PRIORITIZING WATER PIPE RENEWAL USING FUZZY SET THEORY

PRIORYTYZACJA ODNOWY PRZEWODÓW WODOCIĄGOWYCH Z ZASTOSOWANIEM TEORII ZBIORÓW ROZMYTYCH

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Abstract: *The aim of this paper is to present the novel approach to risk assessment in combination with failure and consequence analysis, depending on two parameters defined by the fuzzy functions: the repair time of water pipe and the cost of water pipe repair, what allow to determine particular risk levels. The presented methodology can be used to describe the functioning of the public water supply in terms of its renewal.*

Keywords: *water network, water supply, water pipe renewal, fuzzy set theory*

Streszczenie: *Celem niniejszej pracy jest przedstawienie oceny ryzyka w połączeniu z analizą awarii oraz konsekwencjami, w zależności od dwóch parametrów określonych przez rozmyte funkcje: czas naprawy poszczególnych przewodów wodociągowych, jak również kosztów naprawy przewodów, co pozwoli określić, poszczególne poziomy ryzyka. Przedstawiona metodologia może być stosowana w celu opisanie funkcjonowania wodociągów publicznych oraz w zakresie ich odnowy.*

Słowa kluczowe: *sieć wodociągowa, zaopatrzenie w wodę, odnowa sieci wodociągowej, teoria zbiorów rozmytych*

1. Introduction

Infrastructure systems constitute the biggest assets of cities, thus it is important to provide adequate renewal management of ageing water pipe network and enhance the effectiveness of operation. Many research focus on deterioration of water network and rehabilitation methods eg. (Hastak, Baim 2001; Vloerbergh, Blokker 2010) but still there is a need of application of pilot program (resilient to risk disturbance) for water pipes to assess its condition.

Human impact on the infrastructure of collective water supply system is influenced by many subjective factors that are difficult to be represented by a single Gaussian probability distribution function. The average human thinking operates with qualitative notions which are incomplete, imprecise, unclear, contradictory or in any other way inadequate. This imprecision is due to the subjective assessment of a given feature by individual experts, which leads to blurring the boundaries of a set of elements to which this feature applies (Tchorzewska-Cieslak 2011). In many cases risk analysts use linguistic description and cause-effect relationships to assess risk rather than the precise physical or mathematical reference (Pietrucha-Urbanik 2014). Effective risk assessment is based, among others, on probabilistic data, experts opinions and linguistic descriptions. It is the next obstacle which reduces the effectiveness of probability theory in risk assessment, therefore a method that takes into account all of the mentioned features of risk assessment is needed (Cai 1996). If the available knowledge about failures or its consequence is qualitative or subjective, the risk assessment requires applying special analysis methods, eg.: Failure mode and effects analysis - FMEA, Event Tree Analysis - ETA, Interval Analysis - IA, Probability Bound Analysis - PBA and Fuzzy Set Theory - FST. In the article considerations were limited to the risk analysis with method of Fuzzy Set Theory, which is an alternative to probability theory. The ancient classics of philosophy have already pointed out that between truth and falsehood there is the third area having the features of the first two. Mathematical foundations of fuzzy logic were formulated in the mid-sixties of previous century by Lotfi A. Zadeh in the work "Fuzzy sets" (Zadeh 1965), based on the work of Polish mathematician John Łukasiewicz, a creator of multi-valued logic. The theory of fuzzy sets has been used in risk analysis in various fields of engineering in which indistinctness and ambiguity occur.

The vast majority of quantitative methods of risk analysis is characterized by a sharp boundary of change of risk category (eg. the risk factor matrix method or the risk score method) (Rak 2009). In the methods of this type, after determining the quantification of risk, risk is classified into one of the predefined categories. Below a certain point limit the risk is acceptable, above this limit it is unacceptable. L.A. Cox in (Cox 2008) described the problems that may arise during the use of the risk factor matrix method and a role of an accuracy (error, uncertainty) during determining risk components - the probability of undesirable event and potential consequences.

The objective of this work is to characterize the unreliability of the water-pipe network in one of the biggest city in the south Poland. The proposal to apply fuzzy logic in determining the appropriate level of functioning was presented, based on data concerning the repair time of water pipe and the cost of water pipe repair.

