COMPUTER AIDED REHABILITATION OF SEWER NETWORKS

RESEARCH AND TECHNOLOGICAL DEVELOPMENT PROJECT OF EUROPEAN COMMUNITY

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CARE – S

Computer Aided REhabilitation of Sewer networks.
Decision Support Tools for Sustainable Sewer Network Management

WP2 – Structural condition

Report D6

MODEL TESTING AND EVALUATION

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Trondheim, November 2005

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1 Introduction

The aim of CARE-S has been the development of an integrated suite of tools, which provides the most cost-efficient system for maintenance, repair and rehabilitation of sewer networks, with the aim to guarantee security of sanitary sewage collection and storm water drainage in order to meet social, health, economic and environmental requirements. The tools will enable engineers to establish and maintain an effective management of their sewer network.
The project is organised in the following Working Packages (WP):
WP 1: Construction of a control panel of performance indicators (PI) for rehabilitation
WP 2: Description and validation of structural condition
WP 3: Description and validation of hydraulic performance
WP 4: Rehabilitation technology information system
WP 5: Socio-economic consequences
WP 6: Multi-criteria decision support
WP 7: Wastewater network rehabilitation manager
WP 8: Testing and validation
WP 9: Result presentation and dissemination

Report D6 summarises task 2.4 in CARE-S which is dedicated to the testing, improvement and further development of all structural condition tools under work package 2. This work took place during the last year in the project, in parallel to the end-user testing (WP8). End-user reports on tool testing were collected and the findings transferred into tool further development. All end-user reports are already included in D25 (testing report). Those reports which identified bugs and suggested tool improvements are not again included in the report at hand.

Some of the testing has been also carried out by the tool developers themselves, for example in cases where insufficient data at end-user sites prevented a thorough testing. Those test reports are exclusively included in report D6.

2 Overview work package 2

All wastewater networks deteriorate over time, and this has extremely large economic consequences. This deterioration increases the probability of failures such as obstruction and collapse, which may lead to flooding, street and building damage, traffic disturbances, environmental impacts and inconveniences for users connected to this sewer. Partially collapsed sewers have reduced flow capacity, which may lead to flooding. In the worst case of collapse, large holes may result in loss of lives.

The structural condition of a pipe depends on material, construction practices, external load and wastewater characteristics. Previous research has shown that pipes lain within certain time periods have been structurally under-designed, and that construction practices within some time periods have not been appropriate, thus leading to particularly frequent failures.

The formation of hydrogen sulphide that occurs in some wastewater networks will lead to a microbiological deterioration and loss of strength for concrete sewers, and is a very important reason for rehabilitation actions. Other reasons are root intrusion and substantial in- and ex-filtration through fissures and leaky joints.

Structural analysis of sewers is normally based on results from CCTV inspection. In Europe there are several systems currently being used for the classification of individual data from such investigations. A standard European code for the description of sewer damages has been developed and recommended to the Member States. In general, the condition of sewers is classified according to its most severe damage or overall condition to determine the urgency of rehabilitation and calculate the cost of rehabilitation.

The Workpackage 2 of CARE-S supplies tools for assessing the current state of a sewer and tools for predicting its future state. Some tools allow a forecast of the year in which a sewer enters a critical class of condition, thus determining the next inspection date or rehabilitation measure.

The Workpackage 2 of CARE-S is constituted of the following tools:

- CCTVCON (page 5), a CCTV conversion program that allows conversion of data from national coding systems into the CEN coding system. The CEN coding system is chosen as the common coding system for tools relying on CCTV data.
- GompitZ (page 7), defines the relationship between the current state and the expected service time of sewer systems using CCTV classification input.
- Infiltration/Exfiltration model (page 11), allows the simulation of exfiltration of wastewater to the surrounding soil as well as infiltration of groundwater when the pipeline is below the groundwater level.
- Blockage model (page 14), helps the user to assess the probability of sewer blockages and root penetration.
- Load model (page 18) calculates stress values in rigid non-reinforced concrete pipes based on external loads and pipe characteristics.
- ExtCorr (page 22) is a model that calculates external corrosion of concrete pipes.
- WATS internal corrosion model (page 25), simulates hydrogen sulfide induced microbial corrosion of concrete sewers by means of a conceptual approach. All relevant processes in the sewer are addressed.
- Z internal corrosion model (page 31), estimates hydrogen sulfide induced microbial corrosion of concrete sewers by a risk assessment approach.

3 CCTVCON

General description

Structural analysis of sewers is normally based on results from CCTV inspection. In Europe there are several systems currently being used for the classification of individual data from such investigations. A standard European code for the description of sewer damages has been developed and recommended to the member States. In general, the condition of sewers is classified according to its most severe damage or overall condition to determine the urgency of rehabilitation and calculate the cost of rehabilitation.

CCTVCON concerns the visual inspection (e.g. CCTV, man entry, mirrors, photographic camera) classification systems, of which a number of types are in use.

Major systems/standards in use in Europe as well as worldwide are identified. Each system is shortly described and a general comparison made; e.g. in terms of a matrix, depicting the features contained (e.g. types of pipes and pipe materials, manholes and other structures, private connectors, rehabilitated pipes and manholes, and etceteras) and what basic approaches are applied. The extent of use is indicated. I.e. if a method is used nationwide then the country in question is specified, if it is a more broadly used model, the broader geographic use is indicated. The status of the method is indicated, i.e. if it is a national/international standard, a regionally widely accepted method, or local, somewhat accepted method.

Six major systems are identified based on use and applicability within Europe. These systems are – together with the EU system/standard (CEN standard) – included in the CARE-S prototype. The systems are thoroughly analyzed and compared to the EU standard. The comparison includes what types of damages are addressed, weighting of damages, other information regarding the sewer itself and the validity of the model to meet the needs of tools and models for predicting the probability of asset failure.

Selecting the classification system for the project

From the comparison of different classification systems and from other experiences of the project partners the EN 13508 standard was chosen as a common system for the future tasks in the project.

Application of a general standard has several advantages and disadvantages. The main advantage of using one common standard is in the field of application software development. The application programs can use data from any sources which keeps the rules of that standard.

The main problems emerging from using a general standard are as follows: There exists a large amount of CCTV inspection data stored by different coding systems. To be able to make use of this data, translation methods for data from such systems to the general standard is needed.

There is a problem in the field of recording new sewer defects. This is only partly important in the point of view of the project, because the models included in the project are using mainly already recorded data. But a solution should be given for the future recording too.

The application of the EN13508 standard gives solution to both problems.

The different national demands on using the EN13508 standards are satisfied via the own rules of the standard. These are in the EN13508 chapter 5.4 National Equivalent Systems and in ANNEX A National Equivalent Coding System. These rules define precisely how the national users of the CEN system can keep their traditional, familiar, national codes.

Scope of application

Converting files from national coding systems into the CEN coding system

Data requirements

The program recognizes the different input file formats. The current version (2.0.0.1) recognizes the German, UK, Australian, Danish, Norwegian and the CEN formats.
The translation rules (tables) are in an Access database.

Modification of the program

Every translation rule is in Access database. The database includes the national codes and CEN codes, their position in the files and some other tables like list of materials. So the most of the modifications can be done without programming, only by changing the contents of the tables in the in the database. For example adding new codes or changing the existing ones can be carried out by Access database editing without changing the program codes. Only in case of new complex rules or a complete new national code system should the program be rewritten.

4 GompitZ

The GompitZ models defines the relationship between the current state and the expected service time of sewer systems using CCTV classification input. The model is based on empirical and statistical analysis of asset data as well as physical functions to define future conditions states, taking state variables into account.

The GompitZ tool is based on a Non Homogeneous Markov Chain (NHMC) statistical approach, and its use to model the structural degradation process of sewer pipes. A NHMC parameterization is made by the Gompit analysis of CCTV inspection data. For this purpose, the degradation process is formalized as successive transitions between condition classes defined in compliance with the recently adopted European coding system EN13508-2. Gompit Analysis is a Probit Analysis like statistical method that uses the Gompertz distribution and allows taking covariates into account.

General description

Probabilistic modeling of infrastructure degradation using NHMC has been widely used in the last ten years in North America, especially for predicting the future condition of road pavement and bridges. Concerning the degradation modeling of flexible road pavement, (Curtis and Molnar, 1997) models the degradation process in the simple Markov Chain framework, whereas (Li et al., 1997) uses explicitly NHMC, with a Bayesian update technique to compute the transition probabilities. It is also worthwhile mentioning that lifetime data analysis using Weibull distribution has been proposed in France for pavement degradation modeling (Brillet, 1995), but outside the NHMC framework. In the case of periodically inspected infrastructure like bridges, (Madanat et al., 1995) and (DeStefano and Grivas, 1998) propose a NHMC model based on the analysis of condition state increment; the model is slightly more complex than the one presented here, and perhaps more realistic, but intractable in the case of very sparsely inspected infrastructure like sewer pipelines. A simpler model has been set up in the case of sewer pipelines, with only two condition states considered, namely good and bad (i.e. needing to be rehabilitated), the transition probability being computed by assuming that the residence time in the good state is Weibull distributed (Mailhot et al., 2000). All the methods cited in this section have been initially designed to enable the comparison of different rehabilitation scenarios.

The GompitZ statistical tool is based on a Generalized Linear Regression Model, derived from the classical Probit Regression Model using the Gompertz probability distribution (alternative to the Gaussian). The resulting model can be defined as a set of equations that enables the condition states probabilities to be calculated for any age of the pipeline, conditionally on the covariates values, and possibly on the state observed at a given age (previous inspection). The model parameters are:

- “alpha” parameters, as numerous as the number of condition classes - 1,
- “beta” parameters, one per covariate with status = 1 or 2, two per covariate with status = 3 (and obviously zero per covariate with status = 0); there is always at least one beta value estimated for the time variable.

The method used to calibrate the model is the maximization of the log-likelihood of the observations (i.e. the natural logarithm of the joined probability of the condition states of the inspected pipelines). The maximization is worked out using the Levenberg-Marquardt algorithm; the initial parameter vector is estimated by the Kaplan-Meyer method.

The role of the covariates consists in modulating the survival functions in each condition state, whereas the stratum label is used to define categories of pipelines, for each of which a separate calibration (i.e. parameters estimation) is carried out. If for instance the user chooses to consider the sole variables material and diameter, and to use their crossed levels to define strata, the resulting model has no covariates and the model predictions will be at the group level. A pure at group level analysis may also be obtained by considering no stratification and the sole variables material and diameter as covariates. If a stratification e.g. by material is chosen, and diameter, length and traffic are selected as covariates, the effect of the covariates are allowed to vary across materials; the predictions are in this case at the pipeline level, in the sense that it is unlikely that 2 different pipelines could have the same values for the stratification variable and the covariates.

Multi-State Deterioration Process: the Non Homogeneous Markov Chain approach

After having defined the pipeline as statistical analysis unit, an example of definition of the successive structural deterioration states is proposed in terms of the EN13508-2 coding system. The jumps between these states can then be viewed as a multi-state deterioration process, and formalized within the discrete time NHMC framework.

Defining The Pipeline as Analysis Unit

The CCTV-Inspection unit is a sewer pipeline comprised between two manholes that will be called pipeline in the sequel. A given pipeline can be characterized by a set of endogenous variables, i.e. material, diameter, segment length and mean depth, pipe unit length, type of effluent, etc., and environmental variables, i.e. roadway traffic, type of embedding soil, location under roadway or sidewalk, etc. These variables are considered as potential explanatory variables, accounting for the pipeline initial condition state and deterioration speed, and respectively gathered into the covariates vectors Z_0 and Z_1. Vectors Z_0 and Z_1 may also include transformed covariates, or combinations (linear or not) of covariates, possibly provided by a deterministic degradation model. Some covariates may belong to both vectors.

