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Failure risk analysis in the water distribution system

Keywords

risk analysis, failure, risk, water distribution system

Abstract

A water distribution system (WDS) ought to be high reliable continuous operating system. Failure factors in WDS should be identified and prioritised, for example, the causing factors in the most frequent failures in water-pipe network. In this paper, the failure risk analysis of the WDS is presented, and accordingly, a new method consisting the failures index (FI) and the evaluation of risk of failure within the relevant area, based on the assumed categories (tolerable, controlled and unacceptable risk). It is expecting that the methodology for the WDS performance risk analysis would provide the city leadership for decision making support.

1. Introduction

Failure is an unavoidable phenomenon in all technological products and systems [22].

The European Council asked to prepare an overall strategy for critical infrastructure protection. A definition of critical infrastructure is the following: critical infrastructure means systems and functionally interconnected objects being part of these systems, including building objects, units, installations, services, key for state and citizens safety, that also ensure the efficient functioning of state administration bodies, as well as institutions and entrepreneurs (Communication from the Commission on a European Programme for Critical Infrastructure Protection:COM(2006)786). Critical infrastructure comprises the following systems:

- telecommunication networks,
- power distribution systems,
- water distribution systems,
- gas distribution networks,
- road transportation systems,
- rail transportation systems,
- etc.

The management of critical infrastructure is an important issue and requires the individual analysis for every type of infrastructure, including drinking water supply systems. In various crisis situations, e.g. flood, draught, earthquake, technological failure, etc, there is always a problem to supply drinking water to people. Very often the lack of such provision can be a reason of serious diseases and even epidemics [15].

The water distribution system (WDS) is one of the most important systems of the drinking water supply system. Its aim is to supply consumers a required amount of water, with a specific pressure and a specific quality, according to the valid standards, and with the acceptable price[9],[11],[12]. Nowadays, the water-pipe companies try to get quality management certificates, according to the international standard ISO 9001:2000, that requires the procedures to estimate widely understood risk.

The management of risk connected with the WDS can be defined as a process of coordination of the operation of the WDS elements and its operators, using available means, in order to obtain the tolerable risk level in the most efficient way, as far as technology, economic and reliability are concerned [6].

Also the WDS itself can cause a crisis situation when various scenarios of undesirable events, which can cause system operating unreliability, and in consequence, the loss of water consumers safety, occur. Therefore, the development of plans for drinking water supply in emergency, for various critical situations , as well as the detailed analysis of risk of the possibility that undesirable events in the WDS will occur, in order to develop a complex program of the system safety management, is so important [19]. The water distribution subsystem consists of:

- water-pipe network (main, distributive and household connections)
- the specific fittings (gate valves, check valves , hydrants, drainage, aeration, flow meters).

The objective reality in WDS functioning is the possibility that various failures will occur. They can cause:

- losses of water,
- interruptions in water supply,
- secondary contamination of water in water-pipe network.

The main objective of this paper is to present the issue of failure risk analysis in the water distribution system. The paper presents a new method for water pipe network failure risk analysis.

2. Risk factors in the water distribution system

Haimes [3]-[4], suggests that risk assessment looks at what can go wrong as well as its likelihood and consequences. Risk is a measure of the probability and severity of adverse effect. Safety, on the other hand, is the level of risk that is deemed acceptable.
Kaplan and Garrick [7]-[8] introduced the theory of scenario and the triplet questions in the risk assessment process:

- what can go wrong?,
- what is the likelihood?,
- what are the consequences?.

They introduced the following mathematical: definition of risk *r:*

$$r=\{S_i,P_i,C_i\},$$

where:
- S_i denotes the -the risk scenario,
- P_i denotes the likelihood of that scenario,
- C denotes resulting consequences.

Hastak and Baim [5] define the infrastructure risk as the product of the probability (likelihood) of system failure and associated costs of returning the system to service. To perform effective risk assessment and management, the analyst must understand the system and its interactions with its environment, and this understanding is requisite to modeling the behavior of the state of the system under varied probabilistic conditions [1].

