades, but this could be explained by the larger levels of uncertainty associated with the assignment of the middle condition grades derived from CCTV inspection. The RF predicted around 70% of pipes in a poor condition, which is a similar level of performance compared to direct CCTV inspection (~80%, Dirksen et al. 2013). This suggests that ML based approaches such as RF have significant potential to predict condition grade at an individual asset level.

The potential of ML based approaches was supported by a more recent study by Nguyen et al. (2022). This study compared a large number of ML approaches using a smaller asset database than Caradot et al. (2018a), of around 1500 assets. They demonstrated that the RF approach was the best ML approach and that it had a similar level of accuracy of condition grade prediction at a pipe level to the earlier study of Caradot et al., (2018a).

2.10. Overview

There is a considerable range of condition classification methodologies been used in different countries to determine a sewer pipe/asset ranking in a network to systematically allocate investment for either replacement/repair or refurbishment. Most approaches have been developed at a national level. Many national approaches have commonality, for example the US and Canadian approaches have adopted some of the aspects of the earlier UK SRM approach. Even with this national diversity, practically all condition grading approaches use simple algorithms, often developed from "expert knowledge" to weight, combine and aggregate sewer defect code grades obtain from the manual analysis of the CCTV inspection of sewer pipes and coded according to a national coding systems. The approaches therefore provide each sewer segment with an overall condition grade and some approaches provide subsidiary grades associated with individual; different parameters such as structural and operational condition, and impact of failure. Furthermore, the input data differ between methodologies: English and North American methodologies rely mostly on defect coding originally derived from work by WRc in the UK, whereas European methodologies are based either on European coding or older national coding systems. Currently, no conversion system is available to combine and compare sewer condition assessment from different classification methodologies (Chughtai and Zayed, 2011).

Available condition grading systems have two main approaches: priority-based and cost-based approaches. Priority based condition grading approaches are more common. The majority of these approaches derive the pipe condition grade mainly from structural and operational defect scores obtained from the manual analysis of CCTV inspection images. The more complex approaches such as the UK's SRM and the French RERAU based approaches have included grading incorporating impact and the influence of the external environment on determining final pipe condition grades. A smaller number of cost based condition grading approaches have evolved particularly in Germany.

More recent approaches in the UK, France and Germany have tried to incorporate social, economic and environmental factors to better estimate the consequences of failure should individual pipes fail to perform as expected. Practically all condition grading approaches use simple weighting algorithms to link defect observations, estimates of impact or local environmental conditions to grading sub-scores and aggregating them into an overall condition grade. Most of these multi-criteria approaches rely heavily on how different socio-economic and environmental factors are weighted. This weighting is commonly derived from expert opinion so attempting to incorporate a degree of uncertainty. The only exception is work in Germany which has tried to use FL based approaches to reflect the uncertainties inherent in these type of multi-criteria based decision making process. This approach does, however, require significantly less condition data than other statistical or ML approaches.

Comprehensive pipe inspection data is rarely available due to the limitations in the in current in-pipe inspection technology (Tait and Kazemi, 2023). This knowledge gap has resulted in the development of pipe deterioration models. These models are generally developed and calibrated using defect data derived from the inspection of only a few percent of the pipes in a network. Deterioration models fall into three main groups: statistical, e.g. logistic models, random processes, e.g. Markov-chain type models and data-driven ML type models, e.g. RF classifiers. Generally the predictive performance of these models is similar at a network level. At a single pipe level, the results from a very small number of comparative studies indicate that data driven approaches such as a RF classifier offer the best potential predictive performance of pipe condition.

Few legal requirements exist regarding the implementation of sewer condition grading systems, in some countries local regulations, or regulatory requirements commit sewer operators to inspect their network regularly but there is no requirement to use these assessments in terms of optimising the asset management of their systems. In the UK water utilities are required to justify their investment decisions to an economic regulator in their 5 year asset management plans, but there is no requirement to use sewer asset condition assessment methods.

Often the primary role of condition classification methodologies is to transfer extensive amounts of manually analysed visual inspection data using single defect codes into a data sets that are manageable in size and complexity to support asset management investment decisions. Most approaches have a similar overall aim to rank intervention priorities. However, depending on the assessment methods used, some condition grades only contain information on the physical condition of assets, other more complex assessment methods include aspect of the consequences of failure and some even incorporated some consideration of external environment al factors in their overall condition grading.