Defining the Structural Condition States

At any time of the service life of the pipeline, its structural condition can be classified into one of a finite number m of states, 0, 1, 2, . . . ,m-1, ordered to reflect the relative degrees of deterioration of the pipeline. As an illustration one could e.g. consider the following four deterioration states:

- 0 = perfectly good,
- 1 = presence of at most surface damage and/or cracks,
- 2 = presence of fractures,
- 3 = collapse.

A possible definition for the deteriorated states 1, 2 and 3 according to the EN13508-2 coding system could be as specified in Table 1.

Table 1 An example of definition of Condition Classes using EN13508-2 Defect coding

Condition Classes	Defect Codes
1	BABA (Surface cracks) or BABB (Thin fissure) or BAE (Missing mortar *) or BAF (Surface damage, BAFI excluded) or BAK (Defective lining)
2	BABC (Fracture with wall pieces still in place) or BACA (Break with wall pieces still in place) or BADA (Masonry units displaced *) or BAFI (Surface damage with missing wall)
3	BAAA (Vertical deformation **) or BACB (Break with displacement) or BACC (Complete loss of structural integrity) or BADB (Missing masonry units *) or BADC (Dropped invert *) or BADD (Complete loss of structural integrity *)

* masonry pipelines
** flexible materials excluded

A slightly more complicated condition state definition, also based upon the EN13508-2 codes and compliant with the 5 classes system of the Sewerage Rehabilitation Manual (WRc, 1994), is proposed within the Care-S framework, by the Water Research Center (WRc) based in Swindon, UK. Another different classification system is in use in German municipalities, and considers 6 condition classes. Moreover a continuous observation code enables to record the pipeline length concerned by a longitudinal defect that extends over more than 1 meter. It is then feasible to attribute a default length extension of 1 meter to any punctual defect, e.g. a circumferential fissure or break. The EN13508-2 coding system enables to split the total length L of the pipeline into partial lengths. For reasons of usage simplicity, neither the WRc nor the German systems propose this feature. The growing use of automated data processes by urban utilities managers will nevertheless make this refinement more and more tractable in the near future.

Defining the Stochastic Process

The deterioration process can be modeled as the stochastic process, i.e. the time elapsed since the installation of the pipeline. The deterioration process is considered as being driven by Gompertz survival probabilities. Figure 1 exemplifies Gompertz survival curves, which enable to calculate the condition state probability as the difference in the values of two successive curves.

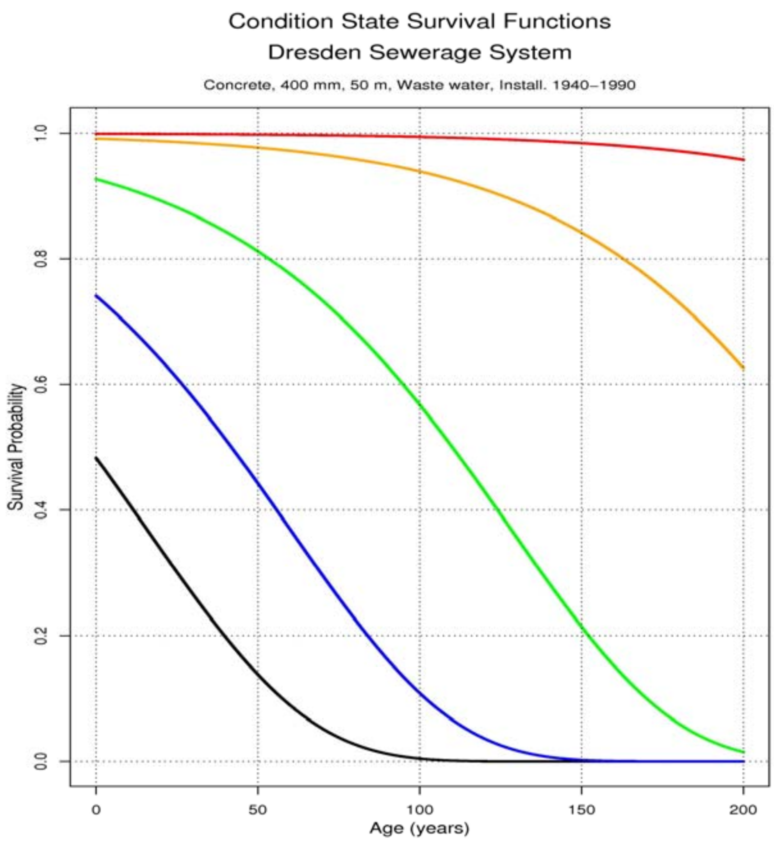

Figure 1: Example of Gompertz survival functions related to the 6 successive deterioration states as considered in the German standard – data from TUD

Forecasting the future condition of a pipeline

The method enables to forecast the state probabilities vector at any time in the future, provided the current state probabilities vector was assessed at time t by CCTV inspection. If the forecasting computation concerns a pipeline that has not yet been inspected, the initial state probabilities vector may be estimated by GompitZ.

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WRc, 1994. Sewerage Rehabilitation Manual (3rd ed.)

5 Infiltration/Exfiltration model

Background

Defects in the wastewater sewer fabric (at joints and on the pipe wall) allow exfiltration of wastewater to the surrounding soil as well as infiltration of groundwater when the pipeline is below the groundwater level. Both these consequences are undesirable as they hinder the overall efficiency of wastewater systems by contributing to pollution of groundwater and reducing the efficiency of treatment plants. The primary requirement for the management problem is a method of assessing the extent of infiltration/exfiltration. The Infiltration-Exfiltration Tool (IE Tool) is designed to serve this purpose. The IE Tool is a computer program that makes available to the CARE-S network rehabilitation procedure a system for the calculation of infiltration and exfiltration from wastewater gravity flow pipelines.

General description

The model is based on leakage through defects on different sections of the pipe wall and joints. Since the depth of flow in a sewer varies during the day, the exfiltration volume will be governed by the depth of wastewater and the position of the defects (Figure 2).

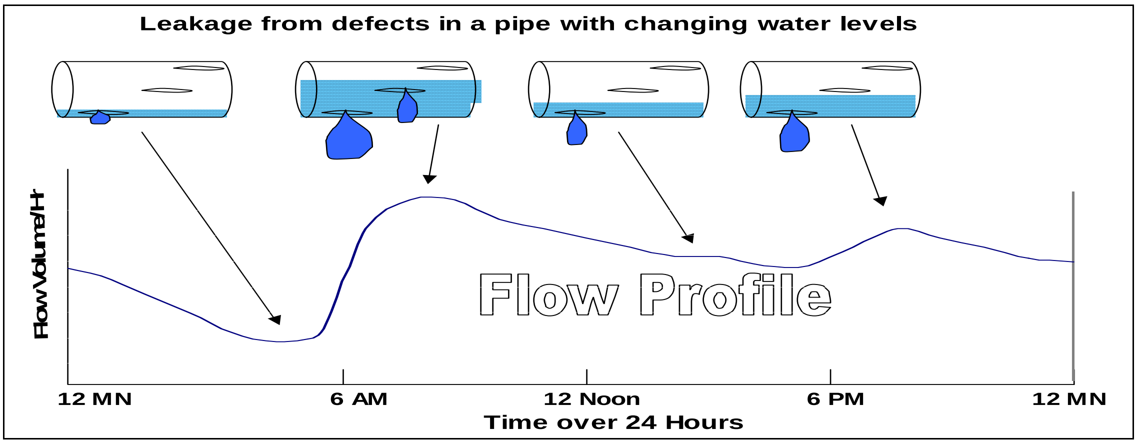


Figure 2 Changing levels of exfiltration with diurnal flow variation

The following assumptions were made for the development of the model:

(a) The wastewater flow within gravity sewer pipes follows a daily pattern described by a hydraulic model. The 24-hour flow is considered as the sum of hourly flows during the day.
(b) The wastewater flowing through pipes exfiltrates into the surrounding soil via cracks and joint defects in the pipe when the groundwater level is below the pipe invert
(c) The exfiltrating wastewater forms a colmation layer (at the pipe wall and in the soil immediately in contact with the pipe). The conductivity of the colmation layer controls the rate of exfiltration.
(d) When the pipe is below the groundwater level, the process is reversed and infiltration occurs through cracks and joint defects. The conductivity of the soil controls the rate of infiltration.
(e) The wastewater pipe system is assumed to comprise of vitreous-clay, concrete, PVC and PE pipes. Any other pipe materials within a system are assigned to the closest within this group. The pipes are assumed to be circular in cross section.

The IE Tool makes use of the pipe asset information in the common CARE-S database. The wastewater flow levels in the pipes at hourly intervals are provided by the hydraulic model in the CARE-S manager. Defects in pipes are based a on a generic defects table for vitreous-clay, concrete, PVC and PE pipes.

The IE Tool is published as an integrated facility within the CARE-S software package.

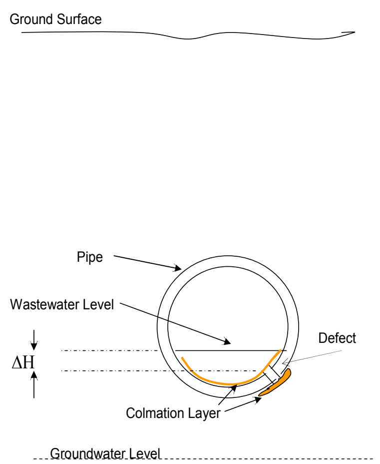
Scope of application

The extent of exfiltration of wastewater from the pipes and infiltration of groundwater into the pipes are viewed as performance indicators in the CARE-S project. The program estimates exfiltration and infiltration volumes for 24 hour periods. While the flow levels in the pipes can be adjusted for different weather patterns through the hydraulic model, the groundwater level is assumed to be at a steady state, and can be only be altered by changes to the asset information data. Rehabilitation and decisions can be made based on variations to levels of infiltration and exfiltration by simulating pipe renewal or replacement through changes to the asset information file.

The basis of the exfiltration and infiltration calculations are outlined in the following sections

Exfiltration

Exfiltration occurs when the defect in the pipe fabric (pipe wall or joint) is below the wastewater level inside the pipe. Whilst the height of the water above the defect determines the flow rate through the defect, the controlling factor is assumed to be the net thickness and conductivity of the colmation layer either side of the defect.



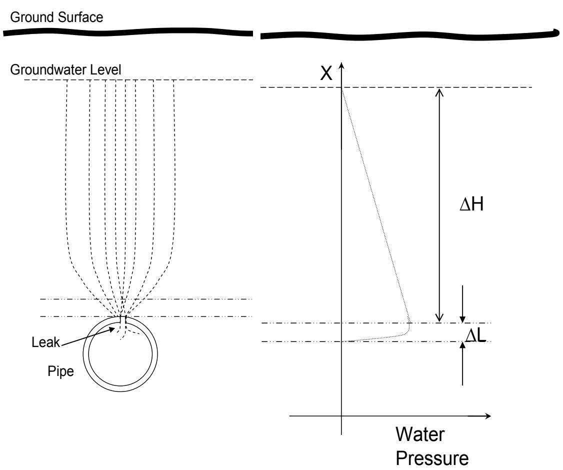
The IE Tool takes into account;
The changing wastewater level over a diurnal period
The wastewater pressure at the level of the defect
Thickness of the colmation layer
Conductivity of the colmation layer

The leakage at any given time is ;
$Q_{(\mathrm{Exfiltration})} = A_{leak} . \Delta H . (k_c / \Delta L)$ (m^3/s)
where,
A_{leak} = Defect area (m^2) (from the generic defects file)
ΔH = Height of water within pipe from defect (m) (calculated by the IE tool)
k_c = Conductivity of the colmation layer (m/s) (input parameter)
ΔL = Thickness of the colmation layer (m) (input parameter)

Infiltration

Infiltration occurs when the pipe is below groundwater level. Whilst the height of the groundwater above the pipe determines the flow rate through the defect, the controlling factor is assumed to be the conductivity of the band of soil directly outside the pipe defect.

