STATISTICAL ANALYSIS OF INSPECTION DATA FOR THE ASSET MANAGEMENT OF SEWER NETWORKS

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Abstract
Investments in sewer pipe rehabilitation must be based on optical inspection and evaluation of sewer conditions with respect to the severity of the damage and to environmental risks. The work presented here discusses the problems of forecasting the condition of sewers in a network from a sample of inspected sewers. Transition functions from one into the next poorer condition class, which were empirically derived from this sample, are used to forecast the condition of sewers. By the same procedure, transition functions were subsequently calibrated for sub-samples of different types of sewers. With these transition functions, the most probable date of entering a critical condition class can be forecast. Thus, rehabilitation needs arising from the modelled deterioration process, can be calculated year by year into the future. The requirements of condition grading systems for the application of deterioration models are discussed.

Keywords
Sewer network, condition assessment, ageing forecast, asset management

INTRODUCTION

Asset management of sewer networks includes the rehabilitation planning of the pipes and the evaluation of the market value of the assets. CCTV inspection data provides information on the actual condition of the pipes and on the priority of rehabilitation needs. Rehabilitation priorities are defined according to the severity of the observed structural or hydraulic deficiency and the vulnerability of the affected environment. From 2003 on, the format of inspection reports is standardised by the European EN 13508-2 code for the classification of failure types. In Germany, to date, various local coding systems exist, which are in the majority based on the ATV M143 standard. Currently, this standard is translated into the European code. Based on the codification, grading systems are applied. These grading systems consider structural integrity and/or hydraulic deficiencies of the pipe and assign the pipes to priority condition classes.

A major issue in the discussion of grading models is whether sewers should be classified mainly with respect to the urgency of rehabilitation work due to the severity of a localised damage, or whether the grading should also indicate the intrinsic value of the sewer, i.e. the extent of required rehabilitation efforts within a reach for a more realistic estimate of investment needs. Therefore, the inspection code and the subsequent classification should be capable of answering questions on how urgent the need of rehabilitation at a particular location is, i.e. the definition of *priorities*, and to what extent the substance of a complete reach already is used up, i.e. the evaluation of the *intrinsic value* of a sewer (Baur 2003). A measure of the intrinsic value is the market value of a sewer network, which can be calculated from the re-installation costs of the assets and the depreciation of the present assets since the year of installation.

In a pro-active approach of rehabilitation planning and asset management, both types of evaluation are requested, for prioritisation of rehabilitation needs and for estimation of the intrinsic value of a network. Hence, ageing models are used to forecast the deterioration process of the sewer network.

METHODOLOGY

The process of sewer deterioration is described by a cohort survival model. In the model, the deterioration process is formalised as a successive transition between condition states, from the best state "good as new" to the worst state, the intervention class. With some probability, sewer pipes survive a number of years within a condition state. The pipes are deteriorating slower or faster under specific local circumstances. So their condition is not determined by age alone. The transition from one condition grade to another is modelled by condition survival curves. Within the cohort survival model, the survival curves are transition curves into worse categories of condition. For the cumulative density distribution functions, the Herz distribution for ageing infrastructure elements is applied (Herz 1996, 1998).

The Herz distribution is used due to some computational advantages and appears to be appropriate to model the deterioration of long-lived infrastructure elements: After some time of resistance, the failure and transition rates start to increase exponentially up to the median age and then turn into a degressive curve approaching a finite maximum value. That is, at this stage, the most resistant infrastructure elements show no increase in their failure rate and, thus, get older but do not age anymore. The failure and transition rate is mathematically linked with the probability density function of the service life and with survival and transition functions. From these functions, residual life expectancies and expected duration of stay in a specified minimum category of condition can be derived. The formula of the transition functions $\boldsymbol{R}(t)$ is given here as follows (Herz 1995).

$$\boldsymbol{R}(t) = (\boldsymbol{A}+1)/(\boldsymbol{A}+e^{\boldsymbol{B}(t-C)})$$

with

- $\boldsymbol{R}(t)$ percentage of pipes that will not have changed into an inferior condition class at a particular age t, indicating the ageing speed
- ***A*** vector of ageing parameters (-), the larger, the smother is the transition.
- ***B*** vector of transition parameters (1/years), the larger, the faster is the transition; asymptotic transition rate at high age
- ***C*** vector of resistance times (years) in condition class

