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Research paper

Reliability of Water Supply Networks

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Abstract

The reliability of ring water supply networks is investigated. Oriented graphs of annular water supply networks are considered. The structural reliability of such networks is determined. For these purposes, it is suggested to use the method of minimal paths and minimal sections in an oriented graph. This makes it possible to obtain an upper and lower reliability limit for water networks of arbitrary configuration with different diameters and lengths of sections. Using minimal paths and minimal cross-sections, equations are obtained for the reliability of annular water supply networks. For any water supply network, functions can be recorded that determine its actual reliability.

Keywords: *ring water supply network, reliability, oriented network graph.*

1. Introduction

One of the most important tasks of today is to improve the efficiency of water supply systems. The water supply system consists of a number of subsystems. The most complex and expensive is the ring water supply network. Its cost can be up to 70% of the cost of the entire water supply system. For the design of such systems, special calculation methods are used [3, 16, 17]. These methods make it possible to determine the optimal diameters of pipelines for ring water supply networks.
The water supply system should provide water consumers with a certain quality of water in the required quantities with sufficient pressure according to the DBN [18]. In addition, the water supply system must have sufficient strength to withstand the specified loads during operation. All its elements should be simple to operate and economical [1, 3]. Thus, the water supply system must perform the specified functions with a minimum of costs for its construction and operation. The system, which is designed in full compliance with the above requirements, is able to perform its functions economically.
As practice shows, this is not enough. It is necessary to know or be sure that the water supply system in operation will not only be able to do all of this but will also perform its functions without inadmissible decrease in the quality of its operation. This knowledge or confidence can be obtained if the required reliability of the system is evaluated and ensured [1, p. 5], which is one of its most important properties.
There are three classes of objective criteria for assessing water supply systems: (1) technical indicators (volumes of water supplied, pressure at characteristic points of the network, number and parameters of pumping stations, length of networks, schematic solutions and a number of others), which are described by equations 1 and 2 of the Kirchhoff laws and closing relations for pumps, tanks and armatures; (2) economic indicators (cost of the system, capital costs, operating costs, net present value, cost of production, payback period, etc.), which are described by the equations of technical and economic optimization for the nodes of the network and its circuits; (3) reliability indicators (probability of failure-free operation, probability of failure, availability, operational readiness coefficient, efficiency of the system, etc.), which are described by the equations of connectivity or reliability of topological structures of water supply networks.
Let us consider the water supply system. Its technical parameters (costs of water supply, pressure, length of sections, pipe diameters, number of pumping stations 1st, 2nd and 3rd lifts, their equipment, water intakes, treatment facilities) are given in the draft water supply system.
It is also possible to estimate economic indicators (cost of the whole water supply system, capital costs and operating costs, cost of 1 m^3 of water, selling price of water to consumers, net discounted income, payback period of the system, etc.), which can also be listed in projects.
However, users of the water supply system are also interested in the following questions: will sufficient pressure be on their floor at any time of the day, are there any breaks in the supply of water, and what is their duration. Operating organizations are interested in the issue of system failure, spare parts availability, time to eliminate accidents, prevention and repair, product quality, etc. These characteristics determine the level of reliability of the water supply system.
In the standard this concept is defined as follows: “Reliability is an object's property, consisting in its ability to perform certain tasks under certain operating conditions”.
A large number of works have been devoted to solving the problem of reliability of water supply and distribution systems [1, 2, 5, 6 - 13, 15].
It is necessary to note the classic works of Abramov NN [1] and. Ilyin YuA [2], who laid the foundations for calculating the reliability of water supply systems.
However, despite the constant attention to the problem in question, it cannot be fully considered. One such task is to quantify the reliability of ring water supply networks, taking into account such parameters as lengths, diameters of network sections and indicators of their reliability.
In this paper, it is proposed to use the upper and lower estimates of the reliability of oriented graphs of annular water supply networks.

The purpose of this work is to determine the actual reliability indicators for real water supply networks with different lengths and diameters.

2. Basic material

The ring water supply network can be represented in the form of an oriented graph

$G = F(E,S)$,

where E is the number of edges (sections) of the network digraph and S is the number of its vertices (nodes).

Each element of the ring network can be in two states of operability: in working order and in an inoperative state. The number of possible states of such a system grows exponentially and is determined by the formula

$$N = 2^n , \tag{1}$$

where n is the number of sections of the water supply network.

Such problems are called NP complete or difficult to solve problems. The time of solving such problems by the methods of direct selection grows exponentially. Therefore, the methods of direct search, with the number of sections $n \geq 60$, become problematic.

Consider a ring water supply network with an arbitrary number of nodes - sources and nodes - drains (consumers). Such a network will lead to a network with a single source. We connect all the source nodes to the null node with absolutely reliable lines. Next, consider a ring network with one source and one drain, i.e. a two-pole network and its oriented graph.

As a drain, one can take any of the nodes of the ring network of water supply, in which there is a withdrawal of water.

Systems of this type are called systems with a monotonic structure. These systems are characterized by a natural property: the replacement of any element of the system by a more reliable element does not reduce the probabilities of connectivity of the system.

In the oriented graph of the ring network, we select the minimal path and the minimal section.

The minimal or a simple chain in the ring network of water supply is the minimal set of workable areas, which ensures the connectivity of the poles of the network graph.

