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A NOVEL DECISION SUPPORT SYSTEM FOR OPTIMISED SEWER INFRASTRUCTURE ASSET MANAGEMENT

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This paper approaches the sewerage asset management challenge from a UK perspective by outlining a comprehensive methodology capable of optimizing the performance of sewerage infrastructure networks using a series of Hydroinformatic tools. The methodology is based on an effective sewer deterioration model used to prioritize survey investigations towards poorly performing assets and then capitalizing on this inspection information by using a sewer rehabilitation optimization environment to identify a series of high benefit – low cost solutions across the catchment. As a result, the methodology acts as a series of strategic decision support tools which are capable of helping sewerage engineers and planners in the evaluation of different intervention programmes of work. A UK case study is provided to demonstrate the benefits of this approach.

INTRODUCTION

This paper explores how AECOM have been working with South West Water, who are one of the ten water and sewerage utility providers operating in England and Wales, to address the challenge of improving sewerage asset performance against constrained budgets. Ofwat, the industry regulator for England and Wales, estimate the total length of sewer assets to be 324,500 km [1]. The regulator also reports that the total average renovation and replacement rate is less than 0.15% of the overall network length - meaning that on average, water companies in England and Wales are relying on their assets serving a useful life, without intervention, of more than1,000 years. Figure 1 graphically represents South West Water's sewerage network renewal rates against the industry average and clearly shows a rapid improvement in more recent years. This has been achieved by adopting a comprehensive asset management methodology founded on the latest Hydroinformatic tools which have been used to predict sewer deterioration and to optimize the specification of sewer rehabilitation programmes.

Only more recently have authors begun to report on the applicaiton of Hydroinformatic tools to the problem of optimal sewerage asset manangement [2], [3]. In comparison, methodologies addressing the optimal management of water distribution systems have been widely reported for numerous years, [4], [5], [6], [7], [8]. It would appear that the management of sewerage assets is less suited to the applicaiton of such Hydroinformatic tools. However, it will be shown here that the sewerage industry is in an excellent position to benefit from the adoption of such tools.