For the infiltration model, the defects are assumed to be at the top of the pipe, and thickness of the controlling band of soil to be 100 mm.



Infiltration at any time is given by;

$Q_{(infiltration)} = A_{leak}.\ \Delta H_{GW}\ .\ (k_f / \Delta L\ ) = 10 * A_{leak}..\ \Delta H\ .\ k_f$

where,
A_{leak}. = Defect area (m^2) (from the generic defects file)
ΔH = Depth of pipe below groundwater level (m) (from asset database)
ΔL = Thickness of limiting soil layer (assumed to be 0.1 m)
k_f = Conductivity of soil (m/s) (from literature, input parameter))

Strengths

The asset data required by the IE Tool is very basic and is readily available from any network asset database. The depth of assets below groundwater level may not be readily available. However with a GIS incorporating groundwater levels, the relevant information could be extracted.

This gives the flexibility of applying the tool to almost any sewer network that has the basic information in a database.

Simulations for renewals and upgrades can be implemented through changes to material types or ages in the database. For instance replacement of concrete pipes of age greater than 54 years with HDPE pipe can be simulated by changing the material codes and installed year in the database.

Limitations

The generic defects file is based on limited CCTV data on sewer pipes in Melbourne, Australia and expert opinion. The degree to which generic defects represents states of deterioration in different countries needs to be tested and validated.

6 The Blockage model

General description

The Blockage Tool (BT) helps the user to assess the probability of sewer blockages and root penetration. The tool is a factorial-based model where the factors are identified by statistical analysis of historical blockage data, calibrated for each user, and is to be run on all pipes in the network as an automatic routine. Typical data available for pipes, and considered of relevance for blockage modeling, are:

- Pipe ID (for pipe identification)
- Material
- Wall thickness
- Diameter
- Length
- Construction year
- Pipe type (sewer, storm water or combined)
- Joint type
- Slope and saggings
- Pipe position in the network
- Soil conditions
- Proximity to trees (for root penetration)

The tool analyses a set of blockage data and network asset data, and calculates the factors used to determine blockage probability.

Scope of application

The blockage tool calculates a blockage probability factor for each individual pipe in the network.

These results can be used for several purposes, the three main ones being:

1. Rehabilitation planning, as input to the multi-criteria analysis in CARE-S
2. Making plans for CCTV pipe inspection
3. Risk analysis of flooding or pollution due to blockages

The tool can be operated as a stand-alone tool or through the Rehab Manager with import and export of data and results.

Data requirements

<u>Input</u>

The blockage tool requires three different input files:

1. the pipe segments file which contains data of all pipes which should be analyzed. If the tool is run throught the Rehab Manager, the Rehab Manager genereates this file, and the tool will only utilise information which is already present in the data base. If the tool is run as stand alone, the file must be created and edited manually.
2. the pipe blockages file, where two situations are possible:
    a. the user has historic blockage data, and the tool analyses this data

   b. the user has no blockage data, which means that the factors used for determining blockage probability must be manually entered instead of being calculated by the program.
3. the pipe segment classification file contains information on the classification of the pipe segment characteristics, in other words, it defines how the blockage tool shall analyse the data. A default file is stored in the rehab manager, but it can/should be edited by the user to include groups of pipe characteristics (based on available data) or define ranges. This makes the Blockage tool quite flexible, as the user can includeseveral different types of information in the analysis, primarily in „Blockage modus“ or „Root penetration modus“.

“Blockage modus”:

Data	**Unit**	**Kind of data**	**data collection**
Pipe Material		Pipe data base (basic information already present in Rehab manager)	- municipality
Size/Diameter	mm		
Age/Year of construction			
Pipe type		- modelling results (- measurements)	
Blockages	#	Date of blockage and pipe ID	- Municipality

“Roots penetration modus”:

Data	**Unit**	**Kind of data**	**data collection**
Pipe Material		Pipe data base (basic information already present in Rehab manager)	- municipality
Size/Diameter	mm		
Age/Year of construction			
Pipe type		- modelling results (- measurements)	
Pipe Depth	m	- manhole invert depth data	- municipality
Soil Type		- maps (printed or digital) - point measurements associated to areas by geometrical measures - printed maps can digitised by using GIS programs	- municipality, environmental agency, geological authorities - land surveying office
Blockages	#	Date of blockage and pipe ID	- Municipality

Output
The output from the tool is a factor which indicates the probability of blockage for each individual pipe that has been assessed.

Model verification, results and discussion

A tool for assessment of probability of sewer blockages was developed in the CARE-S project. This chapter describes in brief testing of the tool on the sewer network in Trondheim. Testing of the blockage tool was carried out for three reasons:

1. Checking the software for “bugs” and to check that the results were according to the selected procedure
2. Checking that the software works together with the CARE-S Rehab Manager

3. Verification of the selected procedure

The bug testing was carried out successfully and bugs were reported and fixed.

The table below shows a comparison of blockage factors for shorter time periods. E.g. the blockage factor for 2004 was compared to the average blockage factor for 1995-2003. Furthermore, the blockage factor for all pipes was compared to the blockage factor calculated only for the pipes with observed blockages.

Table 2: Blockage factors for various time periods

Period and pipe selection	Average (yearly) blockage factor
Blockage factor for all pipes, 1995-2004	0.00226
Blockage factor for all pipes, 1995-2003	0.00227
Blockage factor for all pipes, 2004	0.00235
Blockage factor for pipes with blockages, 1995-2004	0.00295
Blockage factor for pipes with blockages, 2004	0.00309

Table 2 shows that the average blockage factor for pipes with blockages (0.00295) is 30 % higher than the average blockage factor for the entire network 0.00226).

In order to see how the blockage tool could predict blockages, the average blockage factor for 1995-2003 (0.00227) was used as a “forecast” for 2004, where the real blockage factor was 0.00235.

A slight increase in both the calculated (approx. 4 % increase) and observed (approx. 5 % increase) blockage factors is also observed for 2004 compared to the preceding years. The real and the calculated increase is most likely a coincidence, as the average number of blockages was 50 blockages pr year, and there were 49 registered blockages in 2004.

The result shows that the blockage tool is able to point out pipes with higher risk of blockages to a certain degree using the factors pipe material, age, diameter, and type. There are several reasons why the accuracy is not higher:

- Literature study has shown that blockages occur to a large extent randomly (Hafskjold et al, 2004), with little chance of forecasting.
- The number of blockages in the case study is approx. 50 blockages pr year in more than 1000 km of pipe.
- Including more factors to describe blockage probability was not possible because the data didn’t exist. As studies from Australia have shown that root penetration is important for blockages, it is likely that the availability of this data would have improved the accuracy of the blockage probability calculation.

Trondheim municipality has a very comprehensive system for flushing and cleaning the sewer system, and pipes which are known to have repeated blockages are regularly flushed in order to avoid blockages. The low number of blockages pr year shows that this maintenance pays off.

Conclusion

The CARE-S blockage tool enables the user to analyze historic blockage records in order to find trends and calculate blockage probability on a single pipe level. The accuracy of the analysis depends on available data. The results can be used for:

1. Rehabilitation planning, as input to the multi-criteria analysis in CARE-S
2. Risk analysis of flooding or pollution due to blockages
3. Making plans for CCTV pipe inspection and prioritization of inspection candidates

References

Hafskjold et al: “Improved assessment of sewer pipe condition”, European Junior Scientist Workshop, March 2004

7 Load Model

General description

The Load_model is a computer program for gravity sewer pipes that calculates stress values in rigid, circular and non-reinforced concrete pipes based on external loads and pipe characteristics. The relation between load and resistance results in a security factor that is translated into reliability for structural failure. Nomenclature and calculation methods used in this model are based on the European standard CEN EN 1295-1.

The Load_model is published either as a stand-alone program or as an integrated facility within the CARE-S software package.

Scope of application

A pipe will structurally collapse when its resistance gets lower than the stress inducing external and internal loads. The resistance is based on pipe material, diameter and wall thickness. External loads that are considered in the model are soil, traffic, groundwater and additional static surface loads. Frost load is not included since its effect is very dependent on further factors. Internal loads are water volume and pressure gradients. Pressurized pipes are not considered and internal load from water volume can be neglected in this approach. The resulting stress is calculated in circumferential and longitudinal direction. It is additionally dependent on bedding conditions, side support and unsupported length caused by external soil erosion.

The pipe strength calculation will be based on the initial pipe strength at the time of installation. Combined with the loads, each pipe will have an initial risk factor for structural failure. The weakening factors over time are internal and external corrosion that will reduce wall thickness, weakening of pipe material caused by aging (leaching) and erosion of surrounding filling material that will increase the unsupported length. Two other models under CARE-S are calculating the external and internal corrosion of a pipe and are an essential input for the Load_model. Information from CCTV inspections can be used alternatively or additionally to those models. The reduced wall thickness will then result in a new risk factor for the prediction year chosen by the end user.

Strengths and limitations

The tool is designed to take into account the probable data availability at the end user site for sewer assets. The aim is to provide a tool that gives a qualified answer with a minimum of data demands, but the flexibility to model varying conditions.

This is reflected in the editable data for sewer bedding conditions. Construction methods and type and compaction of filling material have changed over the last decades. This will fundamentally influence the stress distribution in the pipe walls and therewith the resistance against structural failure. There is normally very little knowledge of those conditions for older sewers, especially with respect to unsupported lengths caused by soil erosion, which is quite common with leaking pipes. The following parameters are therefore designed to give rough answers to those bedding conditions without special knowledge on each pipe:

- *Unsupported pipe*: The end user can chose 'no' for newer pipes, unlikely to be exposed to soil erosion and a specific length in meter for the most likely unsupported length.
- *Compaction conditions*: A good compaction of filling material helps to lead vertical loads in the soil around a pipe through to friction and deflects therewith part of the load on the pipe. As a very rough rule, the tool asks for the year of construction where the practice of compaction has improved.
- *Bedding conditions*: Basically, the bedding conditions for a pipe can be distinguished into three types: a) The pipe is placed on a level foundation and supported along the bottom line only. b) The pipe is embedded in the foundation and the loads are deflected in a 45 degree angle. c) Additional to embedding, the pipe has a good side support through compaction. A good bedding condition and compaction of filling material will provide a sufficient support around the pipe and prevents an early deformation of the pipe.

Those parameters can be used to perform a sensitivity analysis for the structural strength of a pipe in case the construction conditions are unknown. The effect of trench width and the silo effect are not considered in the calculations due to expected uncertainty of that information.

The calculation of traffic load on a pipe is based on Boussinesq equations, meaning that the earth body above the pipe is regarded as homogenous, isotropic and fully elastic. The traffic is considered as a point load and based on an axle load of 260 kN. The dynamic characteristic of the traffic load is simplified reflected in various coefficients. More advanced calculations could be easily implemented, but would demand a data quality and quantity that does not justify the tool goals.

One of the most important input data is the external and internal corrosion and therewith the remaining wall thickness. Without this data the tool produces only uniform results for the original pipe strength. In case of a missing input, the Load_model provides the possibility to assign a constant corrosion speed in millimetre per year for external and internal corrosion.

