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Comparison Of Statistical Failure Models To Support Sewer System Operation

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ABSTRACT

Achieving appropriate operational performance of urban wastewater infrastructure has become a high priority for water utilities. Recent research has focused on developing models to support proactive maintenance and rehabilitation of sewerage systems. This study evaluates two predictive software tools that use different statistical models: (a) the FAIL software (Martins *et al.*, 2013) and (b) the SIMA software (Rodríguez *et al.*, 2012). Comparisons among a single-variate Homogeneous Poisson Process (HPP) implemented in the FAIL software and two different Non-Homogeneous Poisson Processes (NHPP) implemented in the SIMA software are conducted in this study. Two contrasting urban wastewater systems are studied: Bogotá (Colombia) and SIMAS Oeiras and Amadora (Portugal). Furthermore, three different types of sewer failures named blockage-related failures, sediment-related blockages and structural failures are analysed. In order to evaluate the prediction efficiency of each model, the number of predicted failures obtained using each model were compared with the observed number failures. The obtained results showed that both models were capable to point towards the same number of observed failures. On the other hand, the HPP model range of prediction was wider than the NHPP models, showing that the latter has a higher prediction precision. Three case-studies also evidenced that NHPP models are more accurate when compared with the HPP model: the number of observed failures are within the prediction range in a higher percentage of the fits.

Keywords: Non-Homogeneous Poisson Process, Poisson process, sewer pipe failure modeling, sewerage maintenance and rehabilitation,

INTRODUCTION

Assessing sewer system performance and improving sewerage system reliability are part of modern urban wastewater asset management (Rodríguez *et al.*, 2012). Climate change, economic restrictions, increasing customer requirements, changes in environmental regulations and political pressures make such management activities even more challenging (Martins *et al.*, 2013). Maintenance and operation strategies have traditionally been based on reactive approaches. However, some studies have shown that the cost of reacting to sewer system failures is in many cases higher than the costs associated to a sewer pipe proactive maintenance (Rodríguez *et al.*, 2012). Modelling sewer pipe failures can be used for supporting planning and decision making processes. Pipe failure models may be helpful in identifying which zones are more likely to fail and therefore could provide an objective basis to schedule prioritized maintenance actions (Martins *et.al.*, 2013).

Efforts to improve sewer system management have been carried out using diverse available modelling approaches. Physically-based models, for example, are used to model hydraulic deterioration of sewer pipes based on data of local pipe conditions (e.g. Fenner *et al.*, 2007). Statistical models, on the other hand, use the observed failure events to predict pipe failures. This study presents the comparison of two different statistical software for urban wastewater pipe failure prediction.

FAIL software model

The FAIL software calculates failure predictions based on two alternative stochastic processes, the single-variate Poisson process (HPP) and the Linear Extended Yule process (LEYP) (see Martins *et al.*, 2013). In this study only the single-variate HPP is considered; this is a model built up upon the lack of memory process, which implies that the failure is equally likely to occur at any time regardless the physical deterioration of the physical state of the system. This assumption implies that the system is not wearing out with age nor improving, i.e. the mean rate of occurrence of failure events (λ) is constant. The Poisson counting process satisfies that the expected number of events is proportional to the observation time, where λ is the proportionality coefficient and corresponds to the intensity of the process. In order to find the homogenous process distribution of failures in each pipe, λ is estimated using the maximum likelihood method. In this way, failure rate definition becomes a maximization problem (see Martins *et al.*, 2013).

SIMA software models

The SIMA software uses different failure models based on a HPP and on NHPPs. The Laplace test is applied in order to identify if the system reliability is improving (Laplace test value bigger than 1.96) or deteriorating (Laplace test value smaller than -1.96) (Cox and Lewis, 1966). In the cases that these statistics fall out of the 95% confidence interval, HPP should not be used and a NHPP fit should thus be considered, instead. For the analysis presented in this study, the SIMA NHPP models (Crow's model and Cox and Lewis's model) were used to predict sewer system failures. Crow (1975) proposed to calculate the failure rate as a power law, while Cox and Lewis' model (1966) proposed a log-linear model to calculate failure rate. Both models use two additional parameters: growth (β_1) and scale (β_0). Estimates of both model's parameters are obtained using maximum likelihood (see Korving *et al.* (2006) for further details).

