Identification of the information needs for sewer asset management by assessing failure mechanisms

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ABSTRACT

Asset management is a prerequisite for maintaining the required level of serviceability of urban drainage systems. The required asset management effort to achieve a certain level of service is unclear due to sewer systems process and structure complexity. One of the main questions of asset management is what kind of information is needed, and how this information can be obtained. Sewer failure mechanisms explain the structural/operational failures of sewer elements. This study focuses on determining the information required to be able to detect and identify sewer failure mechanisms. In order to be able to identify the failure mechanisms involved, a HAZOP approach was applied. The main processes and defects responsible for the structural/operational failures of sewer elements were identified, as well as possibility of obtaining the information about them. This information will help in estimating the probability of failure occurrence and generally it will help defining the information needed for proper serviceability.

KEYWORDS

Asset management, failure mechanisms, HAZOP, sewer system

1 INTRODUCTION

Sewerage and urban drainage systems are capital intensive infrastructures aiming at prevention of urban flooding and mitigation of water related health hazards in urban areas (Marsalek 1998). In the Netherlands, for instance, the municipalities spent around € 1,2 billion on sewerage (or € 151/per household/annum) in 2009 (Walder 2011). Over 65% of this sum is related to capital costs. Proper operation and maintenance of such systems together with rehabilitation will ensure long life of the infrastructures while meeting serviceability requirements.

Sewer asset management aims at providing optimum decision on the provision for maintenance, on-going operation and on the provision of the large investments, associated with sewer rehabilitation and replacement (Nederlands Normalisatie-instituut 2008). Decisions (*e.g.* rehabilitation, maintenance) are made based on the available information and experience. Pipe age and CCTV inspections are the primary sources of information used in sewer asset management (Halfawy et al. 2008).

However, pipe age is not a sufficient criterion for asset management (Ana and Bauwens 2007; Stone et al. 2002) and CCTV is only capable of detecting visual defects from within the sewer (Figure 1) (Nederlands Normalisatie-instituut 2003; Deutsche Vereinigung für Wasserwirtschaf 2006). *E.g.* sink-holes cannot be detected directly. Moreover, (Dirksen et al. 2009) concluded that more information is needed for proper decision making because of insufficient quality of visual inspection data. As a consequence, decisions on sewer management are based on partial knowledge due to scarcity of information on the functioning and conditions of urban drainage systems (Elachachi et al. 2006).