2. Failure indicator of water network

Water pipes failure is one of the most important indicators used to evaluate the technical condition of the network and the operational situation of water supply. In the technical literature, this indicator is called "failure rate" and expresses the number of failures per one kilometre of water pipes throughout one year. It is not entirely defined, which damages are eligible for this statistic, but most often it is the total number of pipelines failures. The number of failures and intensity failure for water supply system in relation to the length of 1 km in the unit of time equal to one year using the formula (Kwietniewski et al. 1993):

$$\lambda = k/(L \cdot \Delta t), [\text{no of failure/km} \cdot \text{year}] \quad (1)$$

where: k is the total number of failures on the type of network [-], L is the length of the given type of network [km], Δt is the unit of time equal to one year.

The probability of λ occurrence with less for the water mains is as follows: $\lambda_{M0,25} = 0.06$, $\lambda_{M0,50} = 0.09$, $\lambda_{M0,75} = 0.12$, and the average failure indicator value for water supply connections is $\lambda_{Pavg} = 0.53$ and for distributional pipes $\lambda_{Davg} = 0.62$. The values of failure indicator should not exceed the following required values for the mains $\lambda_{reqM} = 0.3$ [no of failure/km·year], for the distributional pipes $\lambda_{reqD} = 0.3$ [no of failure/km·year] and for the water connections $\lambda_{reqP} = 1.0$ [no of failure/km·year] (Rak 2005). In the examined water network only the distributional pipes do not meet European standards. Detailed analysis of the distributional pipes characterized by a particularly high failure intensity indicated that these pipes are made of cast iron (with an average age - 50 years).

3. Analysis of the water supply system operation

The basic quality parameter of service is its availability, including the duration of interruptions in water supply. This nuisance is proportional to the size of failure, the number of people affected by failure and the duration of interruptions in water supply, what can be described in the following way:

$$IR = I_u/R_i \quad (2)$$

where: IR is the customer interruption, I_u is the sum of unplanned interruptions of water supply and R_i is the total number of recipients.

and

$$T_{avg} = D_T / I_T \quad (3)$$

where: T_{avg} is the average time necessary to restore the water supply in case of unplanned interruptions in water delivery, D_T is the sum of the duration of all interruptions in the water supply and I_T is the total number of water interruptions.

The average time necessary to restore the water supply in case of unplanned interruptions in water delivery in the examined water network is shown in Figure 1.

Fig. 1 Histogram of relative frequency
 and time-frequency summed renewal curve of water pipes

The service availability determined quotient of the time of the continuous water supply throughout the year and the time when there was the demand for water, can be reflected through following expression:

$$SA = (R_i \cdot 1 \text{ year} - R_i \cdot D_T) / (R_i \cdot 1 \text{ year}) \quad (4)$$

where: SA is the availability service indicator.

The average values of presented indicators from 7-years period of time, on the example of the examined water supply system, were as follow: $IR = 1.2$ no of failures per recipient and year, $T_{avg} = 3.5$ h per failure and $SA = 0.9827$.

4. Method for estimating risk connected with renewal of water network

Risk defines the relationship between the probability of threat (P) and the frequency of consequences (C), as shown in the following relation (EN1050 1996, Rak 2004):

$$r = P \cdot C \quad (5)$$

Adopting triangular fuzzy functions describing the individual risk factors was based on data received from water authorities and derived from exploiters of the water supply system. Criteria of the risk assessing suggested in the work were based on the mentioned above information. Levels of risk associated with threats in the water supply system were described by means of the equation 1. An accurate evaluation of the degree of membership in fuzzy sets is generally very difficult because it requires the use of complex mathematical functions. This degree can be determined based on the probability level of potential risk and its possible consequences. The shape of membership function is strictly dependent on the type of problem which we want to present in this way. In practice, the consequences of a given risk can be represented by various measures, such as: financial loss, loss of customer(s) or permanent (or temporary) reduction in the market share. The whole difficulty of applying a triangular function to estimate the value of probability lies in the fact that the estimated consequences are of different units, therefore the consequences were normalized. A practical mathematical tool to present the probability of risk and its consequences by means of membership of fuzzy sets is the so called triangular function.