Tool version 1.0.2 of the Load_model is aimed at demonstrating the basic functionality of calculation of the load bearing capacity. Some functionalities that will improve user friendliness and increase the flexibility of the tool are planned for the following versions. That includes basically the consideration of heavy traffic and conversion tables for missing values, e.g. wall thickness and construction year.

Degrading cement based pipes are the main problem for most existing sewer networks. The tool focuses therefore on rigid pipes. The extension of the load model with other materials like plastic pipes is reserved for a later version. Other degradation equations will have to be included for this purpose. Most problems with plastic pipes today are related to production and installation flaws.

Load bearing calculations are only applicable for circular pipes in this tool version. Additionally, only gravity sewers are considered since pressure pipes for pumping lines consist of other material. Internal pipe pressure is therefore not considered either. Internal water load can be neglected compared to the external loads. For future extensions of the model, the data input file is already prepared for the coming versions of the Load_model.

Data demand

An input file with the pipe data is needed. This file is a text file with these values:

***

PipeName=	<pipe identification>	any pipe identification
Shape=	<circular>	all pipes assumed to be circular
Width=	<pipe width [mm]>	assumed to be diameter
Height=	<pipe height [mm]>	not used
Year=	<installation year>	construction year, when the pipe is laid
Length=	<pipe length [m]>	pipe length, not used
WallThick=	<pipe wall thickness [mm]>	
Depth=	<pipe depth [m]>	
SDR=	<standard dimension ratio>	
PN=	<pressure class>	
Mat=	<pipe material>	all pipes assumed to be concrete
Soil=	<soil class>	valid values: non, med, high
GW=	<ground water level [m]>	positive value
Traf=	<yes or no>	'yes' means high traffic load, 'no' means no traffic
ExCor=	<external corrosion [mm]>	total corrosion depth from ExtCorr model
InCor=	<internal corrosion [mm]>	total corrosion depth from WATS model

Minimum input data requirements

For each pipe the following data is required:

- pipe identification
- diameter [mm] (is derived from shape, width and height. Width is equal to diameter)
- installation year
- wall thickness [mm]
- installation depth [m]

Additional data for version 1.0.2

- traffic load (external load from (heavy) traffic, can also be edited under calculating rules)
- external corrosion [mm] (can also be edited under calculating rules, but there more user friendly as mm/year)
- internal corrosion [mm] (can also be edited under calculating rules, but there more user friendly as mm/year)
- ground water level (equivalent to pipe installation depth, measured from surface)

In case missing wall thickness values, estimations can be done using SDR (standard dimension ratio). This has to be done manually in version 1.0.2, but is planned to implement at later versions.

Additional input data options

Further data that is not provided by an input file can be changed under 'calculating rules':

- Unsupported pipe length (sensitivity analysis for longitudinal stress failure)
- Compaction condition (Load deflection in filling material)
- Bedding condition (3 standard types of embedment)
- Filling material [kN/m^3] (specific weight)
- Traffic load table (if necessary, the default values can be changed, see mathematical description)
- Pipe design strength [MPa] (manufactures value from load test)

Additional input data have already been assigned default values. The suggested values will be reset again each time the program is started.

Output data

The safety factor (W) and probability of failure (P) given for the chosen prediction year is the output from the Load_model. From a previous version, the year of failure (Y) is included in the output file as a fourth parameter. This result has no meaning in this version of the Load_model and should be ignored. It is only kept as a parameter to ensure safe data transfer between Load_Model and Rehab Manager. The user has several possibilities to extract the results from the tool: saving to the database, exporting to an MS Excel File or listing in a tabular form.

Example of output file:

```
***
PipeName=7879
W= 2.798392
P= 0.1
Y= 0
```

8 ExtCorr

General description

ExtCorr is a computer program that empirically estimates external corrosion for concrete pipes, depending on their environmental conditions. A risk factor model with a linear external corrosion has been developed. The tool is kept very basic in order to avoid extensive data mining and sample taking. It gives an educated estimation of external corrosion quantities while keeping the data demand to a minimum at the same time.

The tool is published either as a stand-alone program or as an integrated facility within the CARE-S software package.

Scope of application

The functionality of ExtCorr has to be seen in the context of the calculation of structural condition in CARE-S, together with the internal corrosion models (WATS and Z-model) and the Load_model. The latter depends on the input of external and internal corrosion depth in order to calculate the security against structural collapse. WATS delivers the internal corrosion in millimetre per year with a detailed deterministic model. ExtCorr delivers the total external corrosion in millimetre with an empirical model. While ExtCorr gives a rough estimation of the magnitude of external corrosion, WATS is very detailed, including a hydraulic module. With a high input data demand, WATS will probably be applied for some chosen areas and transferred to the network. ExtCorr can be applied for all pipes in a network at once. The user chooses the scale of areas with similar soil aggressiveness.

Strengths and limitations

The tool is designed to give a rough estimation for the magnitude of external corrosion on sewer concrete pipes. The external conditions are hardly known to a degree where the modelling of a deterministic model can be justified. The chosen approach is therefore adequate to the expected data situation. A risk factor model with a linear external corrosion has therefore been developed for this approach. It can be applied to the sewer network without any information on the assets besides pipe ID and installation year. In this case it serves as a tool for sensitivity analysis.

Two input parameter that can be transferred from the CARE-S Manager are directed at the environmental conditions that can lead to external corrosion. One is on information about soil moisture and the other on information about soil aggressiveness. Soil moisture is obtained from installation depth and ground water level. This data will hardly be imported together with the asset database and can therefore be edited under the CARE-S Manager. For batch editing, the user can choose existing zones or draw polygons around areas with similar environmental conditions.

Additionally to soil and moisture conditions, the cement quality of the concrete pipe plays a role for the resistance against chemical corrosion. A low water-cement ratio will have a greater resistance. The cement quality has improved over time and the user has the possibility to choose three installation periods to reflect this.

The tool contains also a switch function for the installation year from when on good drainage material has been used as filling material instead of surrounding soil. Pipes under that condition are placed under non-corrosive soil type.

The ExtCorr model is in summary a very flexible tool with many adjusting possibilities. All parameters can be edited. The tool is well suited for a sensitivity analysis and should be applied by advanced users who understand quality and uncertainty of in- and output data.

Data demand

An extensive set of data is imported into the ExtCorr model from the CARE-S manager. This file is a text file with the following parameters:

***

PipeName=	<pipe identification>	any pipe identification
Shape=	<circular>	all pipes assumed to be circular
Width=	<pipe width [mm]>	diameter, currently not used
Height=	<pipe height [mm]>	for non-circular pipes, currently not used
Year=	<installation year>	construction year, when the pipe is laid
Length=	<pipe length [m]>	pipe length, currently not used
WallThick=	<pipe wall thickness [mm]>	currently not used
Depth=	<pipe depth [m]>	used for calculation of soil moisture
SDR=	<standard dimension ratio>	currently not used
PN=	<pressure class>	currently not used
Mat=	<pipe material>	all pipes assumed to be concrete
Soil=	<soil class>	valid values: non, med, high
GW=	<ground water level [m]>	meter below surface

Many parameters from the input file are currently not used and will not affect the tool and its results when they are empty. The excessive data fields origin from previous tool concepts or are included to increase the functionality of the tool in later versions.

The **minimum data demand** in version 1.0.2 is:

PipeName=	<pipe identification>	any pipe identification
Year=	<installation year>	construction year, when the pipe is laid
Depth=	<pipe depth [m]>	used for calculation of soil moisture
Soil=	<soil type>	valid values: non, med, high
GW=	<ground water level [m]>	meter below surface

In case of missing data for pipe depth, soil type and ground water level, the user is recommended to fill those data fields in the CARE-S Manager by batch editing under the GIS functionality. Alternatively, in case of missing soil type, the user can apply a switch function in the ExtCorr tool. He can edit a specific year from when on draining material is used as filling material. Before this year, the soil receives a medium corrosiveness and after that year it is non-corrosive.

Output data

The output from the ExtCorr model is the total external corrosion for a pipe in millimetre. The user has several possibilities to export the output data: saving to the CARE-S Manager database, exporting to an MS Excel File or listing in a tabular form.

Example of output file:

```
***
PipeName=1
ExCor= 0.24

***
PipeName=2
ExCor= 1.33

***
PipeName=3
ExCor= 2.06
```

9 WATS internal corrosion model

General description

Microbial and chemical processes related to human waste have always caused problems and nuisances. Spreading of diseases, odors and unaesthetic conditions have been key concerns leading to the installation of sewer networks. By conveying waterborne waste in channels or pipes, odor and health problems are reduced significantly. However, confining the human waste to underground structures does not prevent microbial and chemical transformations to take place; it only constricts the processes to locations where they cause less harm.

Sewer corrosion

One problem that originates from conveying wastewater in sewers is hydrogen sulfide induced corrosion. Internal corrosion of sewers is mainly caused by microbial oxidation of hydrogen sulfide, which is produced under anaerobic conditions. Other internal corrosion processes of practical importance are due to discharge of chemicals into sewers. Such stochastic events cannot be modeled deterministically, and are consequently not included in the WATS model.

Description of the internal sewer corrosion model

The WATS model is a two-phase model – including wastewater and sewer atmosphere – solving a number of coupled differential equations in the water phase and in the gas phase of sewers, including transport as well as transformations. It simulates microbial and chemical transformation processes of organic matter, oxygen, and sulfurous compounds according to Table 3.

Table 3. Processes simulated by the WATS model

Phase	Transport and transformation process
Above the water table	Gas flow along the sewer line. Oxidation of hydrogen sulfide on the moist surfaces of the sewer walls.
At the gas/water interface	Transport of oxygen from the sewer atmosphere into the bulk water. Transport of hydrogen sulfide from the bulk water into the sewer atmosphere.
Below the water table and in pressure mains	Water flow along the sewer line. Transformation processes of organic matter, oxygen, and sulfurous compounds in the bulk water, the sewer biofilms, and the sewer sediments.

The model needs exact geometric information on the sewer layout, similar to what is needed in a hydrodynamic model. The calculation times using a Pentium 4 computer for e.g. 20.000 m of pipe are in the range of 0.5-5 seconds, depending on the sewer configuration.

The model calculates corrosion of individual pipes that are connected by manholes/nodes. It is basically a hydraulic model (for both gas and water phases) to which wastewater quality transformations and exchange processes between phases are coupled. The input for the model is the physical geometry of the sewer (slope, diameter, and so on) as well as dry weather flow inputs.

A large number of experimental data from laboratory, pilot and field studies constitutes the backbone of the model. The model is calibrated and validated under field conditions, resulting in default values for model parameters and wastewater components.

Scope of application

The processes taking place in sewers during conveyance of wastewater are of physical, chemical and biological nature. Physical processes are associated with the build up and erosion of sewer sediments. Chemical and physico-chemical processes are mainly gas transfer across phase boundaries (reaeration and emission of hydrogen sulfide and VOC's) but also hydrogen sulfide becomes chemically oxidized. Biological processes are the transformations of wastewater compounds associated with growth and maintenance of biomass.

Transformations of wastewater in sewer networks are related to processes in the wastewater phase, the slime layer (biofilm) and the sewer sediments. These biological transformations change the quality of the wastewater important for sewer corrosion, odor problems, wastewater treatment and combined sewer overflows. The transformations going on in sewers are strongly interlinked, and the importance of a process cannot be predicted without knowing the importance of all the other processes. As an example, to the question if hydrogen sulfide will occur in a certain gravity sewer, it must first be determined if the conditions are anaerobic (absence of both oxygen and nitrate). To do so, the complete mass balance for oxygen must be established, i.e. reaeration and oxygen consumptions in bulk water and biofilm must be known. In order to predict reaeration, the sewer geometry, temperature and flow conditions must be known, and in order to know the oxygen consumptions in bulk water and biofilms, the quality (composition of the COD) of the wastewater must be defined.

