

# Probabilistic modeling of sewer deterioration using inspection data

J. Dirksen and F. H. L. R. Clemens

## ABSTRACT

Accurate prediction of current and future conditions of sewer systems is crucial to manage the sewer system wisely, cost-effectively and efficiently. The application of historical databases of visual inspection data to sewer deterioration modeling seems common sense. However, in The Netherlands, sewer inspection data is only used to determine the direct need for rehabilitation. This paper outlines the possibilities of using inspection data for deterioration modeling and discusses the problems encountered. A case study was performed on the modeling of the condition aspect 'surface damage by corrosion or mechanical action' using a Markov model.

**Key words** | data quality, Markov model, sewer deterioration modeling, sewer inspection data

**J. Dirksen**  
**F. H. L. R. Clemens**  
Department of Sanitary Engineering,  
Faculty of Civil Engineering and Geosciences,  
Delft University of Technology,  
P.O. Box 5048,  
NL-2600 GA, Delft,  
The Netherlands  
E-mail: [j.dirksen@tudelft.nl](mailto:j.dirksen@tudelft.nl)

## INTRODUCTION

The total Dutch sewer system infrastructure is valued at approximately 47.5 billion Euros (Stichting RIONED 2005). Large-scale construction of sewer systems started in The Netherlands in the 1950's. From this moment on sewer rehabilitation has become an increasing field of expenditure and interest for the sewer manager. Nowadays, annual investments in The Netherlands in sewer system rehabilitation amount to approximately 1 billion Euros (Korving 2004). When installing a new sewer system the total life span is expected to be around 60 years, but the moment at which rehabilitation will actually become necessary is to a large extent unknown. Nevertheless, prediction of this moment is very important in order to manage the sewer system wisely, cost-effectively and cost-efficiently. Since the mid 1990s sewer inspections in The Netherlands have been a daily practice for most municipalities. Although a lot of money and effort is spent on inspecting sewer pipes, the inspection results are not optimally used in The Netherlands. Traditionally, inspection results are only used to determine whether a sewer pipe needs direct replacement. Recently, some software packages have become available which are capable to store, visualize and analyze the inspection results. Most packages have an additional tool

which can be applied to estimate future condition states based on historical inspection results. However, these tools are developed without any form of validation or calibration. Usage of these theoretical models may result in incorrect decisions and a cost-ineffective sewer management policy. In this paper the results of a study into sewer inspection data in order to investigate the application of inspection data for the development of a sewer deterioration model are presented. Data of one particular Dutch municipality was used to outline the possibilities.

## SEWER INSPECTIONS IN THE NETHERLANDS

In The Netherlands sewer inspections are performed by making photo- or video-footage of the inside of the pipe. The footage is evaluated by certified inspection personnel and assessed on condition aspects. Regulations determine on which aspects the inspected sewer pipe is judged. For this particular research only inspection data until 2004 has been used. After 2004 a new European sewer inspection regulation (NEN 3399 2004) has come into effect. Despite the fact that this new regulation shows great similarities

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with the ‘old’ Dutch sewer inspection regulation [NEN 3399 \(1992\)](#), combining the two datasets was not possible. Although inspections based on the two regulations are not alike, the results for the Dutch regulations are indicative for the application of inspection data based on European regulations for sewer inspections.

### Content of inspection files

As described in Dutch regulation [NEN 3399 \(1992\)](#) the condition of the sewer pipes is assessed on 18 different condition aspects using a discrete classification system. As can be seen in [Table 1](#), the aspects are ordered in 3 groups: leak tightness, stability and flow (gradient). The condition states as used in the table should be interpreted with:

- condition state 1: the aspect is not or hardly observed,
- condition state 5: the aspect is present in its maximum appearance.