CASE STUDIES

Two urban wastewater systems were used in order to evaluate models' forecasting efficiency: Bogotá (Colombia, 7.5 million inhabitants) and SIMAS Oeiras and Amadora (SIMAS O&A) (Portugal, 10,000 customers). Customer complaints and failure databases were gathered and classified according to the failure's nature. SIMAS O&A counts with 11,472 pipes with a total length of 367 km. On the other hand, Bogotá has an approximate total sewer pipe length of 7,678 km in both stormwater, foul and combined systems (Rodríguez *et al.*, 2012).

SIMAS O&A failure database compiles maintenance actions for blockage-related failures in the period between 2008 and 2012 (1,921 blockages-related failures in total). Bogotá's failure database comprises nine years of failure records covering the period from 2004 to 2013. In the Bogota case, two types of failures were gathered, namely sediment-related blockages and structural failures.

METHODOLOGY

The number of predicted failures was calculated for square-grid areas in both case studies. For Bogotá, a 170 m squared grid was used, covering an area of approximately 0.03 km^2 each square. The size of the grid cell covers nearly a street block, which simplifies model implementation when used for planned maintenance. For the SIMAS O&A case study, as the historical database was smaller, a cell size sensitivity analysis was conducted to guarantee a sufficient number of historical records required for the statistical fit. For Crow and Cox fittings, a minimum value of five failures was established. Figure 1 shows the distribution of number of failures per square grid for different sizes. A 170 m cell-size was selected for SIMAS O&S whose mean and maximum number of failures per square-cell are 5 and 27 failures, respectively. This grid size led to 1,600 grid cells covering the urban area of the case study of the SIMAS O&A, in contrast to 9,658 grid cells for the case of Bogotá.

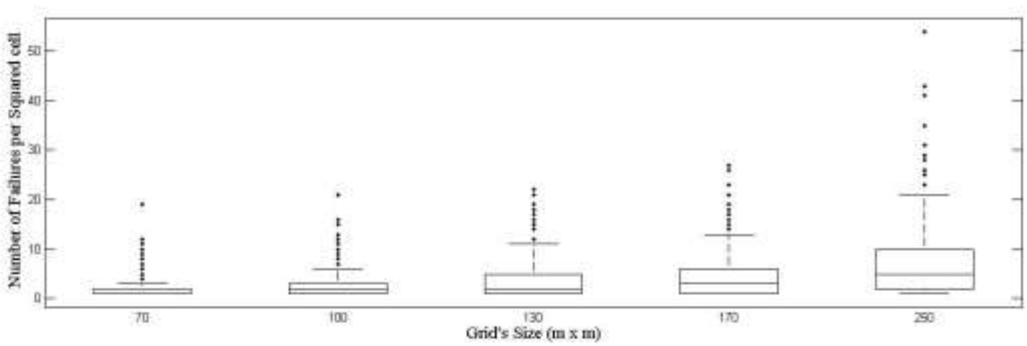

Figure 1. Number of failures for different grid-cell sizes (70, 100, 130, 170 and 250 m) for the SIMAS O&A case-study

For the two case studies, the failure databases were divided in two sets: 80% of the available historic period was used to fit the statistical models, while the 20% remaining information was used to assess the models forecast accuracy. Table 1 shows the fitting data period and validation data period for the two case-studies. For the Bogotá case study, when dividing the period into 0.8 and 0.2 fractions, the number of available records approximately followed the same proportion, while in the SIMAS O&A case-study failure records are concentrated mostly in the last years, which lead to a higher proportion of the data in the validation period.

