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RESEARCH ARTICLE

Modelling of Failure Rate of Water-pipe Networks

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Abstract

The paper describes the reliability of selected water-pipe networks in Polish medium-sized cities X and Z. The main goal of this research was to compare the results of failure rate modelling with the experimental data. On average, in the analyzed time the main conduits and the distribution and service pipes in city X were characterized by failure rates (fail./(km · a)) of 0.27, 0.40 and 0.59 while in city Z the failure rates amounted to 0.30, 0.32 and 0.78. The model described in the literature has been slightly modified (as a result, model M3 has been created) by the author to achieve better agreement with the experimental data. In the future, model M3 will be extended to ensure a larger prediction domain, which will make it more suitable for planning renovation schedules.

Keywords

failure rate · mathematical models · water-pipe networks

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1 Introduction

A water supply network is an essential part of the buried infrastructure. Water of proper quality should be delivered to consumers under the required pressure and in the required amount. In order to achieve these goals it is necessary to continuously monitor the technical condition of the water pipes. Proper maintenance and operation are critical for the reliability and safety of the water-pipe network. The control of the pressure inside the pipes is one of the measures leading to a decrease in the number of failures and in the unreliability of the whole system [4]. Another performance optimization measure is mathematical modelling and forecasting, which use typical models, artificial intelligence and some reliability indicators. Thanks to modelling one can relatively quickly assess the condition of water pipes [20]. According to many authors [3, 15, 17], the modelling of reliability indicators and technical condition and then using the modelling results by water utilities can lead to an increase in water supply network efficiency and in water quality. Also an improvement in the management of the system can be achieved in this way. Moreover, through modelling one can correctly estimate the costs of water pipe reconstruction [2, 21].

2 Aim and range of studies

The main goal of this study was to compare the failure rates determined using the mathematical model proposed in [19, 20] with the results of the author's own investigations based on operational data coming from two water utilities [14]. The model proposed by Shamir and Howard [19] was modified to achieve better agreement with the experimental data. Since the water-pipe network of each city is different it seems important to create a model which will predict failure rates for the particular city and for the specific practical purposes. For a water utility such a model will constitute a suitable tool for maintenance planning.

A comparative analysis was carried out for one reliability indicator (failure rate λ) calculated for the water mains and the distribution and service pipes in medium-sized Polish cities X and Z in the years 1999 - 2012 and 2001 - 2012. The two analyzed water-pipe networks are part of the buried infrastructure of the two cities. City X is situated in a mining area and its old water pipes (made of steel and grey cast iron) are being systematically upgraded and renovated. In city Z mainly house connections are upgraded or replaced when they are characterized by a high failure frequency. The length of the main conduits is stable in the two cities. The length of the distribution conduits has significantly increased – by about 14% and 32%, i.e. by ca. 16 km and 29 km, in respectively city X and Z. The increment in the length of the service pipes is similar in city X and city Z, amounting to about 21%. The material structure (at the end of 2012) of the main and distribution conduits is shown in Figs. 1 and 2. In the two systems over half of the total length of the main and distribution pipes is made of grey cast iron, which contributes to a high frequency of failures. In places where new materials predominate the situation is quite different. Studies carried out in Poland and abroad have shown that pipes made of PVC or PE are characterized by lower failure rates, even below 0.10 fail. / (km · a) [5, 10, 11, 13, 15, 18].

3 Materials and methods

There are many mathematical models which are used to forecast the technical condition, number of failures and reliability of water-pipe networks. A detailed description and a critique of the existing statistical models and physically-based models were presented by Kleiner and Rajani [8, 16]. Today some modelling approaches do not require the use of operational data [6, 9], which theoretically should reduce the time of analysis. However, the quality of modelling in such cases can be lower since the forecasting process is based not on real data (from existing water utilities), but on artificial data. Still the majority of modelling approaches are based on operational information [1, 7, 22]. Therefore it seems worthwhile to compare the results of modelling with experimental data coming from two Polish water utilities in order to check whether the models proposed in the literature are valid for the water-pipe operating conditions in Poland.

The failure rate Eq. (1) was forecasted on the basis of the deterministic model proposed by Shamir and Howard [19], also described in [9, 20, 21].

$$\lambda\,(\mathrm{t}) = \lambda\,(\mathrm{t_0}) \cdot \mathrm{e}^{\mathrm{a}\cdot(\mathrm{t}-\mathrm{t_0})} \tag{1}$$

where

- $\lambda(t)$ The failure rate at time t, fail. / (km · a);
- $\lambda(t_0)$ The failure rate at time t_0, fail. / (km · a);
- t The current time of analysis, year;
- t_0 The initial time of analysis, year;
- a A coefficient dependent on the diameter and material of the pipe.

