Improved assessment of sewer pipe condition

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Keywords: *sewer rehabilitation, pipe condition, sewer blockage, CCTV inspection*

Introduction

Sewer and storm water systems in cities worldwide suffer from insufficient capacity, construction failures and pipe deterioration. The consequences are structural damage, local floods, backflow into basements, traffic disturbances, street and surface erosion, and pollution of ground water and local receiving waters.

At the same time, European cities spend in the order of 5 billion € per year for wastewater network rehabilitation. This amount will increase significantly over the coming decades, due to network ageing, the combined effects of ageing infrastructure, urbanisation and climate change. The enormous value of the wastewater infrastructure, and the increasing need for rehabilitation, indicates a need for a more comprehensive system for management of rehabilitation operations. This can be obtained using the results from advanced tools for assessing the state of the network. Hydraulic and structural aspects, options and costs of rehabilitation and maintenance, and socio-economic costs to society must all be considered and, in the end, the results combined in a multi-criterion decision support system which helps rank the rehabilitation candidates. The CARE-S software provides this functionality.

The first part of the paper gives a general overview of some of the objectives of and research in CARE-S, while the second part concentrates on an example of one of the models in CARE-S, which combines CCTV inspections and other data in order to model sewer blockages.

CARE-S

CARE-S (Computer Aided Rehabilitation of Sewer Networks) is a project currently being carried out under the 5th Framework Program for Research and Development of the European Commission. The project objective is to establish a rational framework for sewer network rehabilitation decision-making in a Decision Support System (DSS). CARE-S is one of 6 projects in the CityNet cluster dealing with urban water issues. It's an on-going project, which started 1 October 2002 and will last for three years. The project involves 14 European and 1 Australian partners, together with wastewater service providers from 20 cities (End Users) representing all parts of Europe. Figure 1 illustrates the work packages in CARE-S.

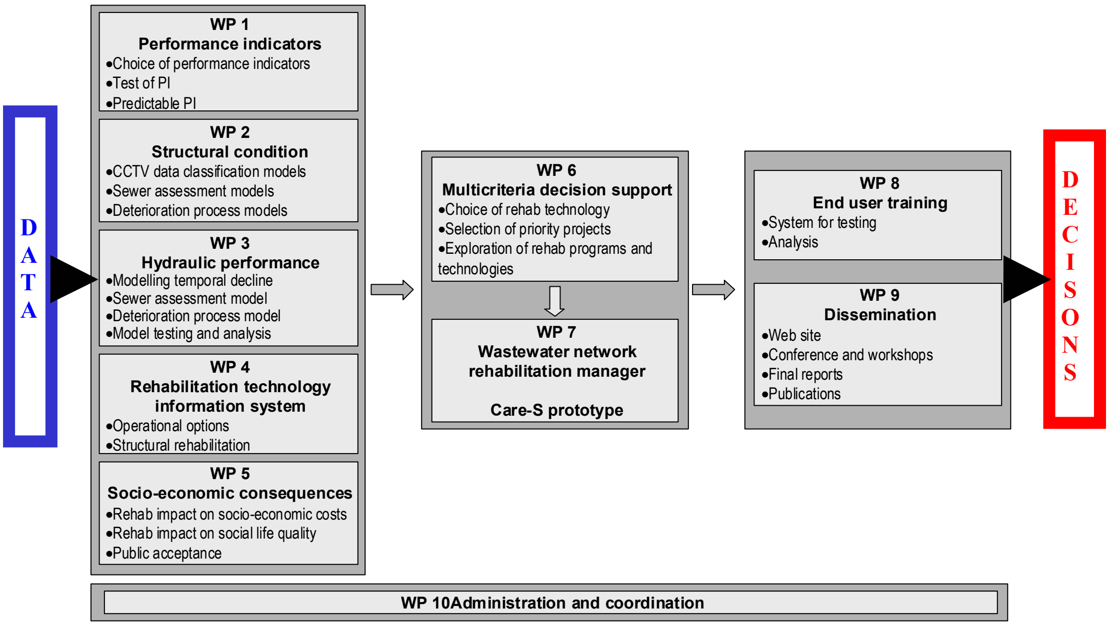

Fig.1: Work packages of the CARE-S project

Already, there exist some analytical tools to assess the technical or functional state of sewers or the needs for rehabilitation. These tools are available commercially or as scientific prototypes. The objectives of CARE-S are to improve some of the existing tools, and link them together with new tools that are developed in CARE-S, and combine the results in a multi-criteria procedure. The tools in CARE-S are:

- a tool generating Performance Indicators (PI) that are relevant for rehabilitation decisions,
- a procedure to define the socio-economic and environmental risks of malfunctioning sewer systems,
- a database to be used for choosing an appropriate rehabilitation technology or operational solution to the problems,
- a tool to define the best long-term strategy for rehabilitation investments,
- a number of tools that allow the hydraulic, environmental and structural condition of the network, including their change over time, to be assessed,
- a multi-criterion decision (MCD) tool supporting the choice of high priority rehab projects,
- a software ‘shell’, called the " Rehabilitation Manager" that will enable consultants and wastewater service providers to use the above products according to their individual needs and available data.

The ultimate product will be a software package that enables engineers to implement a *pro-active approach* to establish and maintain effective management of sewer networks. In other words:

Rehabilitate the right sewer at the right time by using the right rehabilitation technique at a minimum total cost, before serious failures occur.

WP 2: Structural condition
The structural condition of a pipe depends, among other factors, on age, material, construction practices, external load and wastewater characteristics. Pipes laid within a certain period of time are often structurally under-designed which, together with poor constructional practices, lead to frequent failures.

WP 2 deals with assessment of the structural and operational state of the pipes, basically on two levels:

- Level 1 uses statistical analysis on the whole network or a portion of the network to predict future failure rates. These are models that use CCTV and other inspection data or knowledge of the network to calibrate survival functions for different cohorts/groups and, based on this, estimate the future needs for renewal.
- Level 2 uses detailed information about single pipes to analyse the state of that particular pipe, calculating the risk of failure. The models are infiltration, exfiltration, blockages, internal and external corrosion, and structural capacity.

Speaking of failures, 4 structural and operational failure mechanisms are identified:

- infiltration failure, particularly because it is costly and may lower the ground water table
- exfiltration failure, because it pollutes the surroundings
- blockage failure, perhaps the most visible system defect for the customer
- structural failure, is the cause of infiltration and exfiltration and, to some extent, also blockages.

Some guidelines for failure level will be proposed, but this is generally authority specific. One level of infiltration may be acceptable for one End User, while it is a failure for another End User. These levels may also be set not only by engineers, but also by politicians, bureaucrats, jurisdictions, or other.

Systems for CCTV inspection

CCTV (Closed Circuit Television) inspection means visual pipe inspection via remotely controlled camera and is a common method used to gain information about pipe condition. Pipe inspection intervals, techniques and assessment systems vary a lot within Europe. Other inspection methods include visual pipe inspection by sending personnel into the pipe if the diameter is sufficient (>= 800mm), or inspection from a manhole using mirrors or a camera.

The data gained by pipe inspection gives information on the structural and operational state of a pipe. The aims of pipe inspection are diverse, and can be categorized in the following groups:

- Quality control of new pipe installations,
- monitor and document the state of (important) sewers,
- locate malfunctioning points of sewers and,
- inspection of pipes before rehabilitation.

Quality control of new installations and inspection before rehabilitation are the two main purposes of CCTV in Norway. Ideally, CCTV should be used as a strategic device for planning and prioritization of rehabilitation candidates. This is not yet the case for Norway and most other countries, a situation which is likely to change in the future with the application of tools like CARE-S.

The nature and causes of Sewer Blockages

There is currently no known generally accepted definition for sewer blockage, however for the purposes of this review a blockage will be defined as;

“When, due to some reduction in its cross-section, the capacity of the pipe to transport waste water is reduced so that waste water flow is reduced to a ‘significant degree’.”