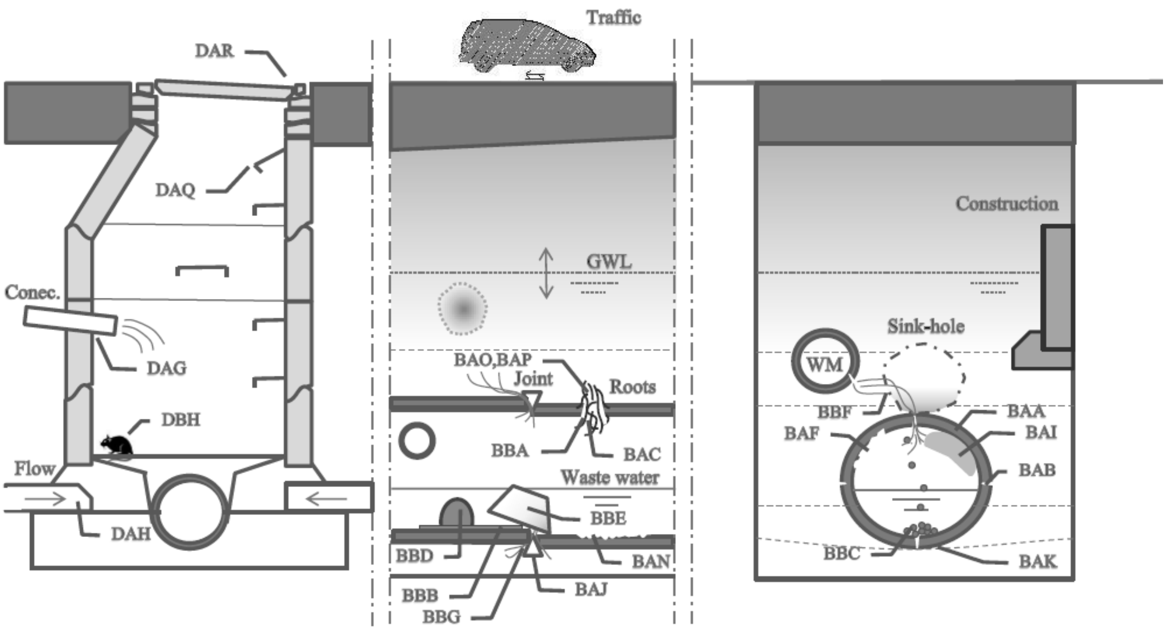

Figure 1. Dutch (NEN-EN 13508-2) visual inspection codes related to the fabric and operation of the pipeline.

The major issue of sewer asset management in meeting the serviceability requirements at acceptable costs is the lack of a well-established relation between required asset management efforts and the level of service provided. This is due to sewer systems process and structure complexity (Ashley and Hopkinson 2002).

A good understanding of failure causes is necessary to ensure their proper operation/repair (Murthy et al. 2002). The term failure mechanism refers to a complete systematic description of how, when, and why the failure comes about, and if any other failure occurs in the chain of events. Many failures, as a qualitative change, of sewer elements emerge due to gradual build-up of conditions leading to the problem. Some of them appear due to sudden incidents. *E.g.* clogging of sewers usually results from gradual build-up of sediment or grease caused by different kind of factors influencing hydraulic performance of sewer, or from structural failures which are caused by different kinds of factors that influence sewer structural stability (Marsalek and Schilling 1998).

It is clear that the sources of information dominantly applied nowadays, CCTV inspections and pipe age, are insufficient to direct sewer asset management (Fenner 2000). It is not clear, however, what type of information of what quality is necessary to fully benefit from sewer asset management. This paper describes the use of the analysis of failure mechanisms as a first step to identify information needs for sewer asset management. In order to be able to identify the failure mechanisms involved, the

HAZOP approach was applied. The HAZOP analysis allows identification of failure mechanisms, as well as identifying sources of information to detect and quantify the identified failure mechanisms. The top events in the failure analysis are derived from the serviceability requirements for sewer systems.

2 METHODOLOGY

In order to be able to identify the failure mechanisms involved, a HAZOP technique was applied. HAZOP, HAZard and OPerability, uses special guide-words combined with process conditions to systematically consider all possible deviations from normal conditions (Figure 2).

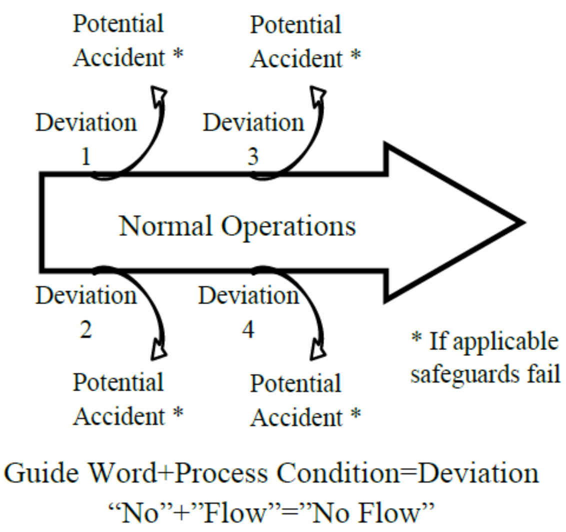

Figure 2. Schematic diagram of HAZOP analysis.

In a HAZOP study, a multi-disciplinary group of sewerage experts have to serve as the review team (Montague 1990). Team members have to bring knowledge of the sewer design and construction, experience in system and equipment operations, experience in equipment testing and maintenance, knowledge on hydraulic/hydrological/hydrogeological processes, knowledge of safety objectives and procedures, and experience in applying the HAZOP technique.