As mentioned by, e.g., Kleiner [8], the above model is simple, but it has some limitations. Its main assumption is the exponential increment of the failure rate in an analyzed period of time. Also Walski and Pelliccia [21] referred to the above mentioned model, indicating that also other factors (e.g. pipe size and temperature) should be included in the model. They calculated the time of optimal pipe replacement using another equation proposed by Shamir and Howard. According to their results, based on operational data from water-pipe networks in the USA, reported in [21], replacement was not needed at that time. The regression models proposed by Walski and Pelliccia were evaluated for selected water supply systems.

It should be noted that each water network is different as regards its changeable operating conditions, the climate and the pipe material quality. The coefficients and parameters used in the model are specific exclusively for a particular water system. Therefore it seems reasonable to apply the such modelling approach, which can also be used for forecasting in the future, to the water-pipe networks in the selected Polish cities. Coefficient “a” varies in the range of 0.05 - 0.15 [19, 20]. Three values of this coefficient (0.05, 0.10 and 0.15) were used to predict the failure rate in the water network in city X and Z, respectively. The simple model described by relation Eq. (1) was chosen for the comparative analysis to vividly demonstrate that many changeable parameters (e.g. pressure traffic [3]) should be taken into consideration in the prediction of the technical condition and the failure rate. Unfortunately, some detailed information, which theoretically should be included in the model, is difficult to obtain from water utilities in Poland and abroad. For this reason the failure rate level generally has been assessed on the basis of relationship Eq. (2) where all the variables are known [5, 10, 11, 13, 23].

$$\lambda = \frac{\mathrm{N\,(t)}}{\mathrm{L} \cdot \Delta\mathrm{t}} \tag{2}$$

where

- N The number of failures, unit;
- Δt The analyzed period of time, year;
- L Length, km.

In order to achieve better agreement and to include the operating conditions of the water pipes, a modification of model Eq. (1) was proposed by the author. The modification, described by relation Eq. (3), concerns the modelling of the failure rate. It was found that the difference between model Eq. (1) and the second-degree polynomial yielded good results in the modelling of the failure rate in two Polish cities X and Z. An attempt was made to use a linear function instead of the polynomial, but the agreement between the modelling results and the experimental data was not satisfactory from the engineering point of view. As mentioned above, water utilities do not record all the necessary information about the operation of the system. Very important data such as: the pipe-laying depth, the kind of soil, the pressure traffic, the age of the pipes and other are not available for modelling purposes. This is why a simple formula is needed to predict the failure rate. In the proposed modification (a second-degree polynomial) of the model described in the literature, only