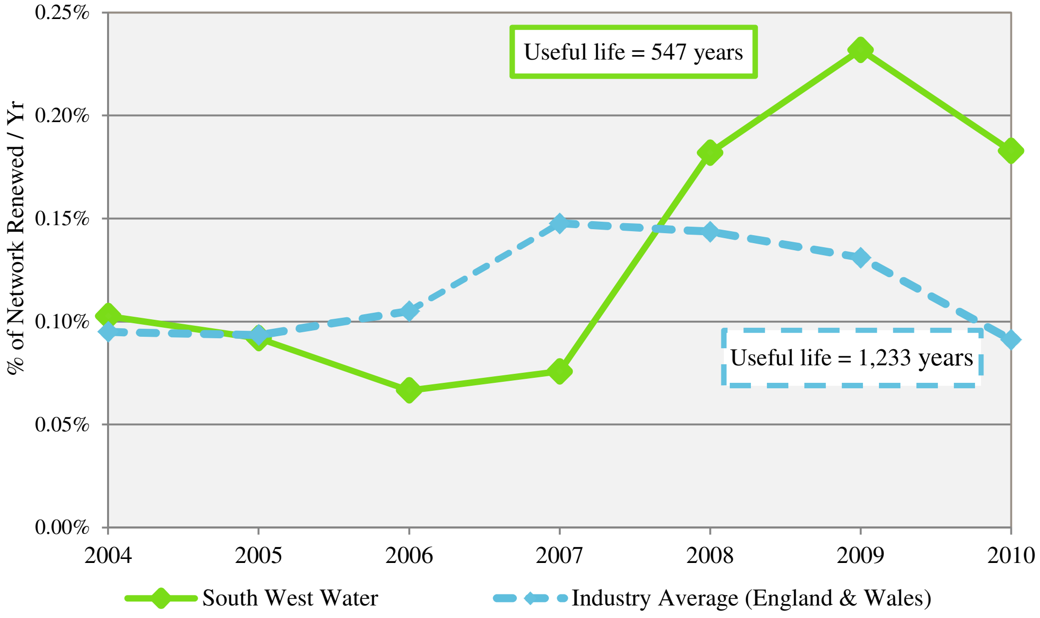

Figure 1 – Sewer network renewal rates in England & Wales

Most notably, the increased availability of standardized CCTV sewer inspection information [9], [10], [11], has been used as platform for the development of a number of sewerage asset management tools by researchers and practitioners. For example: predicting the future condition of sewerage assets [12], [13], [14]; the identification of optimal inspection timings [15]*; and* the development of cost effective intervention programmes [16], [17], [18]. The authors of this research have also utilize the availability of standardized condition inspection information in the development of their deterioration and inspection prioritization model as well as applying a multi-objective optimization model to the condition information in order to identify high benefit – low cost rehabilitation schemes.

DETERIORATION MODELLING

In order to define, evaluate and forecast the probability of sewer collapse, a unique sewer deterioration model was established to predict the future condition of the network. The model uses the analysis of historic CCTV survey information to identify specific deterioration trends for different cohorts of sewer. Extrapolation of these deterioration trends allow for the entire sewer network to be expressed in terms of its length within each of the appropriate condition grade scores (1 to 5) at any point in time, whereby the WRc Method of Sewer Condition Classification (MSCC4) [10] is used to define condition grade. Against this understanding of past, current and future condition, a collapse rate is predicted from a statistical analysis of historic events against the observed sewer condition profiles for each cohort. The result is a novel relationship which is drawn between sewer collapse rate and sewer condition profile; using a linear function that allows for the future prediction of collapse rate over-time.

Sewer condition is uniquely expressed in this model as the length of each sewer within each of the five condition grades which are derived by modelling the sewers gradual transition from grade 1 (as new) to 5 (defective or collapsed) using a Semi-Markov chain. Semi-Markov chains are a long established technique for the mathematical modelling of infrastructure deterioration [19] and they are commonly referred to as a simplification of the deterioration process because the modelling is often performed at asset level, with a single sewer occupying only one of a number of states e.g. 1 to 5. However, by adopting a condition profile based approach, the authors have established a more representative modelling technique for sewerage assets that reflects the fact that a single sewer maybe in multiple states at a single point in time [20]. This is achieved through the analysis of historic condition surveys to determine how the actual proportions of a sewer gradually transition into the five condition grades using a Semi-Markov matrix. In essence, the condition “profile” of a sewer is the proportion of its length within each condition grade (1 to 5), shown in Figure 2. For this analysis, a condition “profile” is computed for all available historic survey information, using a bespoke algorithm to determine the proportion for each survey record.