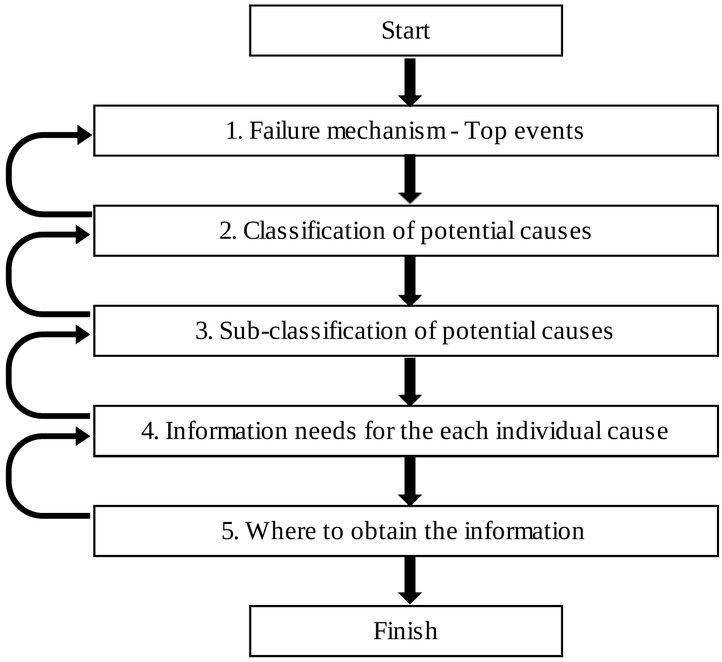

Figure 3. Procedural outline followed in sewer failure assessment

This qualitative technique was carried out during a set of meetings. The expert team first determined the top events causing sewer failure, and then reviewed each top event using the HAZOP analysis steps given in Figure 3. Potential initial causes of sewer failure were identified within the fault tree analysis. This is a top down, deductive failure analysis. It quantifies both overall probability failure of serviceability and relative contributions of individual causes of sewer failure (Ten Veldhuis *et al.*, 2009). Probability of occurrence values will be assigned to the lowest events in the tree in order to obtain the probability of occurrence of the top event. Possible sources of information, necessary for assessing impacts of failures on meeting the serviceability requirement, were determined based on knowledge of the chain events of sewer failure and information needed on their initial causes. The final documentation of the study was based on complete documentation review by a decision makers who did not attend the actual HAZOP meetings. To predict the probability of failure occurrence for each component and to identify critical components, the software package Isograph Reliability Workbench incorporating FaultTree+ (version 11) will be used. This is computer program used for reliability and safety analysis, which can determine the critical components in system and the consequences and risks of system failures (Isograph 2011).

3 RESULTS AND DISCUSSION

3.1 Failure mechanism – top events

The main processes and defects responsible for the structural/operational failures of sewer system in this study were identified, as well as the possibility of obtaining the information about them. Table 1 shows the top failure events which affect the sewer system serviceability and the main causes why these events are occurring.

Table 1. Top failure events of sewer systems and their main cause.

Failure	Top event	Cause	
System Performance	Flooding Frequent CSOs Soil contamination Exposure to health hazards	load > capacity	load ↗ and/or capacity ↘
Element Performance	Collapse of structural elements Breakdown of mechanical elements	load > strength	load ↗ and/or strength ↘

Failures are differentiated into two main groups, system and element performance. System failure is defined as failing to meet serviceability requirements with respect to system performance, such as urban flooding. Element failures are defined as the failure of a specific sewer object or element, either collapse or breakdown. Element failures not necessarily lead to system failure. *E.g.* if one pipe of a maze sewer system is fully clogged, it will most likely not have an effect on overall system performance, as wastewater will find another route to flow downstream.

Top events occur as soon as the load (e.g. hydraulic loading of system, traffic loading of sewer pipe) exceeds the capacity or strength.