Condition grades therefore have very different meaning and comparisons between approaches should be interpreted carefully. Water utilities using different evaluation system are therefore not able to benchmark the effectiveness of any approach for use on their network. Few studies has been published that compares compare the results of different classification approaches and the impact of different approaches on asset investment decisions.

3. Future Directions

Condition assessment approaches, particularly in the EU have become more complex to apply especially by including (i) estimates of likelihood and scale of consequence and sometimes intervention costs. The original idea of condition grades was to aggregate complex visual observations of in-pipe defects into a single numerical "aggregated" grade. The above review has indicated that current inspection capabilities mean that all assets cannot be inspected in a timely fashion so that deterioration modelling will also be required for a considerable period of time. One big knowledge gap is how individual in-pipe defects are created and develop. Current systems have a relatively small number of observations taken at a relatively low frequency. So there is little empirical evidence as to how defects develop. Some defects, e.g. wall corrosion may develop slowly and continuously before resulting in sudden pipe failure. Others such as a crack may be created and then suddenly fail as local stresses are concentrated by this type of defect. There is a need therefore to study a small number of pipe defects that make of a large proportion of in-pipe defects and also have a high impact when they fail. A recent survey report from Germany (DWA, 2022) stated that intruding connections comprised 27.3 % of structural defects followed by holes/perforations (25.7 %) and then displaced joints (18.9%). Blockage was the most common operational defect. Studies on defect process development and failure should therefore be undertaken for these common defects as little is known about the initiation and formation processes of such defects.

Considering the state of the art in deterioration models. Random process models work well at a network base/scale. More careful examination shows difficulties in the centre of grading scales. Currently there are three types of deterioration modelling (i) cohort-based statistical approaches (ii) random processes, so for example Markov chain-based approaches and (ii) data-driven Machine Learning classifiers. There are two uncertainty types (i) original defect data coding, which defines a defect type but not really the physical characteristics of a defect (ii) uncertainty in converting defect data into grades, grading schemes are integer ranges so studies have indicated the potential for mis-grading especially in the middle of any grade range and especially if a defect is common. The key weakness in current approaches is that it is difficult given the defect data quality and accuracy of current deterioration models to pinpoint pipes with defects that are of such a severity that their failure is going to lead to a major loss of performance.

Makana et al. (2022) described and examined the wide range of factors that can result in the sudden or progressive deterioration of pipes. The influence of each factor is context dependent, dynamic factors change over time and can include the age of the pipe, corrosion of pipe material and surrounding soil, static factors remain unchanged over time and can include the pipe installation, material, joint type and size, and the surrounding soil/bedding material. Operational factors can include the sediment concentrations, wastewater content, and temperature that may all influence in-pipe physical, chemical and biological processes that can impact on pipe deterioration.

It is clear that a better understanding is needed of the mechanisms that cause pipe failure or lack of performance rather than just using data of failure to predict average rates of deterioration or asset survival. Currently defects are considered as random events, it should be possible to postulate a number of potential processes that create and develop in-pipe defects to better predict their state and then link this state prediction with the performance that a pipe is capable of delivering with its state.

A number of processes for in-pipe defects can be proposed (i) construction/manufacturing error, (ii) continuous corrosion/ non-continuous corrosion, (iii) facture type process that lead to sudden failure, and (iv) sudden and large increases in external environmental pressures that exceeds the pipe resilience causing sudden failure. Given the wide range of potential defect development mechanisms that it is expected that the relationship between pipe condition and performance (and achieving desired levels of serviceability) can be highly nonlinear. Figure 1 describes a range of conceptual defect generation and development models for sewerage assets that links physical defect development and the consequent impact on system performance. It can be expected that many defect development processes can be considered to occur linearly with time (Process type A). The asset defect develops the size of its severity consistently with time. An alternative scenario is that a defect unexpected and rapidly develops its severity (B), this may be in isolation of any other processes, but many observations of in-pipe defects suggest that this scenario is likely to be combined with a period in which the defect developed consistently over a period of time (A).