Failure is defined as an event in which the system fails to function with respect to its desired objectives. Failure can be grouped into either structural failure or performance failure. A structural failure, such as pipe breakage or a pump failure, can cause demands not to be met [10]-[13].
The complexity of the distribution system (many kilometres of pipes of different materials and ages), occurrences of physical/chemical/biological processes and the lack or absence of timely data make forensic analyses of water quality failure events very challenging [17].
With regard to a specific character of water-pipe network operation the system of failure repair is inseparably connected with the maintenance of network operational reliability and a priority is to provide consumers with suitable quality water [13]-[16]
As far as water-pipe network is concerned, we have a database of failure but the database contains only the final data which do not identify the primary causes of failures. We can answer the question what kind of failure took place, e.g. corrosion, transverse crack, longitudinal crack. It is much more difficult to identify the cause of failure. It can be shown on an example of failure connected with pipeline corrosion. The possible causes can be the following:

- ground corrosivity,
- lack of anticorrosion protection (passive and active),
- water corrosivity.

Failures of water-pipe network and its fittings are the random events and they can be caused by the events connected with:

- groundwork (eg. water-pipe is mechanically damaged by an excavator),
- water-pipe technical state,
- errors at mounting or sudden temperature changes[5],[12].

The causes of high failure frequency in water-pipe network are often:

- the incorrectly assumed concept of network structure (network in open, annular or mixed system),
- incorrect gates layout,
- wrongly chosen operating hydraulic conditions (too high working pressure, lack of fittings protecting against hydraulic strikes).

The transition to an explicit risk management philosophy within the water utility sector is reflected

in recent revisions to the World Health Organization's (WHO) Guidelines for Drinking Water Quality [20]- [21].
One should remember that water-pipe network operates with the changeable pressure and flow parameters, which is connected, mainly, with a change in an amount of water used by consumers over time. The important problem which occurs in many urban water-pipe networks is also a considerable water-pipe network redimensioning, which causes drop in water flow speed, water-pipes silting up and, as a consequence, the unfavourable flow conditions that can cause the deterioration of water-pipe network water quality.
The most often the failures in the WDS concern:

- pipe body (cracks, tearing off, corrosion pits),
- joints or expansion units (leak in connections),
- fittings, such as gates, valves, reducers, hydrants, aerations, bands , spotters, etc.

The important problem concerning subsystem operation is a system of capturing, processing and archiving data on all failures in the WDS operation.
Database must be developed and computer systems, e.g. SCADA must be used .
The factors which form the probability that the negative consequences occur are, among others, the following:

- the probability that the undesirable event occurs,
- frequency and a degree of exposure,
- the possibility of avoidance or minimization of the negative consequences.

Risk assessment is a process consisting of a number of the systematic steps, in which the study of different kinds of threats connected with the WDS operation is carried out [9]. The basic purpose of this kind of activities is to collect the information necessary to estimate the safety of the system.
Risk assessment should contain:

- establishment of a ranking of the undesirable events (failures),
- determination of the level (value) of risk,
- proposal of the activities aimed at risk minimization,
- establishment of time after which the risk can obtain its critical value, as a result of different processes, eg. materials ageing.

To evaluate the risk analysis of a water distribution system a relationship should be established between pipe failures and other parameters of the system, such as:

- type of water – pipe network (diameter):
  – main (ϕ>300mm),
  – distributional (ϕ 100mm÷300mm),
  – household connections (ϕ<100mm),
- depth and pressure,
- age of network,
- material (quality and type),
- corrosion (ground hydrological conditions),
- place of network (dynamic load, density of underground development).

3. Method for the identification of the areas of risk of failure

The proposed method consists in the classification of factors of risk of failure in water-pipe network, assigning n them the ranking point values R_i and the point weights W_j and then the calculation of the susceptibility to failures index (FI).Every class has assigned the ranking point value R_i, depending on a degree of the influence of the given factor on the susceptibility index and risk value. For the purposes of this paper the following notions have been defined:

For the factor weight value R_i:

- R_i=[0-1] – ignored,
- R_i =[2-4] – low importance,
- R_i =[4-6] – medium importance,
- R_i =[7-8] – important,
- R_i =[9-10] – very important.

R_i – rank of factor number *i* (a degree of importance), i=1,…n
n – a number of factors (classes).

For the factor weight value W_j:
- W_j =1-low,
- W_j =2-medium,
- W_j =3-high.

W_j – weight of factor number „j" :
j=1,…m

In this way we obtain the susceptibility to failures index (FI) calculated from the equation 1.

$$FI = \sum_{i=1,j=1}^{n,m} (R_i \cdot W_j) \qquad (1)$$

Risk (r) is a function of the parameters: the probability (likelihood) P that representative emergency scenario occurs (*S*), the magnitude of losses (C) caused by *S*:

$$r=f(P,C,)=\sum_{S}(P\cdot C) \quad (2)$$

where:
S - a series of the successive undesirable events (failures),
P- the probability (likelihood) of *S* or a single failure (a point value, depending on the failure rata value)
C- a point value of losses caused by *S* or a single failure, depending on the value FI.