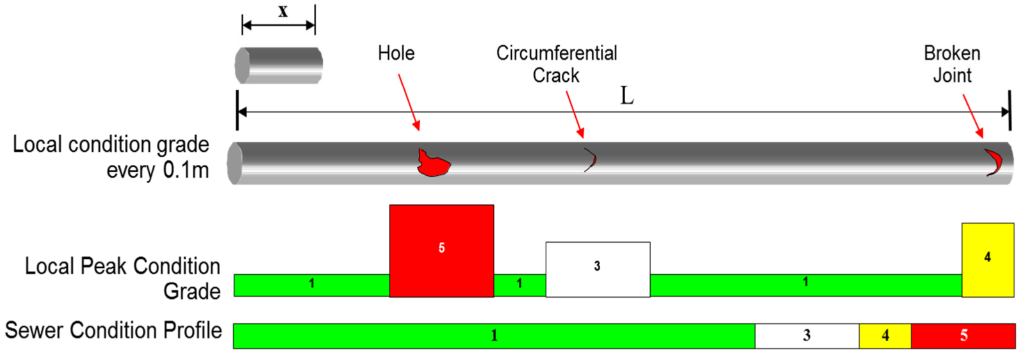

Figure 2 – Sample sewer condition profile

This deterioration modelling process aligns itself with a similar methodology used for the statistical modelling of water distribution pipe failure and sewer failure respectively, [21], [22]. Both of the approaches group the entire network into fictitious pipes based on their attribution for which the relevant variables of the deterioration model are calculated using a length weighted mean. In this instance, the leading diagonal of the Semi-Markov deterioration matrix form the variables which are calibrated by minimizing the sum of least squares against the observed data for condition grades (1 to 5) over-time, Figure 3. When all the proportions of the sewer in each of the conditions grades are grouped together, this is referred to as the sewer’s condition profile. The condition profile can be calculated for an individual sewer or it can be used to express the overall condition of a group of pipes (cohort) using the length weighted mean approach. In this instance, the condition profile is calculated for all sewer cohorts but only within a single survey year. The survey year is held as a segregating factor because it represents the age of the pipe at the time of the survey and is thus the time variable in the assets deterioration profile, Figure 3.

Once the survey and sewer attribution data are analyzed, a semi-Markov deterioration matrix is calibrated against the observed sewer condition profiles on an annualized basis for each cohort of sewer, Table 1.

Table 1 – Example of a Calibrated Semi-Markov Deterioration Matrix

		From Grade				
		1	2	3	4	5
To Grade	1	**99.8%**	0.0%	0.0%	0.0%	0.0%
	2	*0.2%*	**98.7%**	0.0%	0.0%	0.0%
	3	0.0%	*1.3%*	**97.3%**	0.0%	0.0%
	4	0.0%	0.0%	*2.7%*	**99.6%**	0.0%
	5	0.0%	0.0%	0.0%	*0.4%*	**100.0%**

The resultant calibrated deterioration matrix, depicted in Table 1, can be interpreted as follows: The values in the leading diagonal of the matrix are the probable proportions retained in the same grade, e.g., after one year it is probable that 98.69% of the length will remain in condition grade 2. The values directly below the leading diagonal refer to the probable proportions that will deteriorate to the next condition grade, e.g. after one year it is probable that 1.31% of the length in sewer condition grade 2 will deteriorate to grade 3. Using this annualized deterioration matrix to predict future condition, Figure 3 is drawn to illustrate the comparison of the observed condition profiles (vertical bars) and the modelled estimate (linear trend).