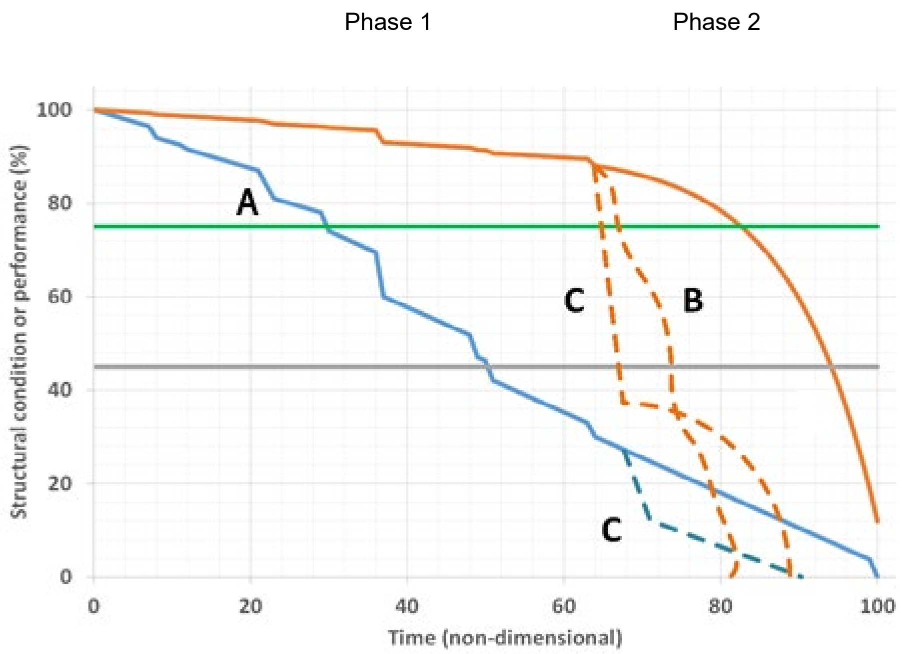

Figure 1 Conceptual deterioration pathways for individual pipe assets, after Makana et al. 2022, the green and grey horizontal lines indicate acceptable levels of performance for the asset with the developing defects. Blue line – defect severity, orange is asset performance.

Under the scenario A+B, in which the defect in the asset slowly develops its severity with time (blue line - initial phase) and it is only when the pipe defect has achieved a certain level of size that the asset performance starts to rapidly reduce (orange line second phase). However the link between defect size and system performance is unknown so the rate of performance reduction is uncertain, especially in the second phase (A, B). Intervention (e.g. repair/refurbishment/replacement) should occur now to prevent the rapid reduction in system performance as this should prevent the asset breaching its acceptable levels of performance. Combining defect severity and system performance needed to plan interventions to consistently meet acceptable levels of performance. Figure 1 clearly indicates that the ability to estimate the time to when system performance becomes unacceptable and timely intervention is required is related to the rate at which system performance is lost in Phase 2. Figure 1 shows that for lower levels of acceptable system performance, there is a higher level of uncertainty in determining the optimum time for intervention. This requires new knowledge to link defect severity and system performance, and the ability to identify sudden performance loss (C) is also required. These requirements mean that much better knowledge of the defect development process for individual types of defect is required. This is not possible when using broad aggregated condition grades. Therefore new asset management procedures need to focus on individual assets and the way in which they develop.

Future in-pipe inspection data therefore needs to identify a defect, map it to a specific development pathway and characterise its size/severity and then estimate its future development. This requires, firstly an understanding of how specific in-pipe defects will develop, under a range of external and environmental loading and secondly more frequent and higher spatial resolution of defect inspection data collected over long time periods to identify where in its development pathway a defect is at it point of inspection. This approach means that the volume and quality of asset inspection data is likely to be much higher, Tscheikerner et al. (2019) discuss the management of such large amounts of sewer asset management data in some detail.

Combining this enhanced knowledge of individual defects into hydraulic network models would allow the impact of such individual defects to be quantified for a range of flows and so the performance impact for individual defects could be ascertained. This approach was proposed and tested by Cardoso et al. (2016) but they lacked the detailed information on individual defects and had to resort to the coarser pipe condition grade information. By understanding the condition and impact of individual pipe defects means that aggregation of assets into uncertainty condition grades is not necessary.

It is still necessary to link estimated system performance with the social and environmental context of the asset but with the higher resolution of the defect focussed approach should enable stronger linkages between a defect, its failure and the surrounding social, economic and environmental context. Higher quality social and environmental spatial data is now available. The use of engineering judgment and professional experience is still required to link the likelihood of defect failure its impact and the external social, economic and environmental factors but with reduced uncertainty there is the potential that fuzzy logic models could incorporate this tacit knowledge is a way that would be transferable between contexts.

