Roland Fülöp:

Selection of water network reconstruction strategies using the space-time failure model

Theses of the PhD dissertation

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Introduction

The maintenance, the optimal reconstruction of the public works asset both from technically and economically aspect were in the center of the interest worldwide. Lots of foreign and some national publications appeared on this topic which has had priority in research and development in the last decade ***(NVP, 2010)***. The National Water Association started a journal, named is Asset Management about this topic. The European Union inquires about the condition of the public works, because 5 billion Euro was spent on them on our continent annually (***Saegrov, 2005***). Its rate is only 0.5% but the expected rate is 2%. (The planned lifetime of the pipes is 50 years in the water supply system). The CARE-W program (Computer Aided REhabilitation of Water networks) which was sponsored by EU started in 2001. It deals with the reconstruction topic of the water supply networks. In the case of sanitary systems the CARE-S (Computer Aided REhabilitation of Sewer networks) started in 2002. The Department of Sanitary and Environment Engineering participated in this last research. The network team of the National Water Technology Platform qualified it as a topic of specific interests. (***NVP, 2010***)

The rate of the water networks that should reconstruct or renew is 75%, it requires 2000 billion Ft investment on price level 2009 ***(NVP, 2010)***. We will only have a chance to replace the deficit of the reconstruction if we have adequate information about the condition of the network, and we need to concentrate on the most hazardous pipe sections when we spend the scarce budget. The base and the most important criterion should be the exact and reliable failure records, pipe material tests and systematic investigation of the pipe sections. These aren't available in Hungary at the moment except for a few water utilities.

We have to prepare for the reconstruction of the asbestos cement and KM-PC pipes based on the available Hungarian data. In case asbestos cement pipes, their high rate of 50% and the end of the planned lifetime justify our distinguished attention.

The usable network and failures records are only available for the short period of 0-4 years at the Hungarian water utilities. This records have some deficiency so we haven't any exact information about the real condition of the mentioned pipes. The classic reconstruction planning based on statistics doesn't work in Hungary. The well working decision support systems based on statistics that were published in foreign articles aren't appropriate for the Hungarian situation because of lack of data. Because of the heaviness of this problem it is necessary to determine the condition of the pipes in this situation. We need to approach the problem from more directions. One possible way is to run pipe material tests.

Not only the designation of the time of the pipe replacement, renewal belongs to the topic of the water supply system reconstruction optimized by decision support system but analyses of other possible interventions, too. The number of burst of the pipes can be decreased by the effect of these interventions, or the damages can be reduced, the lifetime of the pipes can be increased. It can positively influence the service level ***Halhal et al. (1997)***. Our aim is to determine the minimum costs of the reconstruction time of the pipe sections, where we consider reconstruction costs and the costs of the caused damages ***(Walski et al., 1982)***. The heaviest task is the determination of damage value curve because of the forecast of the failures and the quantification demand of the effects of the pipe bursts. The biggest problem is the determination of the failure numbers and its temporal distribution.

The reliable failure forecast module is the base of the every reconstruction decision support system which can be one,- dual,- or multi-criteria. The failure forecast based on statistics can only be made from reliable time series with an adequate quality ***(Park et al., 2008; Rogers and Grigg,2009),*** minimum 5 failure/pipe section.

If we don't have adequate quantity and quality evaluated data, the models that work based on mechanical correlation, the models are more exact but their input data are more complicated and expensive. The adequate cohort is the base of all statistic models, which are made by considering the factors that have influence on the aging of pipes (***Berardi et al. 2008***). The base parameters that play a role are the diameter, the year of construction, the length and material of the pipes.

The additional inner and outer environmental parameters depend on the material. The available and showed models give future failure value for some groups of pipes or for certain pipe sections. We can say the models handle the failures on pipe level. The decisions of reconstruction are made on network level. The temporal changes are described well, but they don't give any information about the place of the failure. The reliable forecast time is 5-10 years in case of most models ***(Kleiner at al., 2000).***

My conclusion is after the overview of the Hungarian situation that the reconstruction of the water supply systems is the most important task in order to maintain the safe water supply for the next 20 years.

The suggested methods in foreign publications can't be adapted directry to the Hungarian situation.