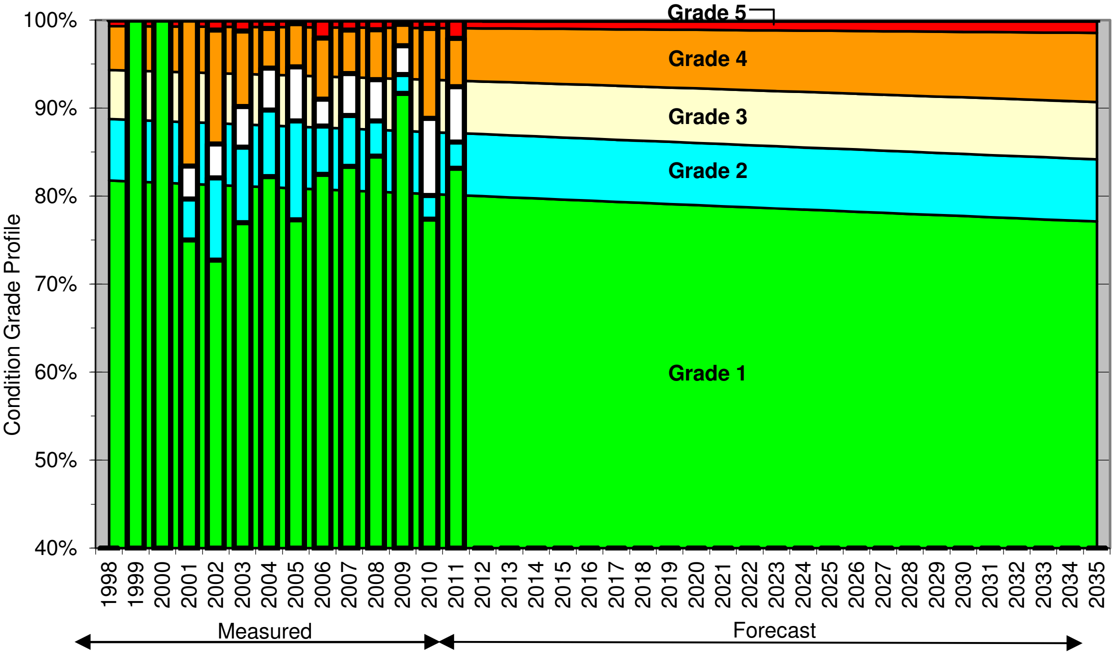

Figure 3 – Example showing measured and forecast sewer condition profiles

Following the development of the sewer deterioration model, the location, extent, age, material and predicted condition of the entire network is better understood. This provides the foundations to estimate the likely investment requirements in the network going forward, whilst also providing the basis for a proactive asset management strategy to be established by prioritizing survey investigations via CCTV towards poorly performing asset groups, e.g., Pitch Fibre sewers laid between 1980-89 where identified in our study as a poorly performing cohort and were targeted for investigation.

OPTIMISING SEWER REHABILITATION

Decision making and planning for sewerage asset renewal/rehabilitation is a process that seeks to evaluate the condition of an asset, its risk of failure, the cost of remediation and to help understand the serviceability improvements that can be realized by different types of interventions. Typically the objectives of a rehabilitation programme are conflicting, which implies that the interventions that vastly improve the structural condition or serviceability of an asset, have typically high associated costs. Therefore, to permit effective planning and investment, it is important that decision makers understand the cost vs benefit trade-offs that exist between different schemes.

The authors have developed an optimization environment for sewer rehabilitation which can be used by decision makers to support their understanding of the trade-offs between high benefit vs. low cost solutions, which ultimately helps with the identification of a rehabilitation strategy that achieves the utilities business goals. The authors present three objective functions which are used to evaluate and trade-off between the benefits of different rehabilitation solutions at catchment, or network, level: (1) maximize condition improvement; vs. (2) minimize investment cost; vs. (3) proactively address serviceability problems.

The first objective function in this model, Equation (1), considers a very simplified approach to the problem of quantifying network improvement. It builds on previous work undertaken in clean water distribution planning by Halhal et al. [7] where-by the authors assumed that any length of pipe replaced in the network would provide for an improvement in overall water quality. Thus allowing the total length of water mains replaced to be representative of the networks water quality improvement. Similarly, the sum of the observed defect scores (S^0) from the coded CCTV condition inspection report for each sewer (i) are used here to represent the current condition of a catchment or network with (N) number of sewers. It also assumes that an improvement in a sewers structural condition can only be obtained by interventions to remediate the observed defects. Therefore, the structural score post rehabilitation for each sewer (S^1) is simply the sum of the structural defect scores that remain unaltered by the rehabilitation solution. As a result, any change to this total can be used to quantify the total benefit provided by the rehabilitation strategy being implemented.

$$Structural\ Improvemnt\ =\ \sum_{i\,=\,1}^{N}\left[S_i^0\ -\ S_i^1\right]\quad where\ i\ =\ 1, 2, \ldots, N \tag{1}$$

The second objective function focuses on minimisation of construction costs. Therefore, it is of fundamental importance that the cost of each rehabilitation strategy is calculated accurately to ensure that the comparison of different strategies is representative of the actual delivery costs that will be incurred. To account for difference in construction costs between different utility providers and their contractors, the model presented in this paper has been developed with the flexibility to include bespoke cost models into its analysis. However, it is important that the chosen cost model is suitably detailed to distinguish between; the type of repair, repair length, sewer diameter and the above ground conditions for excavation based solutions, i.e., highway, verge or grassland. Other desirable features, which improve the accuracy of the forecast costs, include; being able to account for contractor mobilization costs and economies of scale for consecutive repairs.