Field data

A sample of 465 km of inspected and classified sewer pipes was used for this study, i.e. more than 25,000 data sets, comprising 27 % of the total network length with about 1,700 km. The condition grades are derived from CCTV inspection data sampled in 2002 and 2003, according to the local standard based on the German ATV M143 code, following the classification rules in the German ATV M149 code with some local specifications. Here, the assigned condition grade 6 (ZK 6) is the best condition (good as new), and condition grade 1 (ZK 1) is the worst condition requiring first priority for rehabilitation. According to results of previous studies (Baur & Herz 2002), the data set was analysed with respect to variations in material (concrete, clay), and construction period (<1919, 1919-1940, 1940-1989, and >1989). The total length of other sewer types (brick, and other materials) is not yet considered in this statistical analysis (Table 1).

Table 1: Inspected sewer types, total length in km

Material / Construction period	Concrete	Clay	Others	Sum
<1919	152.3	12.7	16.4	181.4
1919 - 1940	71.3	22.2	0.3	93.8
1940 - 1989	28.8	29.0	9.6	67.4
>1989	35.5	57.2	30.3	123.0
total	287.8	121.1	56.6	465.6

The distribution of materials and condition grades in the sample is:

ZK 6, good as new....31 %
ZK 5, good................20 %
ZK 4, fair ....26 %
ZK 3, poor.................15 %
ZK 2, very poor ....6 %
ZK 1, useless...............2 %

Concrete ....62 %
Clay ....26 %
Others ....12 %

Figure 1 and 2 show the distribution of pipes in respective condition grades according to their age.

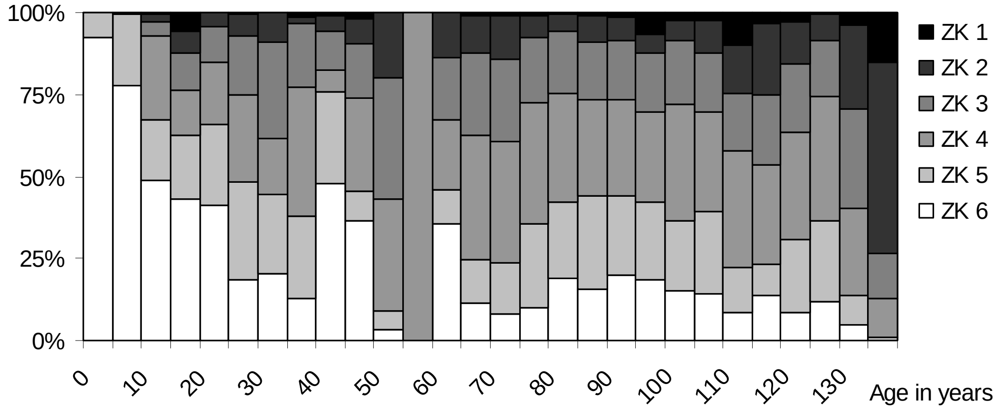

Figure 1: Distribution of condition grades (ZK), relative length

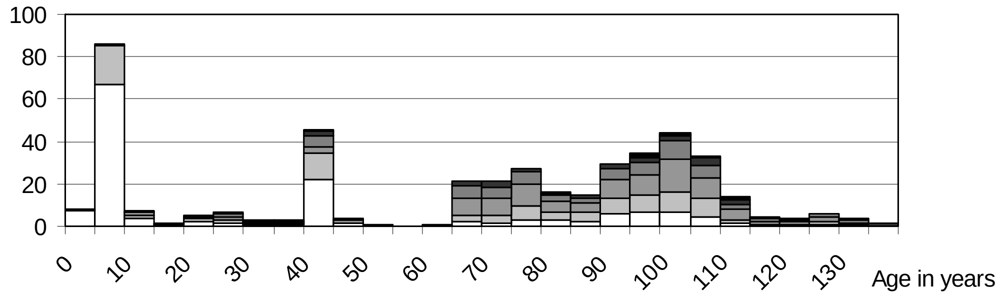

Figure 2: Distribution of condition grades, total length in km

Calibration of transition functions

The data basis for the calibration is the distribution of all condition states - weighted by their inspection length - within the observed range of age. For the present study, sewer pipes rehabilitated in the past are not included in the data base. It is assumed that these sewers have been in the worst condition state ("intervention class") prior to their rehabilitation. According to the rehabilitation activity since 1999, the annual rehabilitation length was about 0.9 % of the total network length. Hence, the service life expectancy of rehabilitated sewer pipes was set to be about 110 years.