The aims of my dissertation

(i) Cost-effective analysis method for the determination of the load capacity of the asbestos cement pipes, that can be directly used in practice. (1th thesis)

(ii) Space-time modelling for the water networks failures. (2nd, 3th, 4th thesis)

(iii) Development of a reconstruction decision support system, that can be used with the imperfect, low quality registry data of the national water works in many case. (5th, 6th thesis)

The methods of the analyses

34 pipe samples came from the 11 water works of different areas of the country. These samples gave base strength parameter for the load model ***(Mészáros et al., 2010; Schlick, 1940)*** of the pipes. I let the analyses made according to the standard MSZ 4742-1:1989. I created a uniform sampling protocol to the data collection, this protocol contains the inner and outer environment data of the pipes. I created my 1^{th} thesis based on the these pipe material tests.

Reconstruction planning based on the statistic is difficoult because of the lack of the data and poor quality of the data. I selected the service area of Zalaviz Zrt within downtown of the Zalaegerszeg where the data of the failures had an adequate quality to develop my reconstruction support system.

The main feature of the analyzed system is that the aspect of the failures are homogeneous the area. I used cell analysis to analyze the spatial place of the pipe failures. I found that the spatial location of the failures is random. Spatial point processes are useful as statistical models in the analysis of observed patterns of points ***(Baddeley et al. 2005, Pélissier et al. 2001),*** where the points represent the locations of some objects of study, like here the pipe failure locations. The homogenous spatial point process was used for description of the similar type event ***(Bogárdi et al., 1982).*** The spatial point process has never been used for description of the failures in the water supply network yet. I validated the homogeneous spatial Poisson process by comparing it with the cumulative relative frequency and the theoretical distribution of failure distance (3^{th} thesis)

The assumption of the homogeneous spatial Poisson process was validated by using double size cells. Then I generated a homogeneous spatial failure distribution (4th thesis) which is the base for the additional calculations in my algorithm and software. We need to treat the spatially and temporally inhomogeneous failures for analyses of the reconstruction alternatives so that in the next step I am able to create the inhomogeneous distribution of the failures in space and time by the separation of the renewed areas (5th thesis). With this the effect of renewal on failures can be analyzed. I used failure impact (FI) index that was calculated on a hydraulic basis to analyze the effects of the breaks (6th thesis) with which the size of the annual closed area was analyzed on the whole water network in Zalaegerszeg. The concerning area failure impact factor was one of the criteria, the costs that were spent on the water network (repair, renewal costs) were the other criteria in my decision support system that I used to analyze the reconstruction alternatives (7th thesis).

Summary of results in the theses

The elements of the reconstruction selection in the water supply system by space-time modeling were summarized in the thesis. The most important elements are the 1st thesis which refers to the pipe material tests, 2nd, 3th, 4th theses which belong to the failure modeling by space time Poisson point process. The dual objective reconstruction decision support was formulated in the 5th and 6th theses.

1st thesis:

I determined a correlation between the bearing capacity and water absorption according to my results of the pipe material tests:

$$P = -1,2 \cdot V + 66,3$$

where:

V – water absorption weight %

P – Compressive strength (MPa)

The importance of the correlation lies in its practical usage if the measuring of the water absorption is cheap and it doesn't require taking out the undamaged pipe section from the water supply system. The calculated compressive strength is only an approximate value, which is precise enough for the selection of the reconstruction technology.

Publication of thesis:

(Fülöp 2012).

2nd thesis:

I verified that the location of the failures in the water supply system can be determined with a 2 dimensional homogenous Poisson process if the spatial distribution of the conduits on the assigned area is uniform, and operational and environmental conditions are similar.

Publications of thesis:

(Bogárdi-Fülöp 2011)

(Bogárdi-Fülöp 2012)

3th thesis:

I modeled the pipe failures in the water supply system by a random spatial point process. In case of parameters that are determined in advance I created the determination method of the expected failures place distribution according to the following steps:

1. I generate a Poisson value for the failure numbers of the analyzed region based on the expected value (Λ) which is calculated from the time interval of failures, this value can be derived from ROCOF function. The Poisson value gives the failure numbers (N) on the region.
2. The Poisson type spatial distribution of the failures can be calculated from the failure value in the first step:
   2.1. Uniform distribution of the failures (N) points on the analyzed region.
   2.2. Generating a random radius d between a uniformly distributed point (2.1) and its nearest neighbour from the distribution function

   $$F_D(x) = P(D \leq x) = 1 - e^{-\lambda \pi x^2}$$

   2.3. Finding a possible failure location where d crosses a pipe. If d crosses several pipes we have to select one of them randomly. This point is a possible place of the failure.