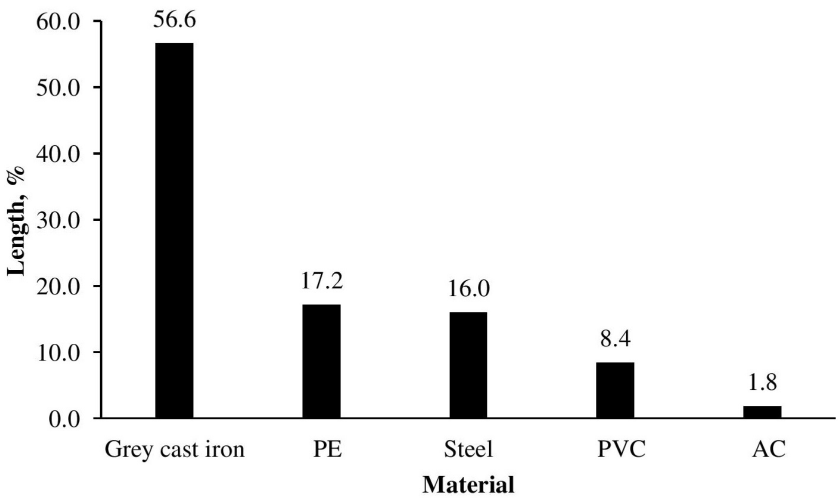

Fig. 1. Material structure of main and distribution pipes in city X

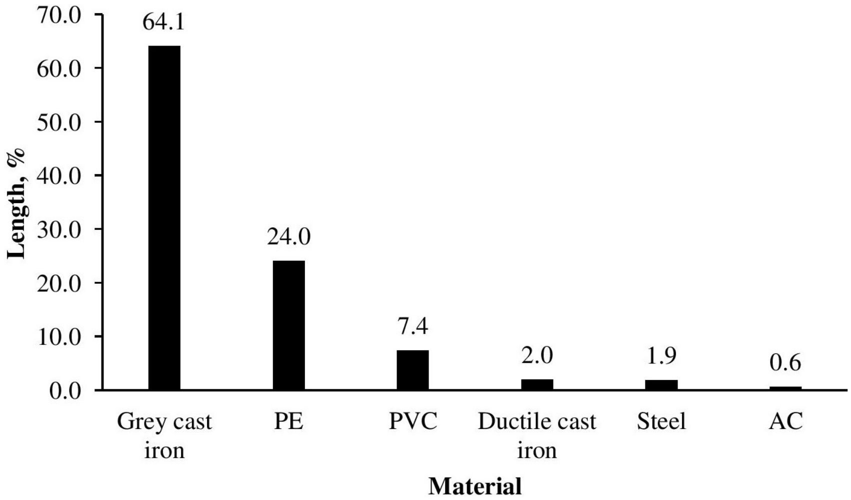

Fig. 2. Material structure of main and distribution pipes in city Z

time is a variable which needs to be known. Constant coefficients D, C and E should be determined on the basis of the way in which the selected water-pipe network is operated and maintained.

$$\lambda(t) = \lambda(t_0) \cdot e^{a\cdot(t-t_0)} - \left[D(t-t_0)^2 + C(t-t_0) + E\right] \quad (3)$$

4 Results and discussion

The experimental failure rate values from the two Polish cities are represented by the solid line. The results obtained using model Eq. (1) and Eq. (3) with three values of coefficient "a" (0.05, 0.10 and 0.15) are denoted as respectively "M1, a" and "M3, a" in the figures. One should bear in mind that model M3 characterizes the water supply network which is currently in operation. Therefore the classic "bathtub curve" of the life cycle of a buried pipe is not valid in this case.

The rate of failure of the main conduits during the 14 and 12 years of their service in respectively city X and city Z has been decreasing Figs. 3 and 4. The maintenance of the water mains has been improving and a smaller number of failures has been registered year by year. On average, in the analyzed time, the main conduits were characterized by similar of failure rates, amounting to 0.27 fail./(km · a) and 0.30 fail./(km · a) in city X and city Z, respectively.

An analysis of Figs. 3 and 4 shows that the failure rate values obtained using model M1 differ significantly from the results obtained on the basis of the operational (experimental) data and the ones obtained using model M3. As mentioned before, model M1 includes only time as a factor contributing to the deterioration of water pipes: as time increases so does the failure rate. But from the engineering and operational point of view the failure rate is rather a random phenomenon depending on external factors, such as: temperature, pressure, pipe-laying depth and pipe material and diameter [5, 21]. Obviously, water-pipe network deterioration increases over time due to many factors (e.g. workmanship, the kind of material and the pressure inside the pipes), but not so significantly as shown in Fig. 3 (line M1, $a = 0.15$). According to Shamir and Howard [19], coefficient "a" depends on the kind of material, but there is no information about the values of this coefficient for pipes made of grey cast iron, steel or other material. It appears from Fig. 4 that the experimental failure rates for 2011 and 2012 were equal to zero. This is the reason why model M3 yielded decreasing failure rate values. The model simply tried to imitate the reality.