Within the calibration process, a curve-fitting mechanism is applied to estimate the transition functions. The transition functions are fitted by minimising the accumulated positive and negative deviations between the calculated values and the observed values at age t:

$$abs[\sum_{i=1}^{n} S_{i,a\rightarrow b}(t) - X_i(t)] \Rightarrow Min \qquad (1)$$

where

$S_{i,a \rightarrow b}(t)$ is the calculated value for the transition function from state **a** into state **b** at age t

and

$X_i(t)$ is the accumulated observed fraction of all condition states better than state **b** at age t.

In figure 3, the principle of the calibration of the transition function from condition grade 4 to grade 3 is shown. The bars indicate the accumulated observed fractions of all sewers in a condition state better than condition state 3.

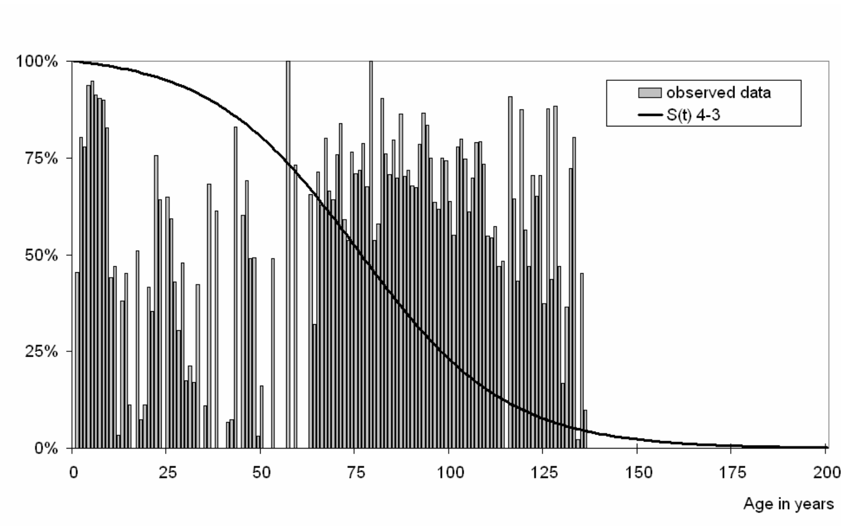

Figure 3: Calibrated transition function from condition state 4 to 3

Figure 4 shows the calibrated transition functions for the classified inspection data of the complete sample of 465 km of sewer pipes in the Dresden sewer network. For the sub-samples according to material and construction period, similar results as in previous studies are obtained (Baur & Herz 2002). Like for other sewer networks in Middle and Eastern Europe, a typical characteristic of the network condition is, that sewer pipes constructed in the period from 1940 until 1989, in general, are in a poorer condition than pipes installed in the periods before.