The third objective function is a feature in the model which allows decision makers to consider the serviceability improvements that different rehabilitation schemes can offer in the network. This third objective function has been integrated via a series of bespoke Geographic Information System (GIS) tools which are run within ESRI's ArcGIS® software. These tools are used to help account for the geo-spatial nature of serviceability incidents when determining and quantifying the serviceability benefits of different rehabilitation solutions, i.e., the prevention of a future flooding and/or pollution event resulting from a collapse. The total serviceability benefit expressed in dollars, Equation (2), is calculated in two parts: 1. The one-off avoided collapse cost, and 2. An annual operational benefit which is assumed to be realized over a 25 years period.

$$Serviceability\ Benefit\ =\ Avoided\ Collapse\ Cost + (Annual\ Operational\ Benefit * 25) \tag{2}$$

An assessment of these costs is undertaken in two stages. Firstly, the one-off cost arising as a direct result of sewer failure is quantified in monetary terms under two categories; Private *(P_R)* and Social/Environmental *(S/E)* costs. Private costs are those that are incurred by the business in response to a sewer failure and include all costs incurred to remedy the collapse. These are typically well understood and can be derived from an assessment of historic costs. Social and environmental costs are those that are incurred by society and/or the environment as a result of a collapse, i.e., disruption to traffic or pollution of a water course. These costs are typically more difficult to define and water utility providers often refer to guidance set out by the Enviornment Agency [23] to help quantify the environmental impact, or, they rely on customer willingness t**o** pay information which is linked to Operational Performance Measures (OPM's), [24], [25].

Secondly, the annualized benefit realized by a reduction in operational activity in the area is calculated via an assessment of the historic operational records and it is assumed that the frequency of these historic incidents would have proceeded at the same rate if a rehabilitation solution were not specified. Therefore, the operational benefits can be expressed as an annualized cost ($/yr) which accounts for the avoided costs by the utility providers operational team. In-order to produce a single monetary value to represent serviceability benefit, it has been assumed that the operational benefits will be realized for a 25 year period. Therefore by combining these two elements into a single serviceability benefit measure, Equation 2, a repeatable mechanism is developed which assesses all rehabilitation solutions in terms of the following benefits: private; social (customer); environmental; *and* operational. Using a geospatial platform to undertake the analysis allows for the proximity of each sewer to critical infrastructure and the environment to be considered, there-by helping to better understand the true cost of failure.

In order for a multi-objective genetic algorithm to be applied to the problem of optimal sewer rehabilitation specification, a decision environment is used to formulate the problem in-terms of; the three objective functions (listed above), decision variables and constraints. Where-by the decision variables describe the different intervention options that can be applied to each asset and the constraints are used to prevent the algorithm from considering uneconomic solutions. Once the problem is expressed in these terms, the optimization model is used to evaluate the performance of numerous intervention options and converge towards the optimal combination of solutions for the catchment. The full system architecture behind the optimization environment is documented in Ward & Savić [26].

CONCLUSION

This paper approaches the sewerage asset management challenge from a UK perspective by outlining a comprehensive methodology capable of optimizing the performance of sewerage infrastructure networks using a series of Hydroinformatic tools. In order to define, evaluate and forecast the future performance of sewerage assets, a unique deterioration model is established to predict the future condition of the network. The model analyses historic CCTV survey information to identify deterioration trends based on key pipe characteristics. Against, this improved understanding of past, current and future condition, a collapse rate is predicted by correlating historic failures against the observed sewer condition profiles. The result is a novel relationship between different cohorts of sewer and their unique rates of deterioration.

From here, a prioritized inspection programme can be delivered that targets those poorly performing (quickly deteriorating) cohorts of sewer. The survey information gather from these studies then feeds into a previously successful sewer rehabilitation optimization model that has been adapted under this new study to provide a mechanism for engineers to evaluate the trade-offs and benefits that exist between different sewer rehabilitation schemes. A series of GIS tools have been integrated within the model to identify the benefits from a serviceability perspective, thus guiding investment decisions towards those assets known to be in poor structural condition as well as causing operational issues, i.e., pollution, blockage and/or flooding events.

As a result, the methodology acts as an end-to-end asset management tool capable of helping sewerage engineers and planners in the prioritization of inspection programmes and the subsequent delivery of an optimized intervention programme of work.

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