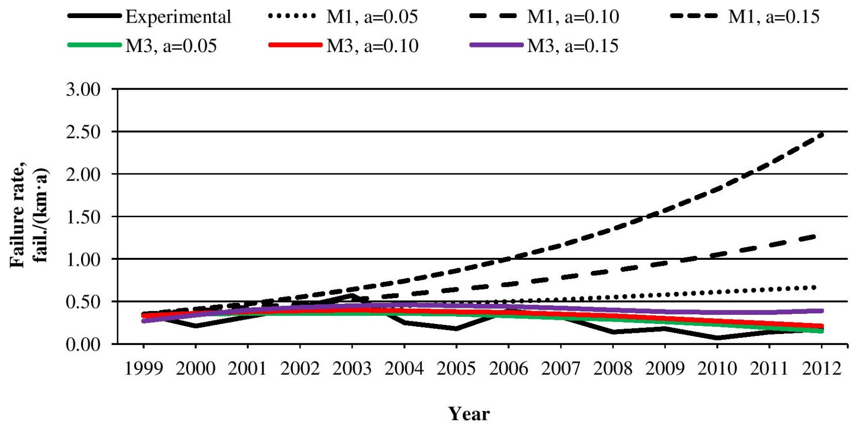

Fig. 3. Experimental and forecasted failure rate of water mains in city X

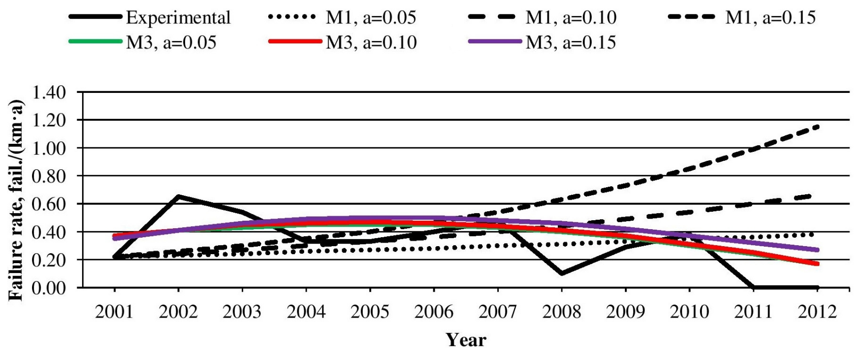

Fig. 4. Experimental and forecasted failure rate of water mains in city Z

In the proposed modification of failure rate modelling Eq. (3) time is also the only variable, but constant coefficients D, C and E contribute greatly to the convergence with experimental data. The proposed values of the coefficients, determined by the author on the basis of the analysis of the operation of the water-pipe networks in cities X and Z, are presented in Table 1. Parameters D, C and E should be treated as empirical coefficients. They have a physical meaning since they depend on physically based factors such as pipe diameter or material. It should be noted that the values of parameters D, C and E will be different for each water-pipe network due to the different operating conditions, such as: the frequency of pipe section renovation, the kind of renovation (materials used), the influence of a mining area, the frequency of pipe inspections, general maintenance and the diameter and function the pipes (main, distribution or service pipes). Therefore each water-pipe network should be considered independently.

Model M3 can be used for predicting the failure rate in other water systems but the values of constant coefficients D, C and E should be determined after an in-depth analysis of the maintenance of the particular water-pipe network since they depend on various factors peculiar for each network, which should be taken into account. Also the knowledge of the history of changes in the values of the reliability indicators, such as the failure rate, is very important and should be taken into consideration in modelling. Constant D is very similar for the main conduits in city X and city Z. The values of coefficients D, C and E are different for each of the cities. This means that the operating conditions and the maintenance are not the same. The deterioration of the water pipes in city X is caused by, among other things, mining. The ground movements caused by mining contribute to failures of the pipes. However, the deteriorated pipes are replaced more often. City Z is not situated in a mining area, but the renovation of the damaged pipe sections is not planned and only the most vulnerable parts are replaced.

An analysis of the failure rate of the distribution conduits in city X (Fig. 5) shows convergence between model M3 and the experimental results. According to the author's investigations, the failure rate decreased slightly from 0.67 fail./(km · a) in 1999 to 0.42 fail./(km · a) in 2012. The model proposed in this paper (Eq. (3)) better predicts the failure rate of the distribution pipes in the two Polish cities than a typical deterministic model. In reality, the failure rate does not increase over time as quickly as it appears from Figs. 5 and 6 (lines M1). Some pipe sections (characterized by a high failure frequency) are replaced with completely new pipes. Failure rate modelling should take into account information about the actual maintenance, e.g. the kinds and time of upgrading pipe sections. The approach proposed in this paper is an attempt to include information on pipe renovation in modelling. Empirical coefficients D, C and E, among other things, provide such information.

The average experimental failure rate of distribution pipes amounted to 0.40 and 0.32 fail./(km · a) in respectively city X and city Z. The failure rates predicted by model M3 for different values of coefficient "a" amounted to 0.38, 0.42 and 0.50 fail./(km · a) in city Z.