The simulation of corrosion and of odor is related to anaerobic conditions (no oxygen and no nitrate is present). Such conditions allow the biological processes like sulfate reduction and fermentation to proceed, which are causing corrosion and odor. Often these problems are observed under the following conditions:

- **After transport in pressure mains:** When wastewater is transported in pressure mains, anaerobic conditions rapidly will develop as no reaeration takes place. Even at low temperatures, significant H_2S and odor will be produced at typical transport times and COD concentrations. Due to volatile substances (like H_2S) being stripped off the water phase, corrosion and odor problems occur downstream of the pressure main outlet, especially where high turbulence exists.
- **In gravity sewers:** Corrosion and odor are seen in some gravity sewer systems. Conditions that increase the risk of such problems are: High temperatures, low pH, low flow velocities, large water depths, large biofilm to bulk water ratio, high COD and BOD concentrations, sediment deposits, and stagnant wastewater in e.g. septic tanks. Furthermore, if such wastewater is subject to high turbulence, stripping of hydrogen sulfide and other odorous compounds take place, potentially resulting in corrosion and odor problems.

The prediction of the different integrated in-sewer processes calls for a simulation tool – a computer model. The WATS model (Wastewater Aerobic/anaerobic Transformations in Sewers) is a dynamic model taking all the important biological and chemical processes in sewers into account. The model can yield information on e.g. wastewater quality, hydrogen sulfide and corrosion rates for any combination of time, space and network configuration.

The WATS model

The WATS model is a deterministic in-sewer process model for simulation of organic matter and sulfur transformations. The model consists of a number of non-linear differential equations describing the transformation of a number of different wastewater compounds. A software version of the WATS model has been developed with the purpose of dynamic simulation of biological corrosion of branched sewer networks.

What does the WATS model simulate?
The WATS model is a deterministic model dealing with transformations taking place in gravity sewers as well as pressure mains.

- *Biological transformations of wastewater COD.* The organic matter (COD) undergoes changes during transport. How and to what extent these changes take place depends on a number of conditions related to the layout of the sewer and the composition of the incoming wastewater. Transformations under aerobic and anaerobic conditions are covered.
- *Biological and chemical transformations of sulfur compounds.* When conditions become septic – e.g. when wastewater is pumped or conveyed in gravity sewers with low reaeration – H_2S is formed. When the H_2S is subjected to oxygen, it will be oxidized biologically as well as chemically. Oxidation takes place in bulk water and biofilm, but also on moist surfaces above the water surface. When oxidized on moist surfaces of the sewer, sulfuric acid is the end product, corroding concrete and metal.
- *Gas transfer at the water/gas interface.* In gravity sewers, the turbulence of the flowing water causes a continuous supply of oxygen from the sewer atmosphere into the wastewater. If wastewater becomes septic or not is determined by the balance between the oxygen supply and the oxygen consumptions of the water phase, biofilm and sediments. H_2S becomes a problem when released to the sewer atmosphere, where it can cause corrosion of moist surfaces.
- *Simulation of transport and transformation in both the water phase and the gas phase.* Transformations in the water phase takes place in bulk water, biofilm and sewer sediments, while transformations in the gas phase only take place on the moist sewer surfaces. Bulk water and gas is transported with different transport velocities within the sewer. Furthermore, gas is lost by ventilation into the urban environment.

WATS focuses on dry weather problems and not wet weather problems. It deals with microbial and chemical transformation processes.

How does the WATS model simulate sewer processes?

WATS simulates microbial and chemical transformation processes of organic matter, oxygen, oxidized nitrogen compounds, and sulfurous compounds (Figure 3).

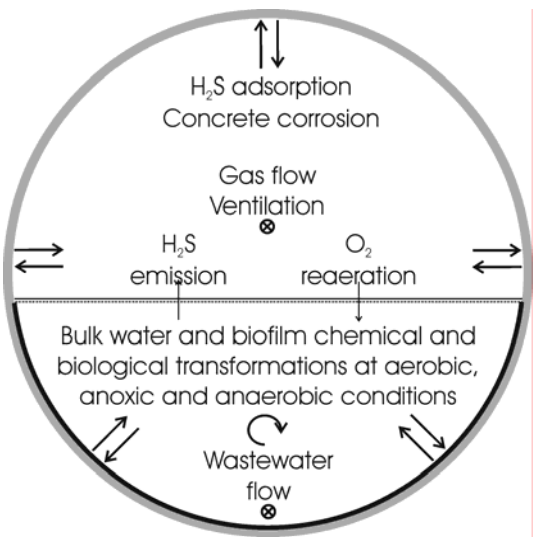


Figure 3: Microbial and chemical processes in a gravity sewer.

Aerobic conditions in the water phase
When oxygen is present, heterotrophic microorganisms cause the main part of the oxygen consumption. They oxidize organic matter (COD) to yield energy for growth and maintenance. At the same time, the organisms use the COD as constituents in the formation of new biomass. Most of the COD present in wastewater is not immediately suited as substrate for the biomass. The molecules are typically too large to pass the cell walls and must be broken down into smaller, more readily degradable compounds. This process is called hydrolysis, and hereby the main bulk of the wastewater COD can be made available for the biomass. There is, however, always a small fraction of COD that is inert and cannot be made available for the biomass. This fraction is included in the slow hydrolysable substrate fraction (Figure 4).

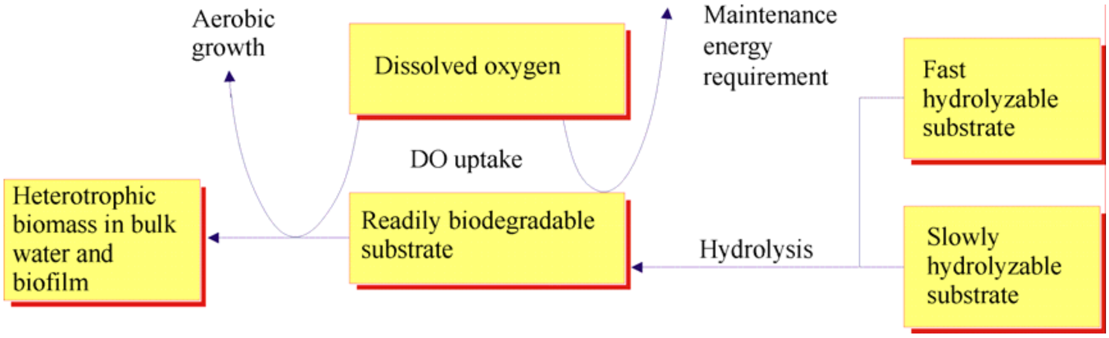


Figure 4. Aerobic transformation of organic matter

Hydrogen sulfide formed under anaerobic conditions becomes oxidized under aerobic conditions. The oxidation process is chemical as well as biological. Both process rates are significant under sewer conditions. The oxidation products are a mixture of oxidized sulfur forms, containing but sulfate and sulfur.

Anaerobic conditions
In the absence of both oxygen and nitrate, the previously mentioned heterotrophic organisms are no longer active. Instead other organisms take over. Some of these organisms ferment organic matter. Others reduce sulfate and oxidize COD. Another group of microorganisms produce methane from the COD. The first process – fermentation – gives rise to end products that are both desirable and undesirable. The end products have typically an unpleasant odor, however, they are excellent substrate for aerobic and anoxic treatment plant organisms. The second group – the sulfate reducing organisms – produce sulfide. Sulfides being related to a number of problems like odors, health hazards, toxicity towards microorganisms and corrosion.

Reaeration and hydrogen sulfide release
The two processes are strongly related, and can be described by the flow characteristics of the water phase. Both processes are relatively slow and consequently often limiting for the transformations in the sewer.

Corrosion
The hydrogen sulfide that is released into the gas phase of a sewer will be oxidized on the moist surfaces within the sewer. The end-product of this oxidation is sulfuric acid, which attacks both concrete and metals and causes corrosion.

Rooting of gas and water
The rooting of water is simulated as stationary flow without dispersion. The reason for not using the full Saint-Venant's equations is that the WATS model simulates dry weather conditions. Here flow variations occur slowly and backwater is seldom an issue. Conveyance of gas is also modeled as stationary flow.

Input data

For the WATS model as well as any other model, it must be kept in mind that *The Model Output will Never be Better than the Model Input*. If only limited data can be made available, experience and knowledge on wastewater composition depending on catchment characteristics must be applied as a substitute and the accuracy of the prediction of corrosion decreases correspondingly.

It is seldom – or more correctly: it is never – possible to determine all inputs and all process parameters for a given sewer. This is partly due to the amount of information needed being rather large, partly due to a large natural variability of wastewater quality and process parameters, and partly due to the fact that we often want to simulate future scenarios. The WATS model must consequently be seen as simulating an "average situation", depending on the chosen system characteristics.

The WATS model is a deterministic model. It has a level of complexity similar to the hydrodynamic models used for simulation of stormwater runoff. For the pipe hydraulics, WATS needs the same data as any hydrodynamic model. In addition hereto, WATS must receive input data on the quality of the wastewater.

Strengths

In-sewer processes are manifold and complexly interwoven. Numerous transformation processes take place in the compartments of a sewer, i.e. in the bulk water, biofilms, sediments and gas phase, and different transport processes interconnect the various compartments. The conceptual WATS model addresses these aspects and allows a conceptual simulation of in-sewer processes and concrete corrosion.

Limitations

The WATS model contains a very large number of model parameters, which call for expert knowledge in order to calibrate the model to a sewer system. This process is complex and calls for an expert user with detailed knowledge on in-sewer processes and on the WATS model. The WATS model consequently comes with pre-set parameter values and without the possibility of calibrating model parameters. Where a detailed analysis including a calibration of the WATS model is needed, the user must make use of experts on WATS and in-sewer processes.

How to obtain further information:

ASCE (American Society of Civil Engineers) (1989). Sulfide in wastewater collection and treatment systems. ASCE manuals and reports on engineering practice no. 69, p. 324.

ASCE (American Society of Civil Engineers) and WPCF (Water Pollution Control Federation) (1982). Gravity sanitary sewer design and construction. ASCE manuals and reports on engineering practice no. 60 or WPCF manual of practice no. FD-5, p. 275.

Hvitved-Jacobsen, T. (2002). Sewer Processes – microbial and chemical process engineering of sewer networks. CRC Press, pp. 237. ISBN 1-56676-926-4.

Melbourne and Metropolitan Board of Works (1989). Hydrogen sulfide control manual – septicity, corrosion and odour control in sewerage systems. Technological Standing Committee on Hydrogen Sulfide Corrosion in Sewer Networks, vols. 1 and 2.

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10 Z internal corrosion model

General description

The Z-model is developed for rough estimation of the risk of hydrogen sulfide related problems in sewer systems. It is valid for gravity sewers only.