3.2 Classification of potential causes

Failure tree analysis was used to better understand the logic leading to the top event. Sewer system complexity contributes to its fault tree complexity. As a consequence, the HAZOP study resulted in complicated failure tree structures and enormous amount of potential sources of information. One example of the HAZOP study is presented in some detail here. For instance, flooding can be caused by hydraulic overloading of the system when discharge cannot (completely) be transported. Flooding due to decrease of capacity may be caused by human error, external effects, or by their combination (Table 2).

Table 2. Classification of potential causes of flooding due to decrease of capacity

Flooding	Causes due to decrease of capacity
	1. Human error
	1.1. Production error
	1.2. Design error
	1.3. Construction error
	1.4. Operation and Maintenance
	1.5. Abuse
	2. External effects
	2.1. Root intrusion
	2.2. Partial collapse
	2.3. Sedimentation
	2.4. Ingress of soil
	3. Human error & External effects
	3.1. Other construction

3.3 Sub-classification of causes

Each cause defined in Table 2 can be explained by a number of sub-causes. For instance, there exists very limited knowledge on ingress of soil (Korving et al. 2003), and ingress of soil is barely noted during visual inspection of sewer (Ibrahim et al. 2007). Consequently, more knowledge is needed on this process. The possible sub-classification of causes of ingress of soil derived in the HAZOP for ingress of soil as an external effect causing flooding is given in Table 3.

Table 3. Classification of possible causes of ingress of soil and their information needs.

2.4. Ingress of soil	Cause	Information needed on cause	Where to get information
2.4.1. Improper pipe positioning	- improper quality of backfill	1. soil characteristics of backfill	a. from the constructor b. from the measuring
	- lack of supervision	1. who and if there was supervised	a. from the municipality
	- pipes barely connected	1. position of pipes	a. from the constructor b. from the inspection
2.4.2. Damaging during refilling/compaction	- cores material in backfill	1. soil characteristics of backfill 2. how it was compacted	a. from the constructor
	- lack of supervision	1. who and if there was supervised	a. from the municipality
2.4.3. Improper bedding/foundation	- improper consolidation of bedding	1. characteristics of bedding	a. from the constructor
	- improper foundation	1. soil characteristics of foundation	a. from the constructor
	- lack of supervision	1. who and if there was supervised	a. from the municipality
2.4.4. Wrongly constructed connections/joints	- lack of professionalism during construction	1. as-built report 2. inspection results	a. from the constructor
	- lack of supervision	1. who and if there was supervised	a. from the municipality
	- improvisation due to local conditions	1. as-built report 2. inspection results	a. from the constructor
2.4.5. Improper choice of pipe and joint type/material	- un/experienced engineers	1. checking of design protocol	a. inside the design company
	- lack of quality check	1. checking of final report	a. from the contractor
	- lack of appropriate data	1. checking the quality of initial data necessary for the design	a. sources of initial data: (e.g. material → manufacture)
2.4.6. Weakened structural elements	- low strength properties of plastic pipes	1. deformation of pipes	a. from the inspection (e.g. CCTV)
	- sever pipe deterioration	1. sever cracks, pipe brakes, infiltration	a. from the inspection (e.g. CCTV)
2.4.7. Groundwater table	- high groundwater table	1. measurement of groundwater table	a. from the measuring (ground water table)
	- aggressive ground water	1. ground water quality	a. from the measuring
2.4.8. Type/position and maintenance of trees in the area	- trees with deep roots	1. type of trees	a. from the local community
	- trees located close-by the sewer	1. location of trees	a. from the local community
	- good soil conditions	1. soil conditions	a. from the measuring
2.4.9. Inappropriate load transfer	- improper traffic load	1. nature and density of the traffic	a. from the municipality
	- load due to construction around the sewer	1. if proper measures were taken during construction 2. structure conditions	a. from the constructor b. from the inspection

The possible causes of ingress of soil are numerous and widely various in nature. They can be divided into the group of causes due to inappropriate material selection and construction errors and into the group of causes due to sewer deterioration influenced by different kind of factors.