**Table 1** | Condition rating system for The Netherlands

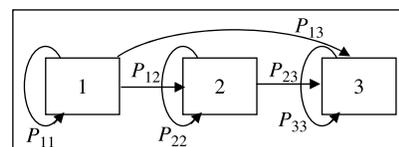
	Aspect	Condition states
Leak tightness	Infiltration of groundwater	1, 2, 3, 4 or 5
	Ingress of soil from surrounding ground	1, 2, 3, 4 or 5
	Longitudinal displacement	1, 2, 3, 4 or 5
	Radial displacement	1,2 or 5
	Angular displacement	1 or 5
	Intruding sealing ring	1, 3 or 5
	Intruding sealing material	1, 2, 3, 4 or 5
Stability	Damage	1 or 5
	Surface damage by corrosion or mechanical action	1, 2, 3, 4 or 5
	Fissure (cracks and fractures)	1, 2, 3, 4 or 5
	Deformation of cross sectional shape (only for flexible materials)	1, 2, 3, 4 or 5
Flow (gradient)	Intruding connection	1, 3 or 5
	Root intrusion	1, 2, 3, 4 or 5
	Fouling	1, 2, 3, 4 or 5
	Encrustation of grease or other deposits	1, 2, 3, 4 or 5
	Settled deposits (sand and waste)	1, 2, 3, 4 or 5
	Other obstacles	1, 2, 3, 4 or 5
	Water level	1, 2, 3, 4 or 5

When defining the condition states it was intended to define measurable boundaries (e.g. percentage of reduction of cross sectional area); some condition aspects are only specified for two or three condition states; the reason for this is that definition of more states was practically not possible. In the manual, pictures are presented of the various states as a guideline and illustration.

## LITERATURE STUDY ON DETERIORATION MODELS

### The Markov model

In literature the Markov model is commonly referred to as a ‘Markov chain’. This model describes a system by its states and possible transitions between these states. Using the Markov model the system can be schematized as in [Figure 1](#). The condition states are schematized as boxes, the possible transitions as arrows. The system states are defined by the states of the elements comprising the system; various states are possible such as functioning, derated, standby, completely failed and under maintenance ([Høyland & Rausand 1994](#)). The transition probabilities are defined as the probability that an element of the system will transfer from one state to another during one time step. Because these transition probabilities are assigned to one time step the model is discrete in time and a suitable time step has to be chosen. The transition probabilities depend only on the present state, not on the history of the element. This independence is called the Markovian property. From the literature it is known that Markov models for infrastructure deterioration are quite common; e.g. road bridges being a frequent candidate for analysis. [Madanat & Wan Ibrahim \(1995\)](#) determined the transition probabilities for concrete bridge decks using Poisson and negative binomial based regression techniques. Some deterioration models for sewer pipe networks have been developed. [Wirahadikusumah \*et al.\* \(2001\)](#) modeled the deterioration of combined sewer



**Figure 1** | Schematization of a Markov model.

pipes using a Markov model calibrated to an exponential regression curve. Baik *et al.* (2006) estimated the structural deterioration of sewer pipes managed by the City of San Diego's Metropolitan Wastewater Department by estimating the transition probabilities using an ordered probit model.

### The semi-Markov model

The difference between a Markov model and a semi-Markov model is that the latter allows time dependence by assuming that the time spent in each state is randomly distributed. Therefore the transition probabilities depend on the present state of the system as well as on the time already spent in the present state. Because these systems are time dependent the Markovian property does not hold anymore.

For the distribution of the total time spent in each state, different distribution functions can be applied. Possible distributions are: the exponential, Rayleigh, normal, log-normal, gamma, Weibull, Gumbel and Herz distributions. Models based on the Herz distribution are in the literature referred to as the cohort survival model. Baur & Herz (2002) applied the Herz distribution for models predicting sewer deterioration. Black *et al.* (2005) investigated the applicability of semi-Markov models to asset deterioration. The Weibull function was also applied by Kleiner (2001) to schedule inspection and renewal of large infrastructure assets.

## CASE STUDY IN THE NETHERLANDS

In order to indicate the possibilities of sewer deterioration modeling in The Netherlands using inspection data, the inspection database of one municipality is scrutinized.