In this paper, blockages (which may also be called "chokes"), are thought to be incidents that occur during dry weather conditions. The 'significant degree' in the above definition will then be when the sewer pipe is no longer able to transport the dry weather flow, and the sewage finds another way out of the system (backflow to surface, basement, storm water system, etc.). Furthermore, a blockage can be:

- Chronic – a partial obstruction which reduces hydraulic capacity and which can build up over a period of time – it rarely causes a total obstruction (e.g. sediments building up in a pipeline 'sag').
- Acute – a sudden, usually total, obstruction of the pipe (e.g. a structural collapse or an undesired, large object entering the sewer).
- Combinations of the two (e.g. when an undesired object in a pipe, partially blocked by sediments, causes a complete clogging).

Blockages can be caused by a number of mechanisms including:

- Root growth
- Build-up of sediment and accumulation of gross solids, due to local poor hydraulics
- Grease

These mechanisms are mainly the reasons for the chronic blockages. The acute blockages have mechanisms that are more diverse and difficult to explain, and also more random. This makes prediction of acute blockages very difficult or even impossible.

CARE-S WP2 will address blockages in several ways (ongoing):

- describe in a report the reasons and mechanisms that cause blockages
- develop a factorial-based risk model with risk factors identified by statistical analysis of historic blockage data (calibrated for each user)
- model some of the mechanisms in detail

A literature review has been undertaken which revealed that sewer blockages are not a 'hot' research topic, and no other attempts to model blockages have been found.

Results from analysis of historical blockage data from Trondheim
Trondheim has a comprehensive pipe database and GIS system. Various types of pipe data are stored, and "GIS operations" can be performed to analyze the data. The blockage data set studied consisted of 788 blockages in a total of 31514m of sewer pipe that occurred in Trondheim between 1990 and 2003.

For 262 blockages between 1999 and 2003, the observed causes were reported in special forms by the field personnel. 142 of these blockages with reports could be matched with blockages in the data set described in the previous paragraph.

In addition, personnel from the municipality of Trondheim were interviewed to find out more about the blockages.

Table 1 shows some statistics of the Trondheim sewer system, and the blockage rates for the three sewer types.

Table 1: Fundamental statistics for the Trondheim network

Sewer type	Total length (m)	Length of blocked pipes (m)	Number of blockages	Blockage/km/ year
Combined Pipes	333353	16073	371	0.086
Waste Water Pipes	304315	13331	379	0.096
Storm Water Pipes	368469	2111	38	0.0079
All pipes	**1006137**	**31515**	**788**	**0.060**

Some of the more detailed results obtained by studying the data set were:

1. The upstream end pipes in the network (in the branches where the network begins) are more likely to have blockages. The chance is almost 2 times higher than for other pipes.
2. The chance of having a blockage in pipes with a diameter of 225 mm or smaller is 3 times larger than for pipes with diameter larger than 225 mm.
3. Thin walled concrete pipes have twice as many blockages as thick walled concrete pipes.
4. Clay pipes (mainly laid before 1920) have almost twice as many blockages than other pipes.
5. Combining result 3 and 4, it seems that brittle thin-walled pipes are more likely to have blockages than other pipes.
6. No clear correlation was found between blockages and the age of pipes. Manufacturing and construction standards were found to be more important for blockages (e.g. point 3, thin-walled concrete pipes were manufactured in 1945-65).
7. Waste water pipes and combined pipes have the same blockage frequency. The frequency of blockages in storm water pipes is 10% of that of the other two groups.
8. In three areas where average pipe section slope was measured for pipes with blockages, the average slope for Kolstad was 2,9%, for Singsaker 2,4%, and for Nordberg (Oslo) 3,4%. Hence, the average slopes for these blocked pipes seem to be high enough to transport the sewage effectively, and average slope cannot explain the blockages.
9. The number of blockages that occur in manholes is approximately 20%. This is significant when the total "length" of the manholes is taken into consideration.
10. Approx. 20% of the blockages recurred, i.e. two or more blockages were registered on a manhole section (but not necessarily in the exact same spot), in the 13 year data period.
11. Pipes that are regularly cleaned (flushed) had no registered blockages after this maintenance action was introduced.
12. Some rough conclusions can be drawn from the limited data set of blockage registration forms (262 forms):
    - 75 % were due to unpredictable situations (large object in pipe) or they have no apparent reason and just happen randomly (unknown and other),
    - 10 % were due to construction (slope),
    - 20 % could be detected by CCTV and/or or avoided by better operational routines (sediments, grease, roots).
    - Clear and consistent reporting of causes of blockages is very important in order to research them, and the End Users should be encouraged to improve reporting routines. It's possible that some of the 75 % should have been distributed to the two other categories because of lack of sufficient reporting.