3.4 Information needs per individual causes

The information needs per individual cause are already shown in Figure 3. A number of these needs are highlighted below.

Workmanship errors contribute to large extend to the occurrence of ingress of soil. Applying poor practise during the sewer construction may be the cause of different kinds of defect like leakage at joints and even a complete structural failure (Boden et al. 1975). Infiltration of groundwater, and potentially, ingress of soil into the sewer will most likely happen through the pipe joint rather than through some other defect in the pipeline (Fenner 1990). The amount of entrained soil due to infiltrating water depends on the soil characteristics of the backfill. Finer particles of soil can be flushed out easily with water into the sewer. Therefore, it is very important for pipes to be properly connected and for the backfill to be of proper quality. Improper compaction of the backfill can also contribute to passage of soil into the sewer. (Fenner 1991) showed that the intensity of water and soil migration into the sewer is influenced by the bedding/foundation characteristics. Improper bedding/foundation would allow pipe settlement and fine soil grains with water would be able to move through the joints. Information on construction process and as-built report would help in determining the possibility of occurrence of ingress of soil.

Lack of supervision is an important issue when it comes to construction of connections and joint placement. It is generally accepted that during and after the sewer construction field testing should be executed to ensure that the joints are watertight and formed satisfactorily. The same kind of check should be performed on the constructed connections. The presence of openings in the pipes or structure should be prevented, because if they are present water, and possible, soil will be allowed to enter the sewer. Improvisations during construction due to local conditions can be important in influencing structural stability of a sewer. Lack of professionalism during construction and improper improvisation can create cracks and holes in the pipe structure through which soil will be able to pass. As mentioned earlier, information on construction process and as-built report would be useful.

The selection of pipe and joint type/material can also significantly influence the possibility of soil intrusion occurrence. Pipe durability depends among other on pipe materials due to different structural characteristics (Sousa et al. 2009). *E.g.* if sewer is built from plastic material the most likely pipe defect is deformation (WSA/FWR 1993). Openings at the location of connections may occur allowing the passage of soil into the sewer. The inspection could provide valuable information about the current performance of the drain and sewer system and its components for prevention of possible ingress of soil. The major causes of joint related structural defects is an improper selection of joint type (Park and Lee 1998). An improper selection of the joint type or selection of poor quality may easily lead in a short period of time to infiltration of water and consequently soil. Checking of final reports and quality of material could be useful information for estimating the possibility of appearance of ingress of soil.

Groundwater intrusion can occur when the ground water table is above sewer invert level. Soil particles can be flushed in through the existing defect with the infiltrating groundwater as a result of erosion and suffusion which could cause ground loss and subsequent lack of support to the sewer through the loss in soil density or the formation of the cavities (Davies et al. 2001a). On the other hand, erosion of cohesive soil through the defect may occur due to hydraulic overloading or due to strong changing of water conditions in the sewers. Over the time voids formed by internal erosion can enlarge to the point of total loss of structural integrity. Furthermore, groundwater in highly corrosive soil may have adverse effect on some sewer joint materials (Davies et al. 2001b). Over the course of time the joint material could deteriorate enough to allow passage of soil into the sewer. Information on groundwater level and quality is necessary to be able to determine groundwater infiltration and possible soil passage.

Root intrusion may contribute to migration of soil by expand existing openings in sewer, allowing surrounding soil to enter through the defect (Schrock 1994). Tree species and their distance from the sewer are factors that may contribute to soil passage and overall sewer damage (Randrup et al. 2001). Also, if the soil conditions of trees located close to the sewer are good this may contribute to an increase of tree intrusion. Trees would be bigger as well as their roots, which will increase a possibility of tree intrusion. Information on characteristics of the trees and their location in the area around sewer would contribute to root intrusion prevention.