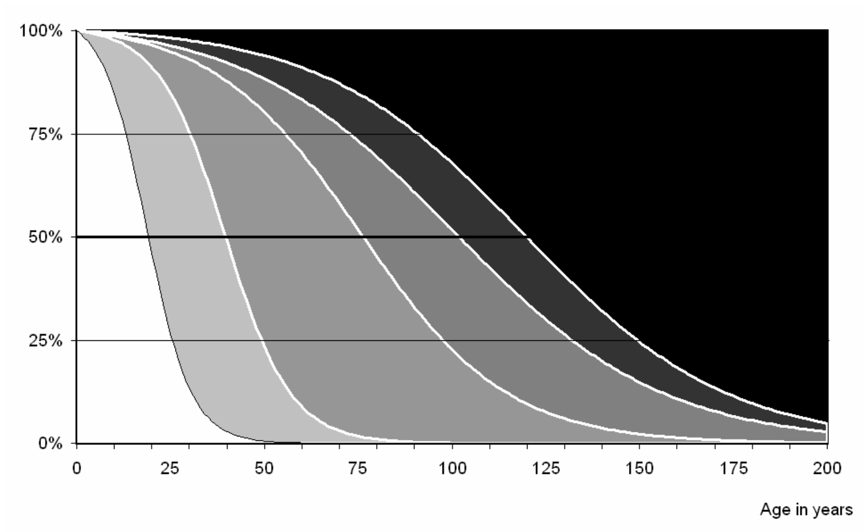

Figure 4: Calibrated transition functions for the investigated sample of pipes

Asset management: condition forecast and inspection planning

From the existing stock and the calibrated transition functions, the future condition of the network is simulated. In Figure 5, the development of the network length from 1875 until today is drawn, and the development of the ratios of the 6 condition classes in this sample is forecast until the year 2100.

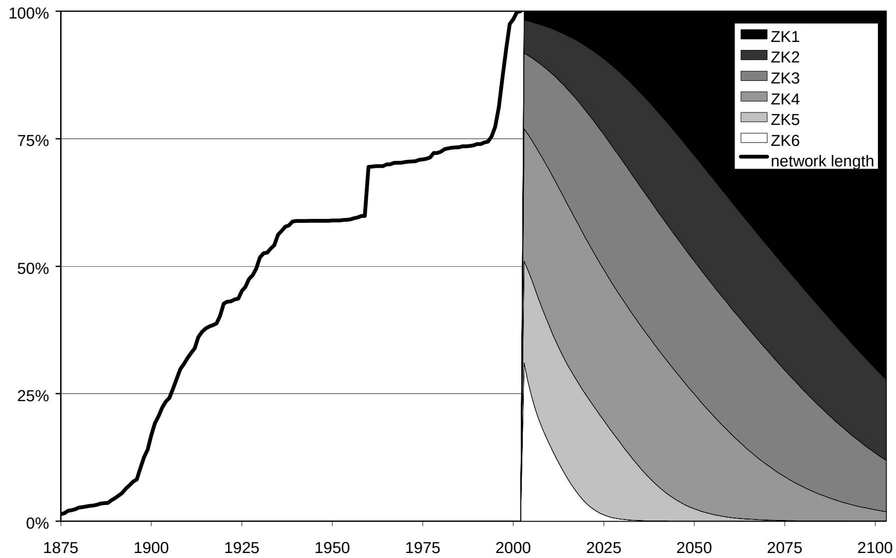

Figure 5: Condition forecast for the inspected sample of sewer pipes

There are two benefits of the condition forecast for the asset management: using the results of the ageing model, future investment needs can be calculated for different rehabilitation strategies, characterised by constant budgets, minimum condition standards requested in the network, or other network performance indicators (PI) that can be predicted. There is a special sub-task dedicated in CARE-S to these predictable PI. Secondly, the inspection result for individual pipes can be used for scheduling their future inspection dates. That means, consequently, those sewers shall be inspected that are likely to approach a critical condition state in the next years – and future investment needs for maintaining a requested standard can be calculated.

DISCUSSION AND OUTLOOK

Within the CARE-S project, ageing forecasts on the structural network condition are discussed for two other approaches. The DeForm model assumes constant transition rates from one condition grade to the next worse, by using an internal grading system (Williams 2003). Le Gat (2003) calculates transition rates between condition states and applies these rates to model the deterioration of sewers with a non-homogeneous Markov chain approach. Transition probabilities are calculated for explanatory variables. Here, the condition grades used are assigned to the pipes according to defect codes of the EN 13508-2 system. Similarly, Kleiner (2001) is modelling the deterioration of infrastructure elements as a semi-Markov process, and draws conclusions for scheduling inspection and renewal in the network. The common underlying assumption of all models is the appropriate description of the sewer pipes' deterioration process by the subsequent transition of a pipe with its age through all condition grades.

Detailed investigations of the deterioration process of particular failure types, the modelling of a failure type specific “ageing path”, are subject of another sub-task in CARE-S (Williams 2003). Under particular circumstances, the approaches look promising, especially if failure types can be clearly described, so for example the corrosion of concrete sewer pipes. Other failure types, which are characterised more “general”, such as blockages or ex- and infiltration, and which occur more coincidentally and which suffer from a lack of information on the detailed physical processes, are more difficult to be covered by deterioration process models. In addition, one important aspect of statistical life time analysis, the time of the occurrence of a defect, e.g. a fissure in a clay pipe, and the time of detecting the defect by inspection, in general are not identical.