To analyse risk defined in this way the matrix methods can be used [12]. According to equation 2 the qualitative risk matrix was developed, assuming a descriptive point scale for the particular risk parameters. In *Table 1* the two parametric risk matrix is presented, assuming the following risk scales and corresponding point weights [18]:

- Probability (P):
  - little – 1,
  - medium – 2,
  - large – 3.
- Consequences (C):
  - little – 1,
  - medium – 2,
  - large – 3.

Table 1. The two parametric risk matrix

C / P	1	2	3
	r		
1	1	2	3
2	2	4	5
3	3	6	9

According to the basic matrix for risk assessment given above we can analyse different undesirable events, assuming the following scale of risk (*Table 2*).

Table 2. The risk categories

a number of points	risk categories
1÷2	the tolerable risk
3÷4	the controlled risk
6÷9	the unacceptable risk

In *Table 3* and *Table 4* the proposed classes of factors for the analysis of the identification of the areas of risk of failure in water-pipe network and the weight values R_i , W_j and P are shown. If the given factor does not occur in the analysis of values R_i and W_j, we assumed the value 1.

Table 3. The proposed classes and the weight values R_i and W_i

Class (i)	R_i	W_j		
		1	2	3
Type of water-pipe network	10	connec tions	distributi onal	main
Age of network	8	<30 years	30-70 years	>70 years
Material of network	7	plastics	gray cast iron	steel
Hydro-geological conditions	6	good	medium	bad
Network monitoring	5	above stan-dard	standard	lack
Anticorrosion protection	4	com-plete	standard	lack
Place of network	3	good	medium	bad

Table 4. The proposed weight values P depending on the failure rate.

failure rate $\frac{number\ of\ failure}{km\cdot year}$	P		
	Little 1	Medium 2	Large 3
	connections		
	≤1	(1÷3]	>3
	distributional		
	≤0.5	(0.5÷1]	>1
	main		
	≤0.3	(0.3÷0.5]	>0.5

In *Table 5* the assumed losses categories depending on the value FI are presented.

Table 5. The proposed losses categories according to FI.

Losses category (C)	FI
Little C=1	<80
Medium C=2	[80÷120]
Large C=2	[120÷160]

In this way we can create the so-called maps of risk, draw the areas of tolerable, controlled and unacceptable risk on the plan of network.

4. An example of application

For example, the analysis of the WDS failures in a town with a population of 80 000 was carried out, based on the data obtained from the waterworks.

Water is taken from bank and siphon intake of the river, flows to the water treatment plant (WTP) and after getting drinking water parameters (according to valid regulations) is pumped to the municipal water-pipe network.

The WPT production capacity is 38 400 m^3/d and the mean water consumption in the town for an average inhabitant is approximately 140 dm^3/d.

Pressure in water-pipe network in this town is in the range 0.25 – 0.7 MPa.

Next, the number of failures in the particular kinds of water-pipe network has been analysed, referring to the water-pipe network length . The values of failure rate presented in *Table 3* were calculated according to equation 3.

$$\lambda = \frac{k(t, t + \Delta t)}{l \cdot \Delta t} \tag{3}$$

where :

k (t, t+Δt) –a total number of failures in a time interval Δt, in the given kind of network,

*l*_ length of the given kind of network (main, distributive, house connections) where failures occurred, in the given time interval [km],

As results from the WDS failure analysis, for the exemplary town in 2001-2008:

- 65% of the total failure number happened in water- pipe network:
  - 16% of them in the main network,
  - 59% of them in the distributive network,
  - 25% of them in the connections,
- 35% of the total number of failures occurred in network fittings:
  - spotters,
  - gate valves,
  - hydrants,
  - flow meters.

Based on the data concerning the water-pipe network failures that could be attributed to the specific streets, 4 streets, where the traffic difficulties caused by the water-pipe network repair occurred the most often, were selected, the mean failure intensity λ for the particular segments of the network for every street was calculated, and the results are presented in *Table 6.*

Table 6. Failure rate for the selected streets in the analysed WDS.