Inappropriate load transfer may cause a different kind of damage to the sewer as well as ingress of soil. A sewer can be affected by a variety of loads, like a traffic load and load due to close by construction etc. (Davies et al. 2001b) showed that chances of traffic load damage increase with the number of vehicles passing over the sewer. Cracks may appear and with time they can become severe enough so water and soil could pass considering that the ground water table is already high enough.. Furthermore, vibrations during near-by construction may cause severe damage to sewer in very short period of time allowing soil passage into the sewer. Information on the traffic frequency and construction process would help in assessing sewer damage.

Table 4. Possible sources of information needed for assessment of ingress of soil.

	As-built reports	Soil characteristics	Inspections	Field measurements
Pipe positioning	+	+	+	+
Refilling/compaction	+	+		
Bedding/foundations	+	+		
Connections/joints	+		+	
Pipe and joint type/material	+			
Weakened structural elements			+	
Groundwater table				+
Tree intrusion		+	+	+
Load transfer			+	+

Table 3 shows that the most of information needs on possible causes of ingress of soil could be found at the municipality and the constructor. Overall, from the Table 4 it can be seen clearly that there are four groups of possible sources of information. Standard sources of information in the practise are inspection during construction and CCTV inspections.

However, there are a lot of other possible sources of information that can be considered. *E.g.* measurement of traffic density and information about the trees in the local community could contribute to ingress of soil prevention. Large amounts of information necessary to assess the ingress of soil can be obtained from the as-built final reports and from knowing local soil conditions.

4 CONCLUSIONS

The HAZOP technique proved to be applicable to analyse the information need for sewer asset management. The main processes and defects responsible for the structural/operational failures of sewer elements were identified, as well as possibility of obtaining the information about them. Moreover, this analysis showed that pipe age and CCTV inspection, as primary source of information used in sewer asset management and models, provide limiting knowledge about the actual sewer conditions and that beside them exist a lot of different sources of information from which asset management could benefit.

Further research will concentrate on qualifying and quantifying failure processes, as well as determining the availability of the information. For achieving this Reliability Workbench program (verison 11) incorporating Isograph's FaultTree+ product will be used. Overall, this should improve the accuracy of probability of failure estimates.

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6 REFERENCES

Ana, E., and Bauwens, W. (2007). "Sewer Network Asset Management Decision Support Tools: A Review." *Presented at International Symposium on New Directions in Urban Water Management*, UNESCO Paris, France.

Ashley, R., and Hopkinson, P. (2002). "Sewer systems and performance indicators--into the 21st century." *Urban water*, 4(2), 123-135.

Boden, J., Nath, P., Trott, J., and Farrar, D. (1975). *"Research on underground pipelines at the Transport and Road Research Laboratory"*.

Davies, J., Clarke, B., Whiter, J., and Cunningham, R. (2001a). "Factors influencing the structural deterioration and collapse of rigid sewer pipes." *Urban Water*, 3(1-2), 73-89.

Davies, J. P., Clarke, B. A., Whiter, J. T., Cunningham, R. J., and Leidi, A. (2001b). "The structural condition of rigid sewer pipes: a statistical investigation." *Urban Water*, 3(4), 277-286.

Dirksen, J., Goldina, A., Ten Veldhuis, J., and Clemens, F. (2009). "The role of uncertainty in urban drainage decisions: uncertainty in inspection data and their impact on rehabilitation decisions." *Strategic Asset Management of Water Supply and Wastewater Infrastructures*, 273.

Deutsche Vereinigung für Wasserwirtschaf. (2006). *DWA-M 149-2: Zustandserfassung und -beurteilung von Entwässerungssystemen außerhalb von Gebäuden Teil 2: Kodiersystem für die* *optische Inspektion (Condition assessment and evaluation of drainage systems outside of buildings Part 2: Coding for visual inspection).* Germany.

Elachachi, S., Breysse, D., and Vasconcelos, E. "Uncertainties, quality of information and efficiency in management of sewer assets." *Presented at Joint International Conference on Computing and Decision Making in Civil and Building Engineering*, Montréal, Canada.

Fenner, R. (1990). "Excluding groundwater infiltration into new sewers." *Water and Environment Journal*, 4(6), 544-551.