Tab. 1. Values of constant coefficients D, C, E in the city X and Z

	a	City X			City Z		
		D	**C**	**E**	**D**	**C**	**E**
Main conduits	0.05	0.003	0.000	0.017	0.006	-0.033	-0.148
	0.10	0.006	0.003	0.019	0.008	-0.030	-0.149
	0.15	0.014	-0.029	0.077	0.012	-0.041	-0.128
Distribution pipes	0.05	-0.003	0.108	-0.084	0.004	0.002	-0.029
	0.10	0.003	0.113	-0.078	0.007	0.010	-0.034
	0.15	0.018	0.051	0.035	0.014	-0.009	-0.004
Service pipes	0.05	0.004	-0.006	-0.061	0.014	-0.025	-0.118
	0.10	0.009	-0.001	-0.058	0.021	-0.006	-0.131
	0.15	0.021	-0.054	0.038	0.039	-0.052	-0.058

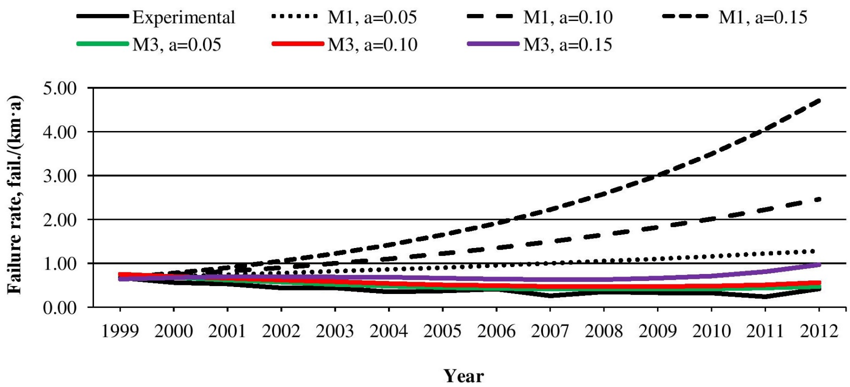

Fig. 5. Experimental and forecasted failure rate of distribution pipes in city X

The climate and the depth of frost penetration are random factors which depend on the region and the year. They are also very important factors having a bearing on the changes in the failure rate year by year [21]. The constant coefficients in the proposed model M3 depend on the local conditions and include information about the temperature changes. The relative errors are listed in the Table 2.

Indicator λ for service pipes in city X and city Z is shown in Figs 7 and 8, respectively. The failure rates for city Z were predicted with higher relative errors than for city X. Still the results obtained using model M3 are better than the ones yielded by model M1. On average, the experimental failure rates for the service pipes amounted to 0.59 and 0.78 fail./(km · a) in respectively city X and city Z. The average failure rates predicted by model M3 for the different values of coefficient "a" were equal to 0.66, 0.70 and 0.86 fail./(km · a) in city X.

From the engineering point of view, the relative errors for the main pipes and the distribution pipes are acceptable. The discrepancies between the experimental data and model M3 are quite large only for service pipes in city Z.

Better agreement (than the one described above) between experimental data and modelling results ($R^2 = 0.989$) was obtained by Tabesh et al. [20] who modelled the failure rate by means of an artificial neural network. Generally, artificial intelligence predicts some operational parameters slightly better than typical models [7, 12, 22]. For example an ANN forecasted the failure rate in one Polish city with agreement at the level of $R^2 = 0.95$ and $R^2 = 0.92$ for service and distribution pipes, respectively [12].

5 Conclusions

The following conclusions can be drawn:

- The reliability of the water-pipe networks was determined on the basis of a single major indicator – the failure rate.
- The forecasting of the failure rate, using the proposed regression model M3, was characterized by an acceptable, from the engineering point of view, level of convergence with the experimental data. The relative errors were in ranges of 3.64 - 29.29% and 4.33 - 42.75% in city X and city Z, respectively. The discrepancies between model M1 and the experimental data were larger because the model assumed that deterioration was simply due to ageing. Such an assumption is correct only if the pipes are not modernized. Model M1 did not include any information about other factors having a bearing on deterioration (pressure, water demand, pipe material, kind of soil, pipe-laying depth, frost penetration, climate) or about the renovation or replacement of pipe sections. The restoration of the deteriorated parts of the water supply system is a very important factor which should be included in the models.
- Water-pipe networks differ from each other and their maintenance depends on many factors such as: the size of the city, the pipe-laying depth, the climate, the age of the pipes, etc. This is why models should include information about the changeable conditions of maintenance and operation. It