Table 2. Fitting and validation datasets and available number of records for each case study

	Fitting Data		Validation Data		*Total Failure Records*
	Period	*Available Failure Records*	*Period*	*Available Failure Records*	
SMAS O&A blockage-related Failures	08/2008 - 05/2011	889 (53%)	06/2011/10-2012	781 (46%)	1670
Bogotá Blockage-related Failures	06/2004-06/2011	5123 (81%)	07/2011-11/2013	1177 (19%)	6300
Bogotá Structural failure	06/2004-06/2012	61167 (63%)	07/2011-11/2013	35251 (34%)	96418

Using the estimated parameters for each distribution, times between subsequent failures were generated and acummulated until the predictive window was exceded. Total number of modelled failure events was reported per run. One thousand iterations were generated and these results were finally compared with the observed number of failures reported in the 20% validation datasets. Figure 2 shows fitting period window (continuum square) and predictive window (dotted square) for both models; the crosses (X) in the figure represent failures and horizontal axes represent time. Using the FAIL software, as the calculated failure rate is constant among time, the fitted λ was used for the whole predicted time between events; also, historical window and prediction window size do not change. For the two SIMA software models, scale and shape parameters were recalculated every predicted time in order to fit a new λ for the next prediction (λ_1 and λ_2 in Figure 2). In each iteration, predicted time between failures is added to the fitting records, reducing the predictive window (form 1' to 2') and enlarging the fitting window (from 1 to 2).

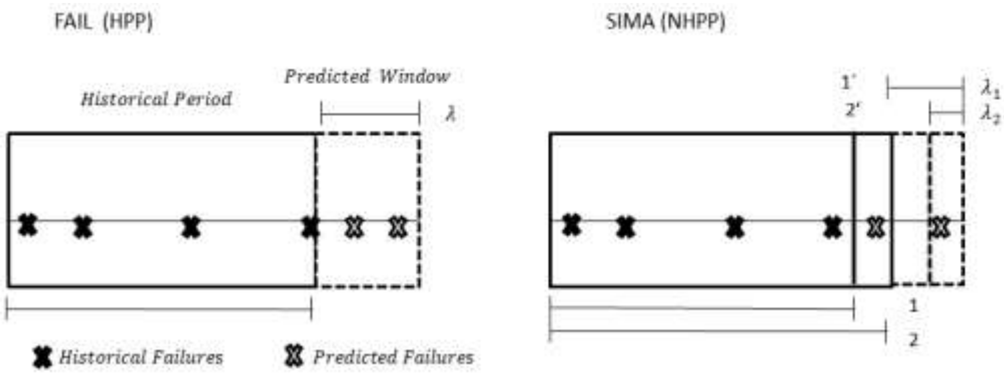

Figure 2. Fitting and predictive windows for HPP and NHPP models

Figure 3 shows the two criteria used in order to evaluate which model best fits the observed data: (a) the first criterion, as a measure of model accuracy, is based on the difference between the number of observed failures and the predicted expected value, calculated as the mean of the predicted number of failures, and (b) the second criterion looks at the width of the 90% of the range of the predicted number of failures as a measure of precision of the model. The 10% outermost values (5% higher and lower values) were ignored.