Fenner, R. (1991). "Influence of sewer bedding arrangements on infiltration rates on soil migration." Proceedings of ICE, *Municipal Engineer (Institution of Civil Engineers)*, 8(3), 105-117.

Fenner, R. A. (2000). "Approaches to sewer maintenance: a review." *Urban Water*, 2(4), 343-356.

Halfawy, M. R., Dridi, L., and Baker, S. (2008). "Integrated decision support system for optimal renewal planning of sewer networks." *Journal of Computing in Civil Engineering*, 22, 360.

Ibrahim, M., Cherqui, F., Le Gauffre, P., and Werey, C. (2007). *"Sewer asset management: from visual inspection survey to dysfunction indicators."*

Isograph. (2011). ReliabilityWorkbench 11. *FaultTree+ Software.* http://www.isograph-software.com/2011/software/reliability-workbench/ (accessed 02 July 2012).

Korving, H., Van Noortwijk, J., Van Gelder, P., and Parkhi, R. (2003). "Coping with uncertainty in sewer system rehabilitation." *Safety and Reliability.* Swets & Zeitlinger, Lisse, *ISBM*, 90(5809), 551.

Marsalek, J. (1998). "Challenges in urban drainage." Hydroinformatics tools for planning, design, operation and rehabilitation of sewer systems, *NATO ASI Series*, 2, 1-23.

Marsalek, J., and Schilling, W. (1998). "Operation of sewer systems." *NATO ASI SERIES 2 ENVIRONMENT*, 44, 393-414.

Montague, D. F. (1990). "Process risk evaluation--What method to use?" *Reliability Engineering & System Safety*, 29(1), 27-53.

Murthy, D., Atrens, A., and Eccleston, J. (2002). "Strategic maintenance management." *Journal of Quality in Maintenance Engineering*, 8(4), 287-305.

Nederlands Normalisatie-instituut. (2003). *NEN-EN 13508-2: Toestand van de buitenriolering - Coderingssysteem bij visuele inspectie (Conditions of drain and sewer systems outside buildings - Part 2: Visual inspection coding system)*. the Netherlands.

Nederlands Normalisatie-instituut. (2008). *NEN-EN 752: Buitenriolering (Drain and sewer systems outside buildings)*. the Netherlands.

Park, H., and Lee, I. (1998). "Existing sewer evaluation results and rehabilitation strategies: the city of Seoul, Korea." *Environmental technology*, 19(7), 733-739.

Randrup, T. B., McPherson, E. G., and Costello, L. R. (2001). "Tree root intrusion in sewer systems: review of extent and costs." *Journal of Infrastructure Systems*, 7(1), 26-31.

Schrock, B. J. (1994). "Existing sewer evaluation and rehabilitation", *F.-. ASCE Manual and Report on Engineering Practice. No. 62: Water Environment Federation Manual of Practice, (ed.)*. The Joint Task force of the Water Environment Federation and the American Society of Civil Engineers: New York.

Sousa, V., Ferreira, F., Almeida, N., Saldanha, J., Martins, J., and Teixeira, A. (2009). "A simplified technical decision support tool for the asset management of sewer networks." *Water Asset Management International*, 5(1), 3-9.

Stone, S. L., Dzuray, E. J., Meisegeier, D., Dahlborg, A. S., Erickson, M., Laboratory, N. R. M. R., and Institute, L. M. (2002). *Decision-support tools for predicting the performance of water* *distribution and wastewater collection systems: US Environmental Protection Agency*, Office of Research and Development.

Ten Veldhuis, J. A. E., Clemens, F., and van Gelder, P. (2009). "Fault tree analysis for urban flooding." *Water Science & Technology*, 59(8), 1621-1629.

Walder, T. C. (2011). *Financing of the Dutch water systems* Netherlands Water Partnership.

WSA/FWR. (1993). *Materials selection manual for sewers, pumping mains and manholes* UK Water Industry Sewers and Water Mains Commitee.