### Data source

The data set used for the study was obtained from a municipality in The Netherlands. Inspection data from 1996 to 2005 were available. The total length of sewer pipelines in the municipality is approximately 95 km. Most sewer pipes (99%) were constructed after 1950 and thus have not yet reached their theoretical end of lifetime of 60 years. Nearly all sewer pipes are made of concrete (86%) of which the majority (83%) are constructed without using

reinforcement. Sixty-five percentage (62 km) of the total sewer length was inspected between 1996 and 2005. Seventeen kilometre sewer pipes were inspected more than once with an interval of 1 to 8 years. Because hardly any inspection results of PVC pipes were available only inspection results of concrete pipes are assessed.

### Selection of the aspects suitable for deterioration modeling

When developing a deterioration model, the only aspects that can be modeled are these that are time independent. Examples of time invariant processes are:

- the thoroughness of pipe cleaning before inspection (e.g. ingress of soil, deposits)
- natural processes (e.g. water level, obstacles)
- management (e.g. root removal)

Aspects that are only marginally influenced by the aforementioned processes and primarily relate to structural degradation are: infiltration of ground water, longitudinal displacement, radial displacement, angular displacement, damage, surface damage by corrosion or mechanical action, and fissure (cracks and fractures). Only these aspects are of interest for deterioration modeling and are discussed hereafter.

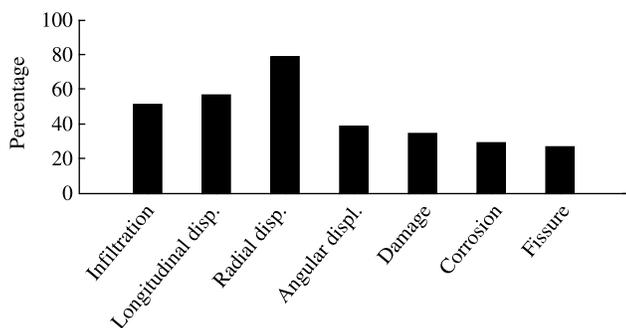
### Quality of the data

Although the inspection of sewer pipes and the applied classification system is regulated by norms, the information present in the inspection records should be handled with care:

- interpretation of the sewer inspection footage is subjective;
- the opinion of inspectors can be conditioned when inspecting the sewer in the same district for a large period of time (for instance, when encountering the same aspect over and over again the inspector could get 'used' to that aspect and could therefore classify the aspect lower than a colleague in a different district);
- aspects may not be visible on the footage.

Korving (2004) investigated the variation in interpretation of footage by comparing the (successful) examination

results of sewer inspection course students. Korving concluded that for 7 of the 18 aspects, the probability of a wrong classification is significant (probability  $>20\%$ ). These aspects are: infiltration of groundwater, radial displacement, intruding sealing material, surface damage by corrosion or mechanical action, fissure, settled deposits and water level. The results of Korving do not readily apply in everyday practice mainly because some aspects were hardly present in the exams, only inspection photos were analyzed and no videos, and the candidates were recently educated. For this reason, the quality of the data of the case study at hand was first examined. The quality of the data was assessed by comparing the inspection results of sewer pipes that were inspected more than once. The number of pipes for which a certain aspect was identified at the first inspection, but not at the second inspection, was used as an indication for the quality of the data. Because not all characteristics of sewer pipes are described in the sewer inspection files data from general information files were also used. From the general information files data were abstracted concerning date of construction and information about sewer pipe rehabilitation. The results of the study therefore do not only relate to the quality of sewer inspection data but also to the quality of the general information file. As can be seen in Figure 2 the percentage of pipes where an aspect is 'disappearing' is significant. Dirksen *et al.* (2007) applied the same analyses to 3 additional municipalities in The Netherlands. The results of this study are comparable to the case study at hand. Therefore it can be concluded that the quality of inspection data is of major concern in The Netherlands.



**Figure 2** | Percentage of pipes where an aspect was 'disappearing' between two subsequent inspections.

### Influence of explanatory variables

The influence of explanatory variables (e.g. type of material, slope, function, gradient, street category, wastewater type etc.) on the deterioration process was studied by first grouping the inspected pipes in age classes. Consequently, the distribution of pipe length or number of pipes over the possible condition states was determined.