The failures in water pipes in the examined city, associated with the water network failures, in the years 2004÷2013, were analysed. Data were obtained from water supply failure records.

The various categories of probabilities are as follow:

- Parameter "A": probability, that repair time of water pipe is $\leq 4 \text{ h} \cdot \text{a}^{-1}$.
- Parameter "B": probability, that repair time of water pipe is $0 \div 6 \text{ h} \cdot \text{a}^{-1}$.
- Parameter "C": probability, that repair time of water pipe is $4 \div 8 \text{ h} \cdot \text{a}^{-1}$.
- Parameter "D": probability, that repair time of water pipe is $6 \div 10 \text{ h} \cdot \text{a}^{-1}$.

and the consequences:

- Parameter "A": very low: cost of water pipe repair below 400 EUR, without structural material changes or defects, minor scratches, and/or λ is less than 1,0 failure/km·year,
- Parameter "B": low: 200 to 600 EUR, less than 10% of pipe distortion and/or λ is more than 1,0 failure/km·year,
- Parameter "C": medium: cost of water pipe repair from 400 to 800 EUR, from 10% to 20% of pipe distortion, leaks in connection can occur and/or λ is more than 2,0 failure/km·year,
- Parameter "D": high: cost of water pipe repair from 600 to 1000 EUR, leaks in connection can occur, badly condition of a pipe, large pipe distortion and destruction, cracks, the collapse of parts of the water pipes, and/or λ is more than 2,0 failure/km·year.

The implementation proposed in the work of fuzzy logic lets for determining the risk associated with renewal necessity depending on two parameters defined by fuzzy functions: duration of deficiency in supplies of water and the cost of water pipe repair and will enable to determine individual levels of risk.

Based on the above analysis the water supply company can determine the risk connected with occurring failure. According to these data, the waterworks company can provide a plan of water network renewal.

The standard categories of risk levels R are defined by the relationship between the fuzzy variables of risk occurrence P and its possible consequences C . The rules of inference were defined and presented in the Figure 2.

Fig. 2 Fuzzy risk matrix with recommendations for renewal

On the basis of the presented matrix of the risk connected with guaranteed level of service, the following categories of the risk were suggested:

- tolerable risk; any actions conducting are not necessary; it can be assumed that the water supply system fulfils its functions satisfactorily, with regard to both operational reliability and safety, but further inspections are recommended,
- controlled risk; considering the possibility of further reducing the level of risk or ensuring that the risk remains is at least on the same level, an improvement in the work of some elements of the system (e.g. network monitoring) or repair of some sections of the water-pipe network should be considered, or else rehabilitation through restoring or upgrading the performance of existing water network,
- unacceptable risk; immediate actions in the objective of the risk lowering should be taken; the water supply system does not fulfil its functions, with regard to both operational reliability and safety, construction of a new pipe with the same performed function.

The presented method for estimating risk can be used in operational practice of waterworks companies, especially it will help to improve the effectiveness of the system to meet the statutory service to supply tap water to customers, to improve customer protection and comfort, and will cause the legal alignment between a customer and a water producer. Its practical application generally means the possibility to establish methodology for reliability analysis and assessment, associated with consumers safety in the water supply system.

5. Conclusions and perspectives

The implementation of fuzzy logic proposed in this paper allows to determine the risk of receiving the guaranteed level of water supply services availability depending on defined by fuzzy functions two parameters: the duration of the lack of water supply and the cost of water pipe repair and will allow to specify different levels of risk. The use of the proposed procedures can significantly support risk analysis of water supply network. Establishment of different levels of risk, including an acceptable risk, is a very important issue that requires the use of experience from water practice. The important problem is also to establish the criteria values of risk levels, which should be made by cooperating teams of experts in the field of methods of risk assessment and experienced engineers, as well as based on the statistic data on the water supply system operating. Analysis of fuzzy levels of water service availability allows the use of different criteria, as well as connection between parameters and variables.

Decision-making scenarios taking into account the incurred costs and obtaining relative or large profits offer a strategies choice of conduct. Selection for particular groups of undesirable events associated with the operation of water supply system should be preceded by a detailed risk analysis and assessment.

6. References

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