The results suggest that there are two main groups of reasons leading to sewer blockages:

1. *Initial design*, including type (Storm water / waste water / combined), diameter, material, surrounding soil and position; and
2. *The deteriorated state of the pipe,* including internal condition grade, or defect observations using CCTV (roots, sediments, sagging, grease, etc.).

An attempt was made to link CCTV inspections to sewer blockages, using a model from NORVAR (Association for Water and Wastewater Utilities in Norway), that classifies pipes from observed sewer defects. The correlation between CCTV observations and the occurrence of blockages was poor.

Research in the UK confirmed this result, as no strong relationship between structural damage and major service defects was found. The main conclusion of the UK study was that CCTV is not suited as a useful proactive maintenance tool for sewer blockages. Other results from Australia, suggest that the majority of sewer blockages are caused by roots. CCTV could be a useful tool to locate areas in a sewer with root problems (especially at an initial stage), and monitor root development for calibration of a root blockage model.

CARE-S WP2 blockage model - concept

The concept for the blockage model described in this section was developed with two main concerns:

1. What kind of output was needed from the blockage model to other work packages and parts of the CARE-S software, and
2. with focus on the End Users, and how they could find a blockage model useful.

Other parts of CARE-S assess failure probability for single pipes, and the desired outcome from the blockage model was from this side a failure probability factor, to be used as input for risk maps.

Our End Users were questioned about the blockage model. They were not very interested in modeling blockages in a forecasting manner, their main concern would be to get rid of the blockages as quickly as possible or rather avoiding them at all. However, a failure probability assessment for blockages (e.g. a risk map) would be of interest, together with increased general knowledge on the nature of blockages and mechanisms causing them (this last part will be taken care of in a paper report).

Based on this framework, it was decided to develop an empirical, factorial based, model, where the factors would have to be calibrated for each case/network. It was important to keep the model simple and transparent in order for users to have confidence in it (no "magic black box" was desired). It was also important to make it easy to calibrate, as climate variations, construction standards, and other parameters proved to vary a lot throughout the participating countries. The selected method also makes it possible to include more sophisticated sub-models for some mechanisms, like roots.

A blockage factor matrix was set up. An example of a part of this matrix is shown in table 2.

Table 2: Example of factor matrix for the blockage model (not calibrated)

Asset	Property	Criterion	Factor
Pipe	Type	Storm water	0.13
Pipe		Wastewater, combined	1.5
Pipe	Diameter	Ø<226 mm	4
Pipe		Ø>226 mm	0.8
Pipe	Material	Brittle and thin-walled pipes	2.5
Pipe		Other pipes	0.7
Pipe	Position	Upstream end pipe	2
Pipe		Upstream #2, 3&4 pipe	1.5
Pipe		Other pipes	0.7
Manhole	Bend	60-19 degrees	3
Manhole		30-60 degrees	2
Manhole		<30 degrees	0.5

The *Factor* is the blockage frequency of a criterion divided by the average blockage frequency for a particular *Property*, in other words:

$$Factor_{PROPERTY\ m,CRIT\ n} = \frac{Blockage\ Frequency_{CRIT\ n}}{Average\ blockage\ frequency_{PROPERTY\ m}}$$

In order to find the *Total Risk Factor* (*TRF*) for a particular pipe, all the individual factors are multiplied. If the *TRF* is equal to 1, the particular pipe has the same risk of sewer blockage as the overall network average risk. If the TRF is lower/higher than 1, the blockage risk is lower/higher than the overall network average risk.