As an example, in Figure 3, the results of this study for the aspects 'surface damage by corrosion or mechanical action' and 'fissure' can be found. Considering the aspect 'fissure' it can be seen that older pipes are not necessarily associated with a higher condition state. This lack of direct relation between age and classification was found for all aspects except the aspect 'surface damage by corrosion or mechanical action'. Analyzing the aspect 'surface damage by corrosion or mechanical action' in Figure 3 it can be seen that, in general, for this aspect older pipes are more deteriorated. Therefore it can be concluded that, for this case study, for the aspect 'surface damage by corrosion or mechanical action', explanatory variables probably have a minor influence on the deterioration process.

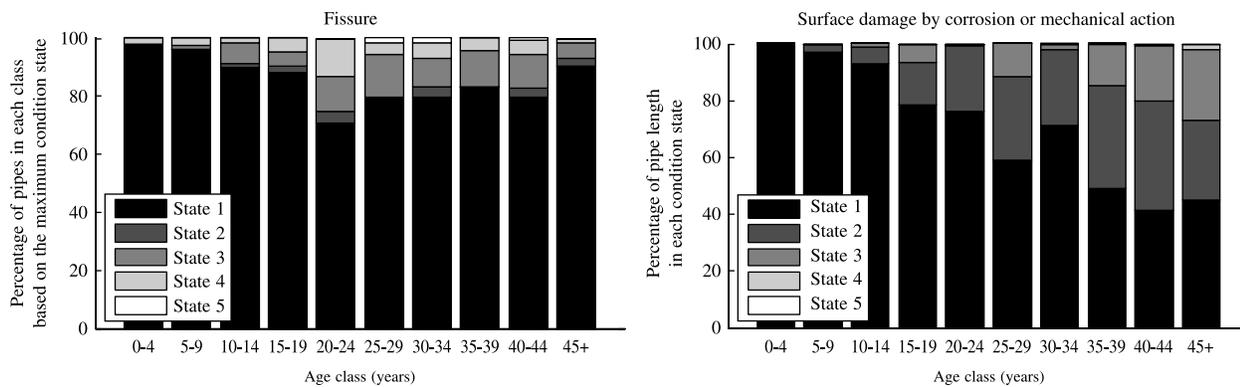
### Case study: deterioration modeling of 'surface damage by corrosion or mechanical action'

In order to show the possibilities of deterioration modeling using inspection data the aspect 'surface damage by corrosion or mechanical action' was selected to be modeled as a case study. This aspect was selected because:

- it relates solely to the structural condition of sewer pipes;
- the percentage of pipes where this aspect was improving between two subsequent inspections is relatively small and
- the influence of explanatory factors appears to be small.

The aspect 'surface damage by corrosion or mechanical action' is classified in 5 condition states, these states are described in Table 2 (NEN 3399 1992).

As can be seen in Figure 3, the condition states 4 and 5 are hardly present in the inspection database. Therefore the condition states 3, 4 and 5 will be combined into one condition state. It was further assumed that newly laid pipes are in condition state 1. This is a reasonable assumption because no second-hand pipes are used.



**Figure 3** | Graphs indicating a possible relation between age and (maximum) condition state for the aspects 'fissure' and 'surface damage by corrosion or mechanical action'.

### Schematization of the system

The Markov model was selected because of its simplicity. Using the Markov model the system can be schematized as in Figure 1, as can be seen, no improvement in condition state is modeled (e.g. from condition state 3 to condition state 1). The transition matrix containing the transition probabilities therefore is equal to:

$$P = \begin{bmatrix} P_{11} & P_{12} & P_{13} \\ 0 & P_{22} & P_{23} \\ 0 & 0 & P_{33} \end{bmatrix} \quad \begin{array}{l} 0 \leq P_{ij} \leq 1, \quad 0 \leq i, j \leq r \\ \sum_{j=0}^r P_{ij} = 1, \quad i = 0, 1, 2, \dots, r \end{array}$$

where  $r$  is equal to the total number of condition states.

A time step of one year is chosen because only annual data has been used. When choosing such a small time step, one has to be careful that the model outcome should not be interpreted as very accurate from one year to another.