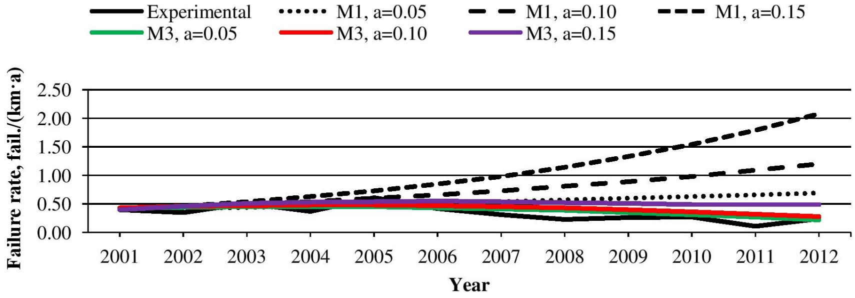

Fig. 6. Experimental and forecasted failure rate of distribution pipes in city Z

Tab. 2. Relative errors of model M3 in the city X and Z

	a	Relative error, %	
		City X	City Z
Main conduits	0.05	3.64	6.17
	0.10	7.00	7.08
	0.15	13.21	10.92
Distribution pipes	0.05	9.79	4.33
	0.10	15.14	7.92
	0.15	29.29	16.25
Service pipes	0.05	6.14	13.00
	0.10	10.50	24.33
	0.15	26.00	42.75

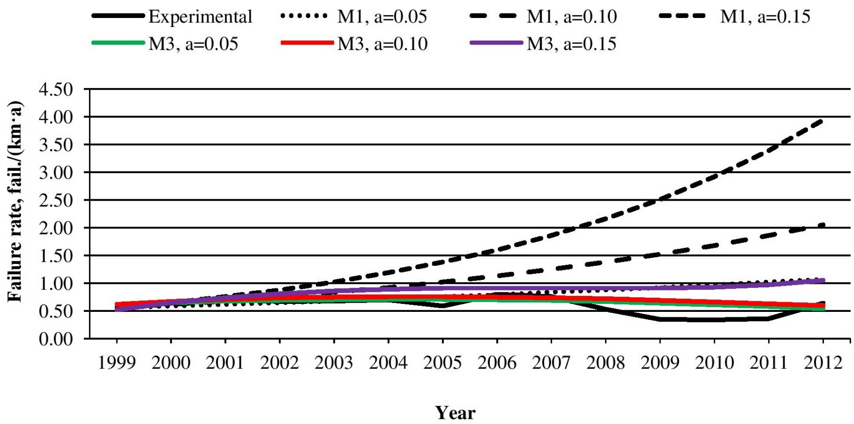

Fig. 7. Experimental and forecasted failure rate of service pipes in city X

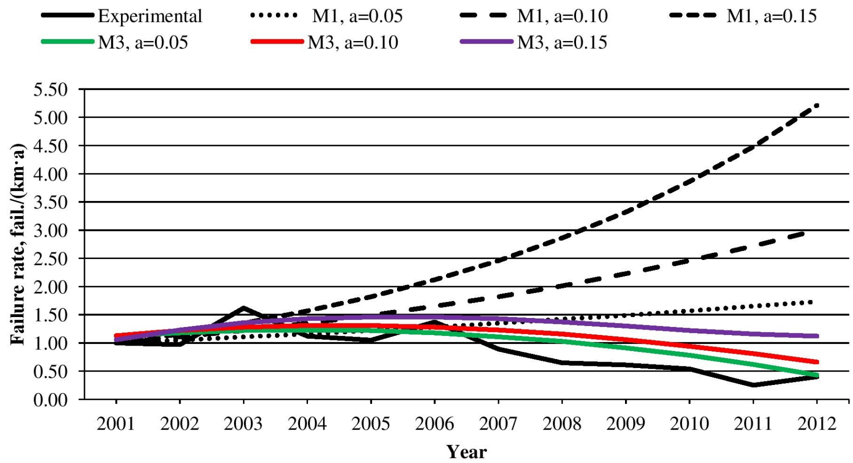

Fig. 8. Experimental and forecasted failure rate of service pipes in city Z

seems that models predicting failure rates for specific cities and for practical purposes should be created. For water utilities such models would be great tools for maintenance planning.

- Data collection is very important for the assessment of the reliability level of a water-pipe network. Theoretically the operational data should be precise and complete, but this is hard to achieve in practice and therefore relatively simple models should be used. In the future model M3 will be verified and improved on the basis of operational data from other water utilities.

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