Development of the Z-model

The gravity sewer assessment is based on a modification of the Z-formula, which is presented by Pomeroy (1970) and later applied by e.g. ASCE (1989), Melbourne and Metropolitan Board of Works (1989) and ASCE and WPCF (1982). The original formula is

$$Z = BOD_5 \frac{P/b}{s^{0.5}(35.314Q)^{0.33}} 1.07^{T-20}$$

where

BOD_5	biological oxygen demand during 5 days (gO_2 m^{-3})
P	wetted pipe-wall perimeter (m)
T	temperature (^oC)
s	slope (m m^{-1})
Q	flow (m^3 s^{-1})
b	pipe width at water surface (m)

According to recent studies on hydrogen sulfide generation (Hvitved-Jacobsen et al., 1998; 1999; Tanaka et al., 2000; Tanaka and Hvitved-Jacobsen, 2001), release (Yongsiri et al., 2003; 2004) and oxidation (Nielsen et al., 2003a; 2003b), it is deemed important also to include the biodegradability of the organic matter to a greater detail than what BOD_5 alone does, as well as including the pH into the equation.

Further information on the biodegradability of BOD can be obtained by the BOD/COD ratio. A high ratio means that the wastewater is relatively faster degradable and a low ratio means that it is relatively slower degradable. According to Henze et al. (2002) the average ratio between BOD and COD is 0.47. Values of 0.6 can be considered as high and 0.4 can be considered as low. The following equation consequently expresses the relative increase or decrease in the degradability of the BOD:

$$1 + \psi\left(\frac{BOD_5}{COD} - 0.47\right)$$

where a value for ψ of 10 is estimated reasonable.

The modified Z-formula hence becomes:

$$Z'' = Z'\left(1 + 10\left(\frac{BOD_5}{COD} - 0.47\right)\right)$$

The dependency on wastewater pH is related to the dissociation of H_2S. Hydrogen sulfide is a weak acid with a pKa value of around 7, i.e. at a pH of 7, 50% exists as H_2S and 50% exists as HS^-. Only H_2S can be released to the atmosphere, and the lower the pH, the higher the release rate consequently becomes. E.g. at a low pH (lower than 5-5.5), the release rate is twice as high as at pH 7. On the other hand, at a high pH (higher than 8.5-9), the release rates approaches zero, and sulfide corrosion in sewers decreases considerably. Furthermore, the oxidation of H_2S in bulk water and biofilm is also dependent on which sulfide species are present: HS^- is significantly faster oxidized compared to H_2S. This fact increases the importance of the pH dependency, namely the fact that hydrogen sulfide problems are much more pronounced at low pH compared to high pH (Hvitved-Jacobsen, 2002).

The dissociation of H_2S is described by:

$$\frac{[H_2S]}{[H_2S_{tot}]} = \frac{1}{1+10^{pH-pKa}}$$

Because a typical pH of wastewater is between 7 and 8, it must be assumed that the Z-formula originally was developed for a pH higher than 7, and a pH of 7.5 being a reasonable assumption for the average of pH values. Assuming that the original study was performed at an average pH of 7.5, the correction factor for the original Z-formula becomes:

$$\left(1+10^{7.5-7}\right)\frac{1}{1+10^{pH-pKa}} \cong 4\frac{1}{1+10^{pH-pKa}}$$

The modified Z-formula hence becomes:

$$Z''' = Z''4\frac{1}{1+10^{pH-pKa}}$$

Combining all modifications, biodegradability and pH, the Z-formula becomes:

$$Z' = 4\left(1+10\left(\frac{BOD_5}{COD}-0.47\right)\right)\frac{1}{1+10^{pH-7}}BOD_5\frac{P/b}{s^{0.5}\left(35.314Q\right)^{0.33}}1.07^{T-20}$$

Scope of application

The application is to be used on gravity sewers only, and gives an estimate of the risk of the occurrence of anaerobic conditions, and hence the formation of H_2S, which will cause corrosion.

According to Pomeroy (1970), Z-values can be interpreted according to:

Z-formula	Estimated magnitude of sulfide problem
Z<5,000	Low risk of sulfide problem
5,000<Z<10,000	Some risk of sulfide problem
Z>10,000	High risk of sulfide problem

In the modified Z-model provided by the Rehabilitation Manager, the user can set these intervals according to local condition and experiences. It is recommended to do so, as the Z-formula originally was calibrated on a specific sewer network, and the calibration hence not necessarily valid for all systems.

Data

When choosing the parameters for the Z-formula, sewer geometry, flow regime, BOD, COD, temperature and pH has significant impact on the outcome of the prediction.

BOD and COD values depend on catchment characteristics like infiltration, industries, transport time, transport conditions and etceteras. The Z-formula is highly dependent on these values and it is consequently necessary to obtain good data. Note that BOD and COD values are not the same all over a catchment, but varies depending on catchment characteristics. Especially knowledge on industries is important in this respect.

When choosing the temperature, the purpose of the simulation must be considered. Analyzing for extreme situations with respect to odor and the toxicity of hydrogen sulfide gas, the yearly maximum temperature is a relevant parameter. However, when the purpose of the simulation is prediction of corrosion risk, choosing the average temperature is the better approach.

pH has a very pronounced effect on the dissociation of hydrogen sulfide, and – as only molecular hydrogen sulfide can be released to the sewer atmosphere – pH also has a significant effect on the resulting odor and corrosion problems. A typical pH of wastewater is in the range of 7-8, but both lower and higher values are not uncommon. pH as low as 6.5 in water with low alkalinity is not unseen, as are pH values as high as 8.5 for waters with high alkalinity. To simulate a catchment, pH values should therefore be obtained.

Values for BOD, COD, temperature and pH are commonly available from routine measurements on the wastewater quality to the inlet of treatment plants. However, variations throughout the catchment should be identified and taken into account.

Strengths

The Z-model gives a quick risk estimate on the risk of anaerobic conditions in the sewer system, and hence the risk of H_2S induced corrosion as well as odor problems. It is easy to use and requires a limited amount of data.

Limitations

The Z-model basically predicts the risk of anaerobic conditions, however, not the duration of anaerobic conditions. As H_2S formation is a rather slow, biological process, the duration of the anaerobic conditions is crucial. When analyzing the output of the model, this should be kept in mind. E.g. if only a small part of the pipes in the catchment show high Z-values, this will NOT lead to corrosion, as the duration of the anaerobic condition is to short to allow H_2S to be formed. As a rule of thump, the duration of anaerobic conditions (i.e. the transport time in pipes with a high Z-value) should be above 1 hour before severe risk can be expected.

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11 Testing of the internal corrosion models

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The two internal corrosion models developed for CARE-S – the WATS model and the Z-model – were tested on an intercepting sewer to verify the applicability of the models. The testing comprised of an intensive measuring and monitoring campaign followed by model simulation of the obtained test results.

The test sewer

The internal corrosion models were tested on an intercepting sewer line between the towns of Storvorde and Klarup in the northern part of Denmark (Figure 5 and Figure 6). The sewer comprises of a pressure main followed by a gravity sewer (Figure 7). The wastewater was analyzed in the pumping station, the outlet of the pumping main, and in two manholes on the gravity sewer.

Figure 5 Air photo of the intercepting sewer. The town to the right is Storvorde, the town to the left is Klarup.

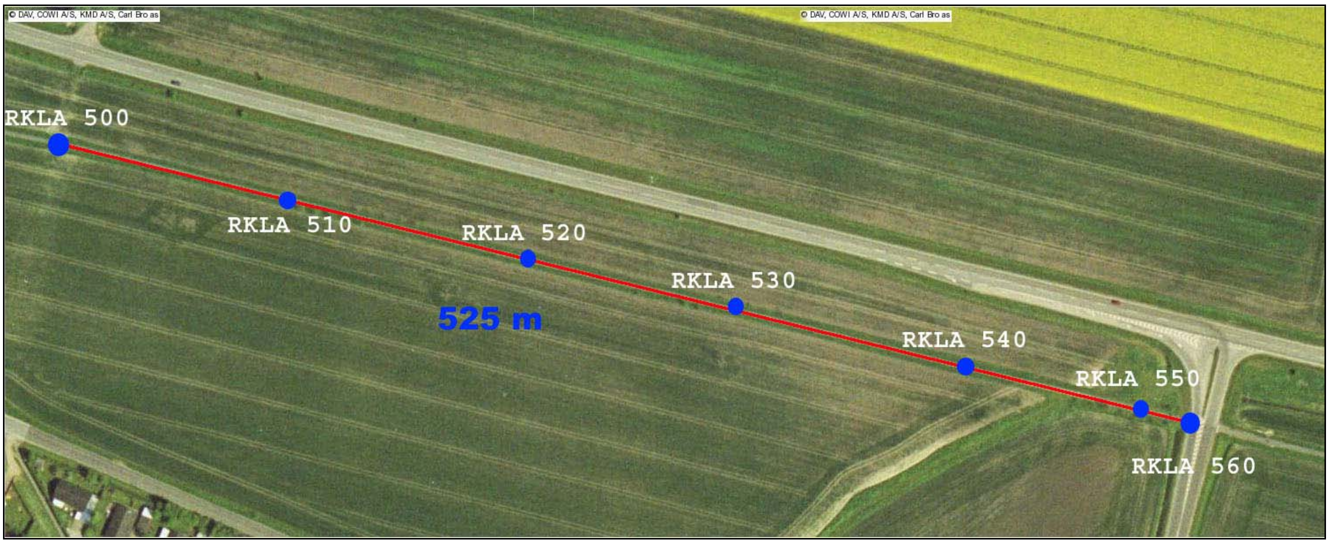

Figure 6 Air photo of the gravity part of the intercepting sewer. Manhole RKLA 550 refers to the pumping main outlet, RKLA 530 to Manhole A and RKLA 510 to Manhole B in Figure 7.

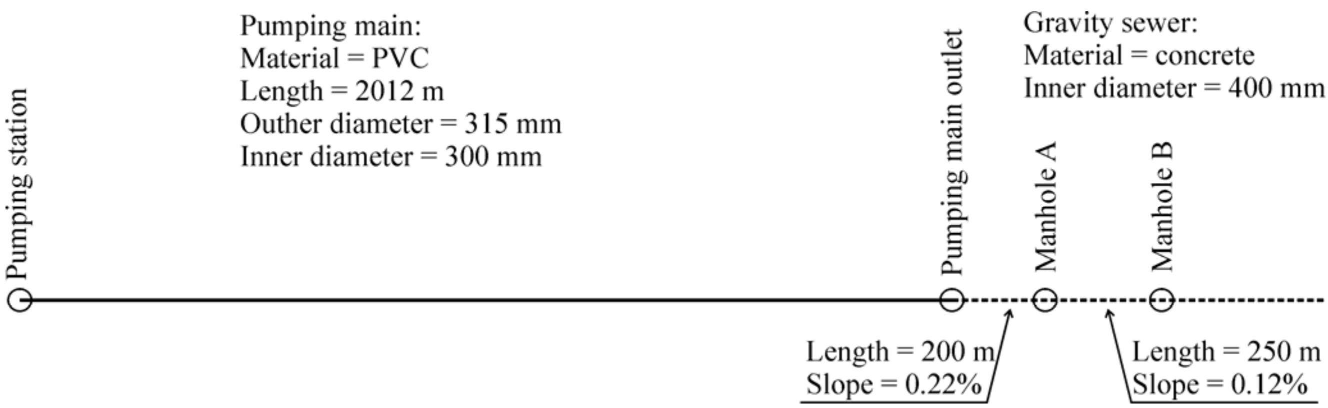

Figure 7 Pipe layout of the intercepting analyzed sewer

During 6 dry weather days in June and July, 1-2 hours were continuously monitored for hydrogen sulfide, oxygen and pH. On each day, two samples were furthermore taken to determine the biodegradability of the wastewater.

Wastewater quality determination

The wastewater intercepted in the sewer comprises mainly of domestic wastewater, however, one food processing industry (soft drinks) at times does affect the wastewater quality significantly, resulting in high concentrations of readily biodegradable substrates.