**Table 2** | Classification of aspect 'surface damage by corrosion or mechanical action'

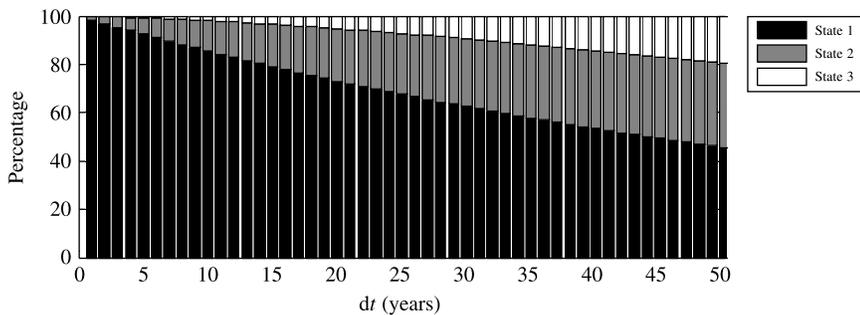
State	Description
1	Aggregate not visible
2	Aggregate visible
3	Aggregate projecting from the surface, reinforcement possibly visible
4	Missing aggregate, reinforcement possibly projecting from the surface
5	Missing wall, reinforcement possible corroded

### Data description

In order to calibrate the model, the total pipe length that transfers from condition state 1 (condition state at the installation of the pipe) to another condition state, in a time period equal to the age of the pipe, was determined. In addition, the double inspected sewer pipes were used to determine the total pipe length that transfers from one condition state to another in the time period between the two inspections. These datasets will be referred to as 'the observations'.

### Calibration procedure

The transition probabilities in the transition matrix are determined by using a likelihood function. This function is a measure for the likeliness of the occurrence of the observations given that the transition probabilities are valid. When maximizing the likelihood function by changing the transition probabilities, the most likely transition matrix can be found. The likelihood function of this system is equal to the product of the probabilities of all observations. The probability of one observation can be calculated using the Chapman-Kolmogorov equations (Ross 1997). By using these equations the probability of transferring from condition state  $i$  to  $j$  in  $t$  time steps is equal to the  $ij^{\text{th}}$  element of  $P^t$ . Because the probability of one observation is relatively small ( $0 \leq P_{ij} \leq 1$ ) the product of all observations approaches 0 which is difficult to maximize. In order to overcome this problem the natural logarithm of the transition probability is calculated. Because the product of



**Figure 4** | Distribution of pipe length over the different condition states, when a pipe is rated classification 1 at  $t = 0$ , by using the calibrated Markov model.

the original values is equal to the sum of the logarithms, the calculated values are summarized. The likelihood for this system is equal to:

$$L = \sum_{t=1}^s \sum_{j=1}^r \sum_{i=1}^r (\log(P_{ij}^t) \cdot N_{ij,t}), \quad 0 \leq i, \quad j \leq r, \quad s \geq 0$$

where  $r$  is the total of condition states and  $s$  the maximum time step between two inspections.  $N_{ij,t}$  is equal to the total length of sewer pipes transferring from condition state  $i$  to state  $j$  in time step  $t$ .

### Calibration result

It was found that given the inspection data the following transition matrix is most likely.

$$P = \begin{bmatrix} 0.98 & 0.02 & 0 \\ 0 & 0.99 & 0.01 \\ 0 & 0 & 1 \end{bmatrix}$$

This matrix can be used to determine the distribution over the different condition states after multiple time steps when a sewer pipe is assessed at classification 1 at  $t = 0$ . The result can be seen in [Figure 4](#).

### CONCLUSIONS

This paper presents the results of an initial study into the application of Dutch inspection data for the development of a sewer deterioration model. A literature study was performed on deterioration models. It was found that

numerous models are developed for deterioration modeling. The Markov model and the semi-Markov model reflect the non-continuous system as used for sewer inspection in The Netherlands. Sewer inspections of one particular Dutch municipality are assessed on suitability for sewer deterioration modeling. It was found that the quality of the inspection data is one of the major concerns. To show the possibilities, a case study was performed on the modeling of the aspect 'surface damage by corrosion or mechanical action'. The results show that the Markov model is a good starting point for modeling sewer deterioration.

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