Using the example in table 2 for an imaginary pipe, a combined sewer pipe, with a diameter 300 mm, material thin-walled clay, which is not an upstream end pipe, the *TRF* will be:

$$TRF = 1.5*0.8*2.5*0.7 = 2.1$$

With the average blockage rate in Trondheim (from Table 1) being 0.0602 blockages/ km/year, the calculated blockage rate for our imaginary pipe will be

Blockage rate = 0.060 blockages/ km/year*2.1 = 0.13 blockages/ km/year

The *Total Risk Factor* may also be used to estimate the risk of blockage for a pipe without predicting the blockage rate. An example of this is shown in table 3.

Table 3: Assessment of risk based on Total Risk Factor

***TRF* value**	**Risk**	**Risk class**
TRF < 1	Low (below average)	1
1 < *TRF* < 3	Medium	2
TRF > 3	High	3

The risk class may be subject to a calibration based on the *TRF* values for the network. A minor portion (<10%) of the pipes in the network should be classified in risk class 3.

Correlation of the properties will be subject to a statistical analysis (which will be carried out later). This is important to avoid including a blockage cause more than once when calculating the *TRF* (e.g. *pipe diameter* and *pipe position in the network* are closely correlated, and so are *pipe slope* and *flow velocity*). Ideally, only properties with no correlation should be selected. It is still desirable to include as many properties as possible in the model, as End Users may have access to different types of information (e.g. one End User may have access to *pipe slope*, while another may have a network model and hence access to *water velocity*).

In the end, some properties in the model will be grouped, enabling the User to select "either/or" (e.g. select either *pipe slope* or *water velocity*, but not both). The grouping of the properties will be a result of the statistical correlation analysis.

Links to other CityNet Projects

One outcome of CityNet is cross-collaboration between the participating projects. In the kick-off meeting in Paris in February 2003, "light contracts" were agreed between the projects where information could be exchanged to further the science. One of these contracts was between APUSS and CARE-S on the exchange of information about CCTV, and so far the result is that report D3, "Classification systems based on visual inspection", has been sent from CARE-S (SINTEF) to APUSS (TU Prague).

In the larger context of urban water management the assessment of the structural state of sewers is also an important issue for determining the volumes of clean water infiltrating the sewers (see CityNet project APUSS), sewage exfiltrating into the ground (APUSS, AISEWRS), structural condition of surfaces (DayWater) and the general wastewater balance (CD4WC).

Conclusions

CARE-S (Computer Aided Rehabilitation of Sewers and Storm Water Network) is a project currently being carried out under the 5th Framework Program for Research and Development of the European Commission. The project objective is to establish a rational framework for sewer network rehabilitation decision-making in a Decision Support System (DSS), resulting in a software package that helps engineers to implement a *pro-active approach* to sewer network rehabilitation and maintenance. In other words:

Rehabilitate the right sewer at the right time by using the right rehabilitation technique.

Several of the models in CARE-S depend on CCTV inspections as input data. In Norway, CCTV has not yet been used much as a pro-active tool for assessment of sewer network condition. Hopefully, projects like CARE-S will encourage End Users to collect better CCTV data and store the data for future use.

Sewer blockages seem to occur where the hydraulic conditions within the pipe mean that the flows are unable to suspend solids, or are unable to prevent the build up of solids on a defect. Issues such as pipe diameter, (local) gradient and flow regime are important for pipe blockages. The occurrence of blockages may be better understood by detailed analysis of the hydraulic conditions within sewers, including the transport of sediment and gross solids, and associating these with the structural defects.

An empirical, factorial based blockage model is under development in CARE-S WP2. The model consists of a blockage factor matrix, where the factors are selected based on different criteria for the pipe properties. Examples of properties are *Pipe Type*, *Diameter*, *Material*, *Position*, and presence of *Roots*. The outcome of the model will be Total Risk Factor, *TRF*, at pipe level.

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