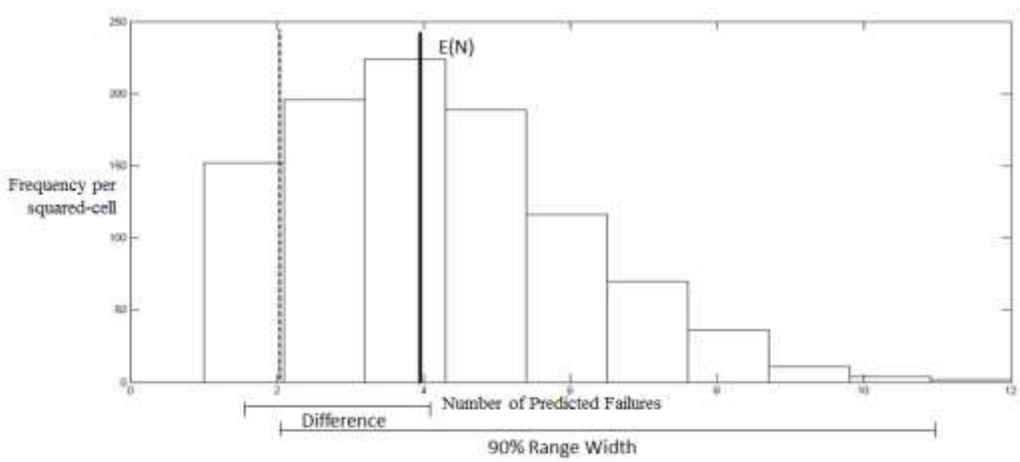

Figure 3. Predicted number of failure records and performance evaluation criteria

RESULTS AND DISCUSSION

Three failure databases were considered in this study: blockage-related failures for the SIMAS O&A case-study, and sediment-related failures and structural failures for the Bogotá case-study. Results for the two models evaluation criteria are reported in Table 2. In general, for NHPP models (Crow's and Cow-Lewis's models) the number of failures range contain the observed values (in average, the observed values of the 60% of the grid cells were among the predicted number of failures range). For the HPP model, only in 20% of the grid cells (in average) the observed number of failure was found within the predicted number of failure's range. In most of the cases, the HPP model did not include zero as a likely number of failures. This means that the model rarely predicted that no failures were occurring in the predicted window; this result was incorrect for more than the 50% of the cases. Letting out those grid cells in which none failures were observed, the 20% previously reported results, changed to 90%.

In order to evaluate the predictive precision of each model, the difference between the expected value of the predicted failure distribution and the observed values were calculated for each fitted grid cell. The results obtained using the NHPP models showed smaller differences when compared to those obtained using the HPP model. In general, HPP model range was larger than the NHPP models, which can be seen in Table 2 for each study case. Both models were capable of predicting the exact value of failures within the predicted window. Still, HPP capacity of prediction may be attributed to the fact that the range of prediction is comparatively higher than the NHPP models.

Table 2. Difference interval (± standard deviation), width range and observed values for each case study

	Blockage-related Failures (SMAS O&A)		**Sediment-related failures (Bogotá)**		**Structural failures (Bogotá)**	
	HPP	***NHPP***	***HPP***	***NHPP***	***HPP***	***NHPP***
Difference (No. of failures)	0-54 (±17)	0-3(±1)	0-79 (±21)	0-19(±7)	0-67 (±20)	0-14(±6)
Range Width (No. of failures)	13-30	7-11	5-48	9-22	5-46	10-18
Observed values among prediction range (%)	18	53	23	72	20	57

CONCLUSIONS

The comparison of statistical predictive models conducted in this study showed that the HPP is not the best alternative when predicting the number of sewer failures. Three datasets and two different sewer systems were used, leading to the conclusion that NHPP seems to be a more appropriated option when modeling sewer system failures. This could be explained due to the pipe deterioration processes that may lead to an increase of sediment-related and structural failure rates; or because changes in the number of inhabitants in urban areas that may generate increased wastewater volumes, flush sediments in the pipes and thus reduce failure rate for sediment-related blockages.

LEYP model, implemented in the FAIL software classifies pipes based on their material, giving a better understanding of the impact of pipe characteristics on the failure mechanisms.

The authors are currently assessing the LEYP model performance in order to evaluate its predictive capacity using the cases-study presented herein and quantifying the impact of sewer system characteristics in models forecasting accuracy. On the other hand, spatial analysis are also being developed in order to evaluate if there are particular areas or pipes characteristics in which the models perform consistently better.

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