For the presented case study, classified inspection data was used in the calibration process. One objective of the study was the comparison of the ageing forecast from the actual sample with the results of a previous study, carried out on the basis of a much smaller sample. In that earlier study, about 1000 data sets, representing 37 km, or 2.7% of the total network of that date, were analysed (Baur & Herz 2002). The inspections of these pipes were carried out between 1994 and 1998, and evaluated according to a grading system that consisted of five condition categories (instead of six condition grades today!). From the two samples, those of the first study and the actual inspection, there are 100 pipes inspected for a second time, identified by their identical upstream- and downstream-manhole ID in the database. It was expected to get a first chance of following the deterioration process of these pipes. Unfortunately, evident inconsistencies are observed: 8 of 100 pipes show a difference in the inspected length of more than 10 %; 9 of 100 pipes are assigned to a condition of at least two grades **better** than before, and no rehabilitation activity is reported. 59 of 100 pipes show inconsistencies in the profile type or diameter.

Insufficient reliability of previous inspection data and inconsistencies between sampled data are major handicaps for the analysis of repeated inspection results with respect to the deterioration process of sewer pipes, and the development of failure type ageing-paths.

There could be various reasons for the inconsistencies:

- there is always a subjective view on the TV images
- CCTV technology improves rapidly, and the quality between tapes today and those from ten years ago differ significantly
- there is a growing experience of the inspecting personnel
- however, experienced personnel is sometimes rare.

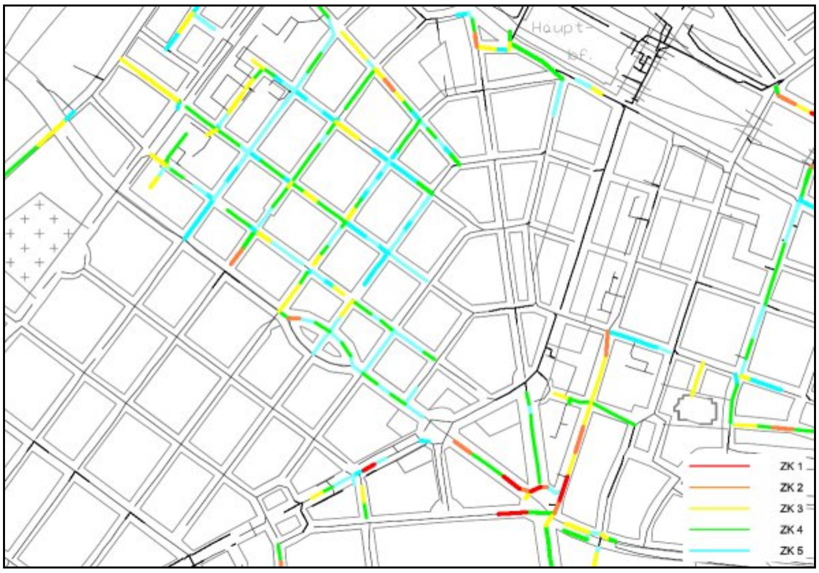

Figure 6: Priority map of an inspected sewer network

For the further development of the presented model, investigations should focus on the classification methodology. Condition grades provide useful information for the prioritisation of rehabilitation projects (Fig. 6). For using condition grades within deterioration forecasting models, they must be defined in a consistent way. That means for instance that a particular condition grade of a sewer pipe should give the same information with respect to the residual service life of the particular pipe, irrespective of the type of defect.

CONCLUSION

The statistical analysis of condition data of sewer networks can be a powerful tool for the asset management of sewer networks. Deterioration models are used for the prediction of the long term consequences of a rehabilitation strategy on the performance of the network and the investment needs, as well as for the prioritisation of rehabilitation projects in the short term. In either case, classification of sewers based on inspection results is required. The classification results of a representative sample can be used for the estimation of the future state of single sewer pipes and the network as a whole. Even for choosing the right rehabilitation technology for a sewer, it is necessary to have an estimate on the residual service life and the service life prolongation provided by different technologies. A main focus of further research and development should be on the methodologies of classification of inspection results, and their applicability to priority setting of rehabilitation projects and to deterioration forecasting models.

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