The showed algorithm can limit the freedom of the spatial point process for pipe objects without losing the typical features.

Publications of thesis:

(Bogárdi-Fülöp 2011)

(Bogárdi-Fülöp 2012)

4th thesis:

I created the algorithm for failure points determination according to Poisson process which is homogeneous in space and inhomogeneous in time for the water supply network, where the water network can be characterized by time-varying specific failure rate. The probability that N failures occur is

$$P[N(A,(\nu,\mathrm{t}+\nu))=\mathrm{n}]=\frac{[\Lambda(\mathrm{t},\mathrm{t}+\nu)\mathrm{A}]^{\mathrm{n}}}{\mathrm{n}!}\,\mathrm{e}^{-\Lambda(\nu,\mathrm{t}+\nu)\mathrm{A}} \quad \text{ahol n = 0,1,2,…}$$

ahol:

$P(N=n)-$	Summarized probability of the failure numbers
$n-$	failure numbers on the analyzed region (n = 0,1,2,…)
$A-$	the area of the analyzed region
$\Lambda-$	intensity parameter of the failure for the time period (t, t+υ) (failures/area or failures/cell)

I developed an application method of the algorithm for networks that vary after the reconstruction. Substance of the algorithm is the separation of failures in space and time on the reconstructed area, the original system is needed to be divided into homogeneous objects.

Publication of thesis:

(Bogárdi-Fülöp 2012)

5th thesis

Because some parts of damages which derive from the lack of the service and nuisance at the consumers are difficult to express in economic terms, I created the failure impact index. The impact index is an expected value of the weighted areas, that belong to the pressure reductioned junctions. I determined the index value from the combination of the water network hydraulic model and space time failure model

Publications of thesis:
(Fülöp 2011)
(Bogárdi-Fülöp 2012)

6th thesis:

I verified that failure patterns that are described with the spatial Poisson process are suitable to be connected with a dual objective decision support system. I developed a decision support system that takes calculated pressure reduction and the consumer impact failure index into consideration. The pressure is calculated by a hydraulic model. The impact of failure can be considered on the whole service area. The method supports the selection of the most suitable reconstruction alternative, the alternatives are determined by the stakeholder.

Publication of thesis:
(Bogárdi-Fülöp 2012)

Possibilities of practical adoption

Within the pipe material test project I also developed a cost efficient test method, which is able to provide the approximate bearing capacity for the static analysis of the pipes using simple laboratory tests. Based on the static analysis of the pipes the water utility can decide about the necessity of the reconstruction (condition assessment), and also about the available reconstruction methods.

I developed a reconstruction decision support method in my research, to which a user friendly Autocad application and an Excel and a HCWP 6.1 applications as utility software belong as well. With these we can evaluate the effect of the given renewal variant effectively in the Hungarian water supply system.

The additional advantage is, that we can analyze the spatial variations of failures without knowing the long term failure events with spatial locations as input data. The water utilities can analyze the effects of the planned reconstruction strategy for a 5- 10 year term with this software package.

The advantage of the developed method is that it can manage the spatial variance, spatial effect of the events. This statement can' t be made about those methods, that don't calculate with the pipe sections in space and they can give prediction of the failures or those effects on a pipe section or on a set of the pipes. I can say that with the decision support system I developed the failures can be calculated on network level, it can be adopted easily to the GIS system, the temporal effects can be tracked in space.

We can declare that an effective reconstruction decision support system was created for the public workers. It can be said considering the showed Hungarian situation and the experience of the failure modeling with the spatial Poisson point process and because of the experience of applying the dual objective decision support as well.

The results presented in the dissertation help not only to make reconstruction decisions but also to analyze other developing options. For example a possible alternative method of reducing damage when a pipe bursts is, if we reduce the closed pipe length. This method doesn't give a final solution for the increasing failure numbers, which derive from the lack of the reconstruction. The principle of the method is that we reduce the length of the pipe section with the optimal placement of the valves. If the number of valves is higher, the operator can close shorter pipe sections and fewer consumer stay without water supply. Increasing of the valves number increase the operating and maintenance costs. The aim of the owner is to find the optimum between the valves' number and damage which come from lack of the service. The presented method is adequate to deal with this problem.

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