Street name (type of network)	Length of segment [km]	λ $\frac{number\ of\ failure}{km \cdot year}$
N 1 (water main)	3.5	0.4
N 2 (distributive network)	1.3	0.3
N 3 (distributive network)	1.3	0.6
N 4 (distributive network)	0.6	0.07

The characteristic of the network needed to determine FI and the values R_i i W_j are given in *Table 7.*

(3)

Table 7. The characteristic of the distributional network needed to determine FI.

Street	Class characteristic	R_i	W_j	$R_i \cdot W_j$
N1	Water main network	10	3	30
	Age of network (25 years)	8	1	8
	Material of network: gray cast iron	7	2	14
	Hydro geological conditions: good	6	1	6
	Network monitoring: standard	5	2	10
	Place of network: big	3	3	9
FI				95
Street	Class (n) characteristic	R_i	W_j	$R_i \cdot W_j$
N2	Distributive network	10	2	20
	Age of network (50 years)	8	2	16
	Material of network: gray cast iron	7	2	14
	Hydro - geological conditions: good	6	1	6

	Network monitoring: standard	5	2	10
	Place of network: big	3	3	9
FI				93
Street	Class (n) characteristic	R_i	W_j	$R_i \cdot W_j$
N3	Distributive network	10	2	20
	Age of network (45 years)	8	2	16
	Material of network: gray cast iron	7	2	14
	Hydro-geological conditions: bad	6	3	18
	Network monitoring: standard	5	2	10
	Place of network: big	3	3	9
FI				105
Street	Class (n) characteristic	R_i	W_j	$R_i \cdot W_j$
N4	Distributive network	10	2	20
	Age of network (10 years)	8	1	8
	Material of network: plastics	7	1	7
	Hydro-geological conditions: good	6	1	6
	Network monitoring: standard	5	2	10
	Place of network: small	3	1	3
FI				63

According to tables 3, 4, 5, 6, 7 and equations (1) and (2), the risk values are calculated and show in *Table 8:*

- for FI⇒C,
- for λ ⇒P
- according *Table 1* we get the risk value and risk categories according to *Table 2.*

Table 8. The risk values

FI	C	λ	P	Risk value	Risk categories
for street N1					
95	2	0.4	2	4	controlled
for street N2					
93	2	0.3	1	2	tolerable
for street N3					
105	2	0.6	3	6	unacceptable
for street N4					
69	1	0.7	3	3	controlled

This type of analysis is very helpful to classify these segments of water-pipe network which need repairing.
If the calculated values indicate the category:
• tolerable – one can assume that the water pipe network fulfills its functions in the satisfying way,
• controlled – an improvement in the work of some elements or repair of some sections of water pipe network should be considered.
• unacceptable – means that the water pipe network does not fulfill its functions and should undergo a complete modernization or even redesigning.

5. Conclusions

- The goal of the paper is to demonstrate the value of an objective risk assessment tool for estimating the WDS decision-maker's sensitivity to failure risk. The usefulness of the objective risk assessment tool was demonstrated by defining three risk-sensitive (tolerable, controlled and unacceptable) decision response alternatives that are encountered by the typical WDS decision-maker.
- Analysis of risk connected with the WDS functioning should be the main element of complex WDS risk management
- The exploitation of urban WDS should take into account the minimization of water losses, operational and safety reliability.
- The procedures of the WDS correct designing, construction and operating should be completed with the detailed subsystem failure analyses, which are a base to estimate the subsystem reliability in a right way.
- A very important role in the procedures of the failure analysis plays the right failure record, as well as opinions and estimations of experts and users. Such analyses are often carried out in conditions of "incomplete information", which makes the performance of right procedures difficult. Information credibility and reliability, as well as a precise database of exploitation

information on the system, have a significant impact on the correctness of chosen methods, assumptions and the final result of the reliability analysis.
- Risk is a measure which defines the safety level of water supply systems. Numerous failures which happen in water-pipe network force waterworks to carry out some modernizations and renovations, in order to minimize risk of failure.
- The presented method for the determination of the degree of exposure to failure can be used to classify the sections of the network for renovation or modernization. Using the operating data, field investigations and analyses made by experts, one can draw up the map of risk on the plan of water-pipe network in a very simple way and be able to identify particular areas of the tolerable, controlled and unacceptable risk.
- The GIS (geographic information system) program could significantly support the application of the described method in practise.
- The pipe failure data have been collected from a real water distribution network. During the study several parameters which affect the failure rate were collected (pipe diameter and type of network, length, age, depth, average hydraulic pressure).

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