The wastewater was sampled by means of autosamplers in the Pumping station, the pumping main outlet and the Manhole A and B. Figure 8 shows one such sampler (ISCO) with 24 sampling bottles. At any time, 4 autosamplers were used in parallel to cover the 4 sampling locations.

Figure 8 Autosampler used to collect wastewater from the intercepting sewer.

The samples were analyzed for hydrogen sulfide using the Cline Methylene blue method (Cline and Richards, 1969).

In addition to the hydrogen sulfide measurements, samples were collected for determinations of the biodegradability of the wastewater by means of oxygen uptake rate determination (Vollertsen and Hvitved-Jacobsen, 1999; 2002). These samples were collected at the pumping station, as the presence of high concentrations of hydrogen sulfide interferes with this analysis.

Bulk water dissolved oxygen concentration and the pH of the wastewater were continuously measured in Manhole B.

Model verification, results and discussion

Wastewater quality

The biodegradability of the wastewater was measured on 12 grab samples. 2 grab samples were obtained each day and on the same days as hydrogen sulfide was monitored. The results (Table 4) show a high variability in the wastewater quality and shows furthermore that the wastewater quality varies significantly over rather short time intervals, i.e. shorter than the residence time of the wastewater in the pumping main.

Table 4 Biodegradability of the wastewater. The sum of the readily biodegradable substrate and the fast hydrolysable substrate equals the substrate that is readily available for the hydrogen sulfide forming biomass.

Sample date	Readily biodegradable substrate [gCOD/m^3]	Fast hydrolysable substrate [gCOD/m^3]	Heterotrophic biomass [gCOD/m^3]
22-jun	4	15	27
22-jun	7	49	20
23-jun	39	76	17
23-jun	41	207	13
24-jun	9	49	36
24-jun	22	71	46
28-jun	11	63	37
28-jun	25	51	35
30-jun	18	79	35
30-jun	9	74	41
04-jul	36	75	33
04-jul	48	121	28
Average	22	78	31

The pH varied between 8.9 and 7.4 over the measuring period (Figure 9). This is deemed a very large variation, and significantly more compared to what can be expected due to influences of domestic wastewaters alone. The variations therefore probably are caused by the only large industry in the catchment, the soft drink factory.

The pH values were obtained as average measures over 1-2 hours, during which the pH only varied little, typically less than 0.2.

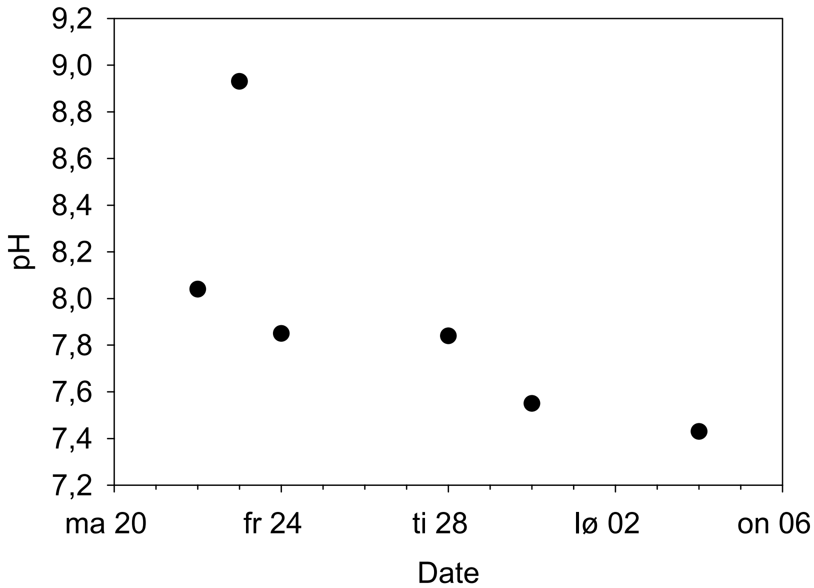

Figure 9 Variations in pH over the measuring period

Temperature

The temperature of the wastewater was obtained as average measures over 1-2 hours and is shown in Table 5.

Table 5 Temperature of the wastewater

June 22	June 23	June 24	June 28	June 30	July 4
13.7°C	13.8°C	13.6°C	13.8°C	13.9°C	14.5°C

Dissolved oxygen at Manhole B

The dissolved oxygen concentration was measured continuously over 1-2 hours in Manhole B on the 6 measuring days. The average results are shown in Table 6.

Table 6 Dissolved oxygen in the wastewater in Manhole B

June 22	June 23	June 24	June 28	June 30	July 4
0.80 g/m^3	0.50 g/m^3	0.30 g/m^3	0.29 g/m^3	0.58 g/m^3	0.76 g/m^3

Hydrogen sulfide measurements

The hydrogen sulfide in the bulk water was measured in the 4 location shown in Figure 7. For the pumping station, 12 samples were taken with 30 minutes intervals and for the 3 other locations, 24 samples were taken with 2 minutes intervals. The samples were obtained at different times, taking the traveling time of the wastewater into account. Hereby it was ensured that the same bulk of wastewater was analyzed and the data consequently were commensurable.

Figure 10 shows as an example the hydrogen sulfide measurements from June 30, 2005. It can readily be seen that hydrogen sulfide is formed in the pressure main and subsequently oxidized and stripped off in the gravity sewer. It is also evident that the hydrogen sulfide concentration varies over rather short time intervals, e.g. the hydrogen sulfide concentration in the pumping main outlet drops from 2.68 to 2.16 within 48 minutes.

Viewing the average values of each of the 6 measurement days (cf. Table 4 and Figure 10), Figure 11 is obtained. It is seen that hydrogen sulfide always becomes formed in the pressure main, and that it always is reduced in the gravity sewer. However, the amount of hydrogen sulfide that is formed is very variable, ranging from insignificant amounts of app. 0.4 gS/m^3 to quite high amounts of app. 5 gS/m^3.

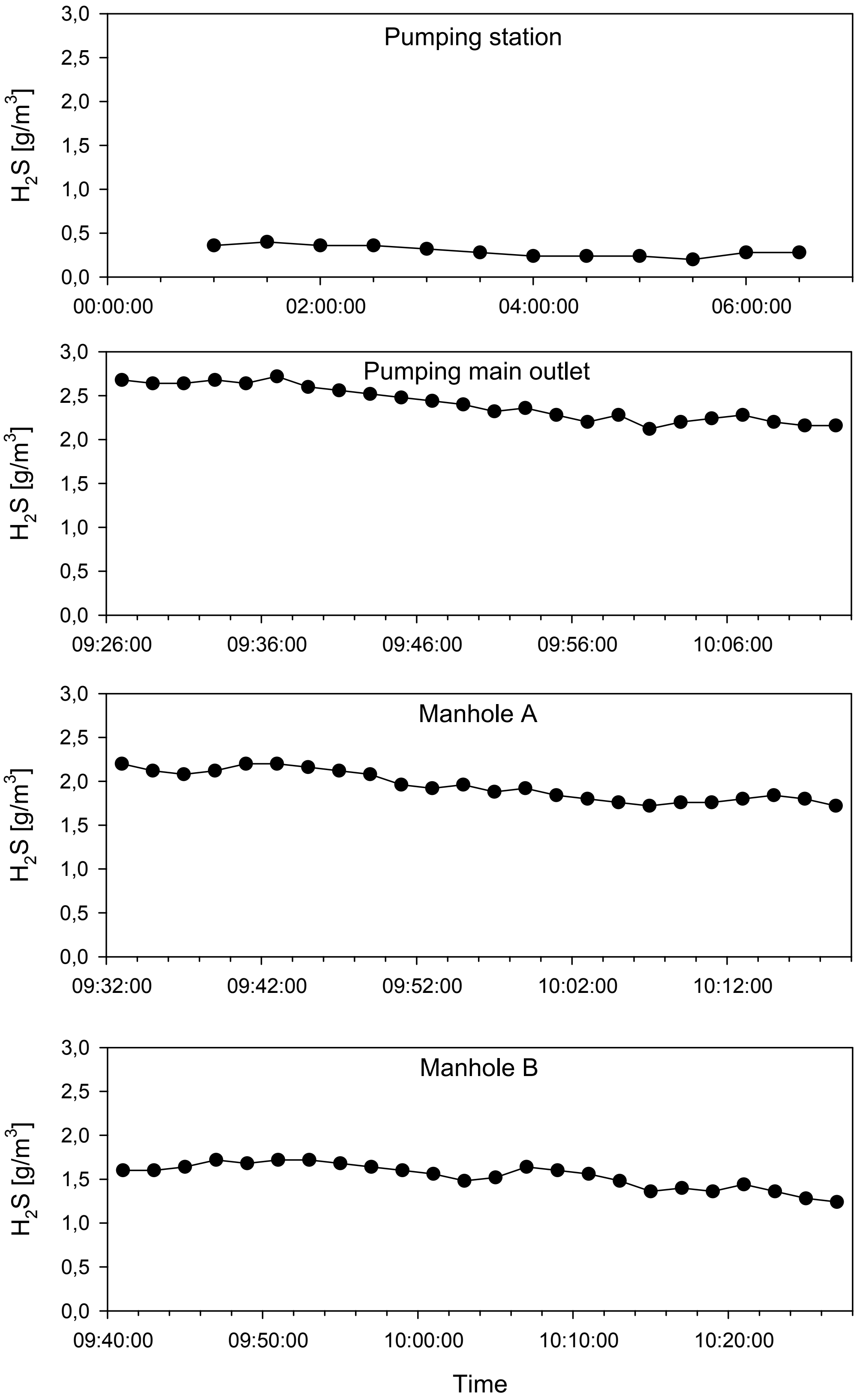

Figure 10 Measurement of hydrogen sulfide in the 4 measuring locations, variation with time. Note the different time scales.

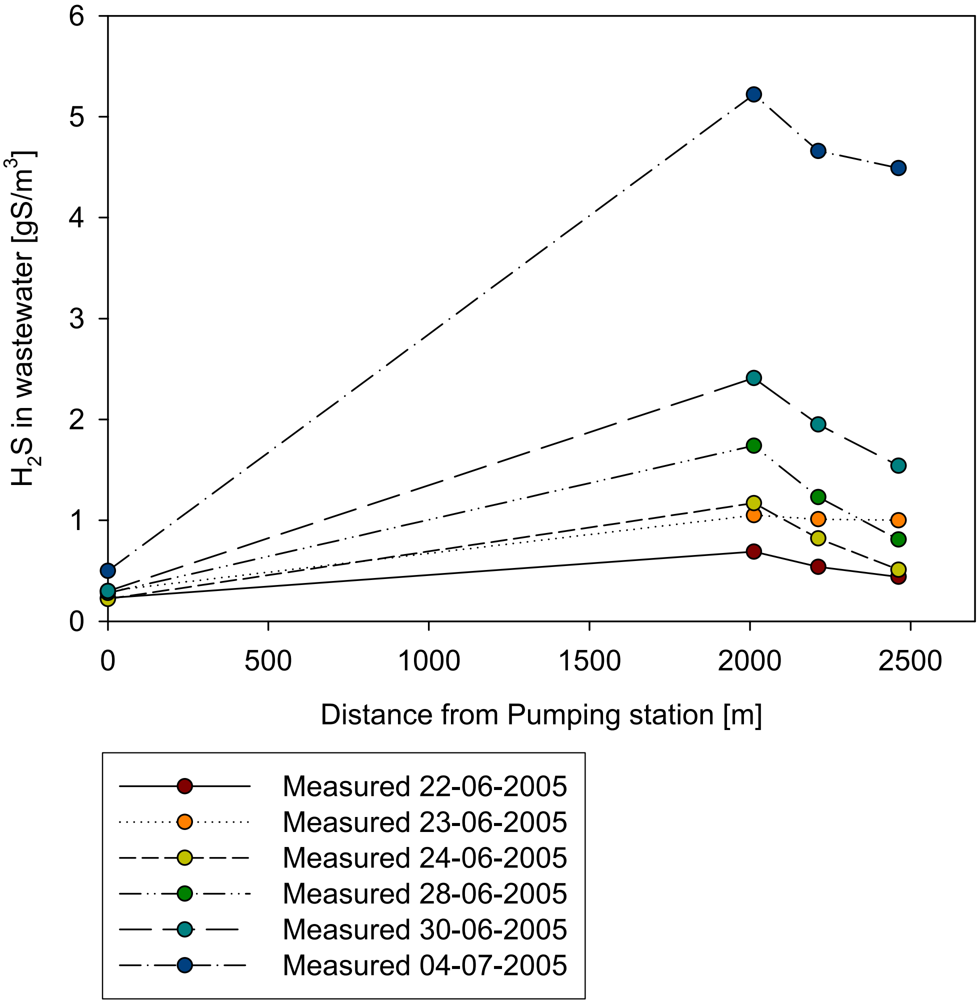

Figure 11 Average measurement of hydrogen sulfide in the 4 measuring locations (cf. Figure 10)