The key message for the future is to develop asset intervention ranking approaches that focus on the influence of individual defects rather than condition grading schemes that aggregate defect data within a single asset. This will be hard to achieve as there are currently a number of national asset condition ranking approaches, focussing on single defect will also require better management and better quality inspection data, requiring additional investment and also a better understanding of the processes and mechanisms that are present when individual pipe defects are formed and develop.

4. Conclusions

The earliest approaches to assign pipe condition grades were rule based and used information on individual or groups of pipe defects. This information was normally obtained from the manual inspection of CCTV images obtained from within individual pipes and identifying and coding defects according to a standard. Many countries' defect coding standards followed a similar type of coding scheme. This similarity in defect coding has historical reasons, as several countries adopted the fundamentals of a coding scheme initially developed in the UK. Pipe condition was normally identified using an integer condition grade, this grade was estimated using a variety of national approaches, such as using information on the most severe individual pipe defect, the density of pipe defects within a single pipe, the accumulation and mean values of all observed defects. Different counties had developed different condition grading approaches, the use of the most severe individual defect within a pipe appeared to be the most common approach in these earlier studies.

These approaches were further developed so that the next generation of pipe condition grading schemes which used a combination of individual observed pipe condition and estimates of the consequence of its failure and the cost of any intervention. This type of approach has resulted in the development of country specific software and other tools to help water utilities to handle the various data sources. The concept of multi-criteria assessment was then applied in which socio-economic and environmental factors were then used as well as the physical condition of the infrastructure were then used to prioritise intervention. These multi-criteria assessment frameworks were developed in several countries and are still in use today. They often relied on weighting factors to score the relevant importance of the physical, socio-economic and environmental factors. The values of these factors were often derived from expert knowledge and so different between countries and even between studies. No consensus has been reached as to the appropriate number and value of these weighting factors and there is considerable variation between the different assessment schemes.

Even with this more holistic approaches there still appeared to be limited confidence in condition assessment approaches from water utilities as regards intervention and investment decisions. It was clear that these approaches still had considerable uncertainty. Firstly they relied on the quality of the data used, in particular the defect asset data. Studies indicated consistent patterns of bias in manually analysed CCTV images. Major defects were clearly observed with high confidence but those in more moderate condition states were not observed well. Bias was also introduced when there was a high density of defects within a pipe. Secondly, there was uncertainty in the use and value of the different weighting factors between the physical, socio-economic and environmental factors. Different studies proposed various parameters to describe the factors and the weighting between the factors was often derived from advice from very limited numbers of experts. In a few studies this uncertainty has been described through the use of computational approaches such as Fuzzy Logic in an attempt to account for uncertainty when trying to weight the various factors involved in any investment decision making process. Case study examples exist in a number of countries so whilst these multi-criteria approaches produced general tends as regards intervention, there was little consensus between countries as to what would be the most appropriate form of a multi-criteria assessment approach for sewer network asset management. Benchmarking between studies and approaches was rarely done.

With no comprehensive asset defect data coverage from current inspection technologies, deterioration models have started to be developed. These models can be classified as using statistical, random process and ML based approaches, based on the limited available asset data. Recent studies have shown similar levels of predictive performance in terms of condition grading for statistical, random process and ML approaches at a network level. However, it was clear that ML based approaches performed, especially Random Forest based models performed better when considering condition assessment of individual assets.

Even with such improvements in deterioration modelling there still seems to be poor take up in many water utilities as model results often do not align with the implicit knowledge of individual sewer networks within water utilities.

It was proposed that there should be a stronger focus on the way in which individual defects or groups of defects affect the required asset performance and how this performance can be assessed at a system level. It was recognised that in the short to medium term that inspection technologies will not be able to provide sufficient defect data so deterioration modelling will still be required. It was clear that data-driven ML approaches offer the most promising approach for predicting condition at an individual pipe level. The predictive performance of such ML approaches could be improved if there was a better understanding of the mechanisms responsible for the development of individual defect types, such understanding would help identify more appropriate input parameters for the ML based deterioration models. There is the potential to link deterioration models with hydraulic network models to simulate the performance and thus failure at an asset level. Such level of failure data combined with spatial data of social and environmental factors would provide much better estimates of the consequences of failure at an individual asset level. One issue still remained was the uncertainty in the process that converted defect data into condition grades. Given the potential improvements in defect deterioration modelling and the higher quality of environmental spatial data proposals were made to eliminate the use of condition grades and to focus on the investigation of the impact individual defects, as they develop, on system performance rather than attempt to aggregate this information into a single condition grade.

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