Validation of the WATS model

The high variation in produced hydrogen sulfide is caused by significant changes in wastewater degradability, cf. Table 4. The wastewater analyzed for biodegradability of the organic matter only approximately reflects the wastewater on which hydrogen sulfide was measured at the downstream measuring locations, as an exact timing of the taking of the samples could not be ensured. It is therefore chosen to simulate the hydrogen sulfide measurements with the highest, the lowest and the average of the measured biodegradability, cf. Table 4. The results hereof are shown in Figure 12.

It is seen that the WATS model is capable of satisfactorily simulating the observed formation of hydrogen sulfide in the pressure main and the subsequent reduction of hydrogen sulfide in the gravity sewer. The reduction of hydrogen sulfide is partly caused by oxidation of hydrogen sulfide in the bulk water and partly due to release of hydrogen sulfide into the sewer atmosphere. The part that becomes oxidized in the bulk water does not cause any harmful effects like odor or corrosion. However, the hydrogen sulfide released to the sewer atmosphere does cause harm in terms of corrosion, health problems and obnoxious odors.

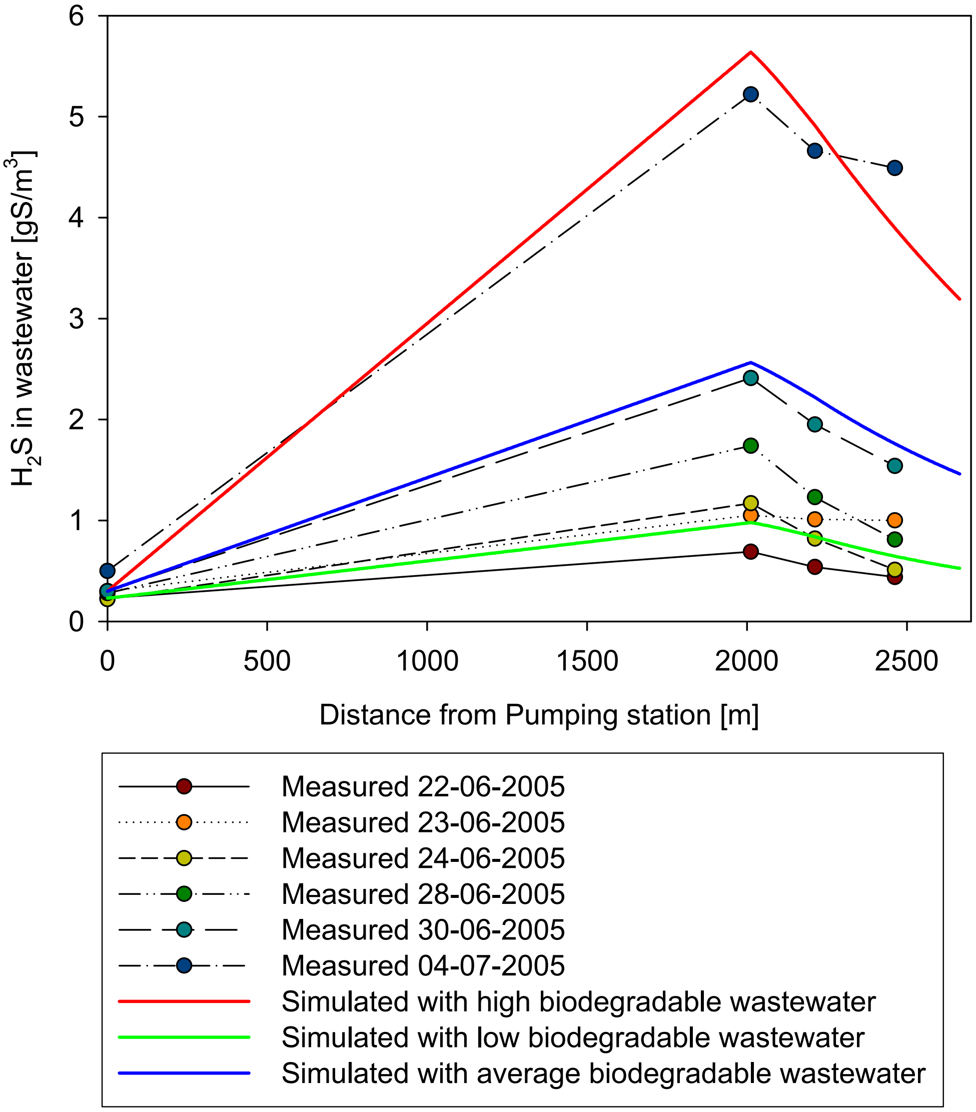

Figure 12 Measurement and simulation of hydrogen sulfide in the 4 measuring locations, all 6 measuring days.

The concrete corrosion rates corresponding to the simulated hydrogen sulfide concentrations are shown in Figure 13. It is seen that there is a significant corrosion in the concrete pipe downstream of the pumping main. The average corrosion during the early summer with temperatures around 14°C is between 0.5 and 1 mm/year in this part of the sewer. To verify this information, pictures were taken of the concrete pipe, which clearly shows that significant corrosion has taken place during the life time of the sewer (Figure 14).

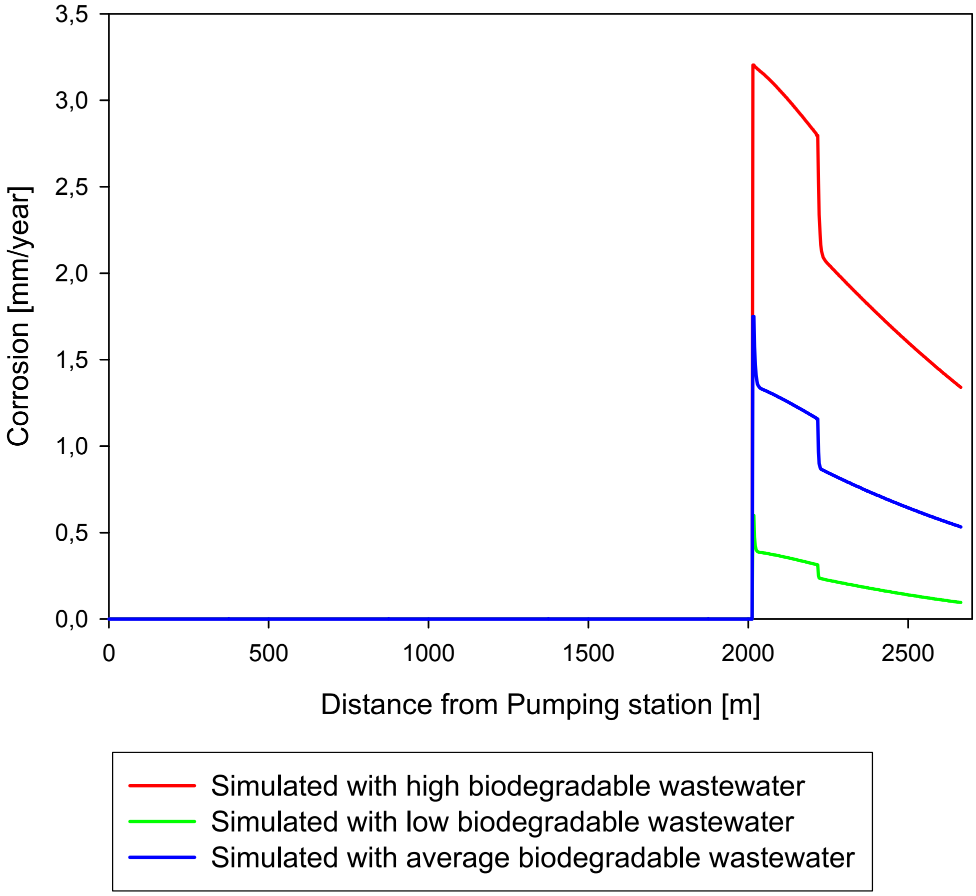

Figure 13 Simulation of corrosion rates

Figure 14 Observed corrosion in the concrete pipe

Validation of the Z-model

The Z-model is a model that predicts the risk of anaerobic conditions in gravity sewers and does as such not predict the actual formation rates of hydrogen sulfide or of corrosion. However, anaerobic conditions are what causes corrosion; this being the link between the Z-model risk prediction and the deterministic rate predictions of the WATS model.

In none of the measured cases the sewer became completely anaerobic. However, the dissolved oxygen concentration remained well below 1 gO_2/m^3 at 14°C (Table 6). This indicates that the risk of the sewer becoming anaerobic at somewhat higher temperatures definitely is present.

Applying the same wastewater compositions, temperature and pH as obtained in this study on the Z-model, the Z-values obtained are all below 7.500; indicating a marginal risk of the pipe becoming anaerobic and hydrogen sulfide related problems to occur (Table 7). However, rising the temperature to 20°C does increase the risk for the gravity sewer becoming anaerobic when highly biodegradable wastewater occurs at the same time. On the other hand, for the average situation, the risk at the higher temperature still remains low, and overall, no corrosion should be expected in case this gravity sewer had not been located downstream of a pressure main.

Table 7 Z-values and risk levels

	Pipe between Pumping main outlet and Manhole B		Pipe between Manhole A and Manhole B	
	14°C	20°C	14°C	20°C
High biodegradability	Risk=Low Z-value=5269	Risk=Medium Z-value=7908	Risk=Low Z-value=7360	Risk=High Z-value=11046
Average biodegradability	Risk=Very low Z-value=3513	Risk=Low Z-value=5272	Risk=Very low Z-value=4907	Risk=Low Z-value=7364
Low biodegradability	Risk=Very low Z-value=1259	Risk=Very low Z-value=1890	Risk=Very low Z-value=1759	Risk=Very low Z-value=2640

The calculated Z-values consequently confirm the observed redox conditions in the investigated gravity sewer, and the Z-model gives good estimations of the risk levels at different temperatures and for different wastewater compositions.

Conclusion

Both the WATS model and the Z-model were tested against detailed field measurements in an intercepting sewer. The WATS model yielded good agreement between filed observations and the simulated hydrogen sulfide concentrations as well as the simulated corrosion rates. The Z-model yielded good risk estimation of the gravity sewer becoming anaerobic and consequently risking formation of hydrogen sulfide.

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