The exclusion of any of the sites (refusal) transfers the bipolar water supply network from the working state to the state of failure. Each minimal path differs from the other minimal paths at least one site.

The minimal cross-section in the ring water supply network is a minimal set of failed elements, the restoration of any of which transfers the network from the failure state to the workable state.

The number of minimal paths and minimal sections from the source node to the consumer node depends on the structure of the ring network.

A consecutive connection from n sites has only one minimal path and n minimal segments. These cross sections pass through each section.

Consider the oriented graph of the simplest ring network of water supply (Fig. 1). It consists of 8 nodes, 10 oriented ribs and 3 closed loops. Node 1 is a source. Node 8 is a drain.

The movement of water in the network is carried out in areas in the direction of the arrows. An annular network can have many minimal paths and minimal cross sections between source and drain. In theory and graphs, the minimal path and the minimal cut (cross section) are called a simple chain (by way of) and a simple cut (cross section), respectively.

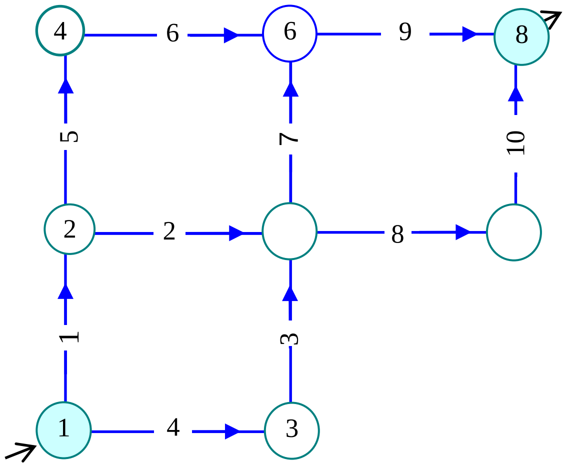

Fig. 1: Oriented graph of the ring water supply network: 1 is a source node; 8 is a drain node.

Dwell on the problem of determining the reliability of water supply from the source node to the node-drain. The minimal path is a set of consecutively connected sections through which water is transported from source to drain (Fig. 2).

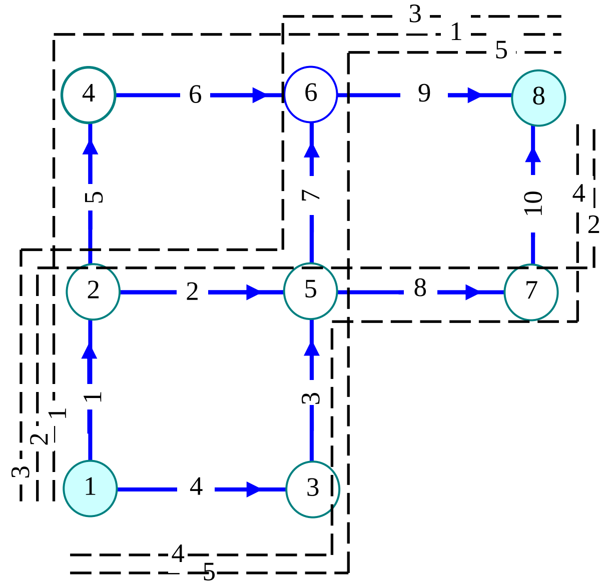

Fig. 2: Oriented graph of 3 circular water supply networks. The minimal paths of water movement from node 1 to node 8 are indicated by dashed lines

Let us describe a structural reliability function for a minimal path. This function coincides with the structural function of the sequential connection of the sections that make up this minimal path.

$$\alpha_j(x_1, x_2, ..., x_n) = \bigcap_{i \in A_j} x_i, \quad \begin{cases} 1, \; if \; x_i = 1 \; \forall i; \\ 0, \; if \; x_i = 1 \; \forall i, \end{cases} \tag{2}$$

where A_j – is the subset of the segments of the ring network, which form a j minimal path; x_i – is the indicator of the state of i first part of the circular water supply network, $i = 1,2,..., n$; $\bigcap$ – is the symbol of logical multiplication (conjunction); n_α is the total number of minimal paths in the annular network, i.e. $j \in 1, n_\alpha$.

Any section of the ring water supply network can be in two states of operability: in working order and in a state of failure. Indicators x_i can only take two values, either 1 is operational, or 0 is a fail-

ure state. The function α_j takes the value of 1 if all elements of this path are OK, and otherwise are equal to 0.
If many paths are considered, the failure of one of them does not always mean the complete cessation of the flow of water from the source node to the drain node.
If many paths are considered, the rank of which $\leq K$ after their violation, can remain in the network of the rank $\geq K+1$.
The minimal cross sections of the oriented graph of the network are shown in Fig. 3. To each minimal section, a structural function can be brought into conformity.

$$\beta_k(x_1,x_2,...,x_n)=\bigcup_{i\in B_k} x_i=\overline{\bigcap_{i\in B_k}\overline{x_i}}, \quad (3)$$

where B_k – is the subset of the segments in the annular network, which constitute the k is the minimal cross section; $\bigcup$ – is the symbol of logical addition (disjunction); $\bar{\ }$ – is the character above the symbol denotes the negation.
We denote by n_β the total number of minimal cross sections in the annular network, i.e. $k\in 1,n_\beta$.

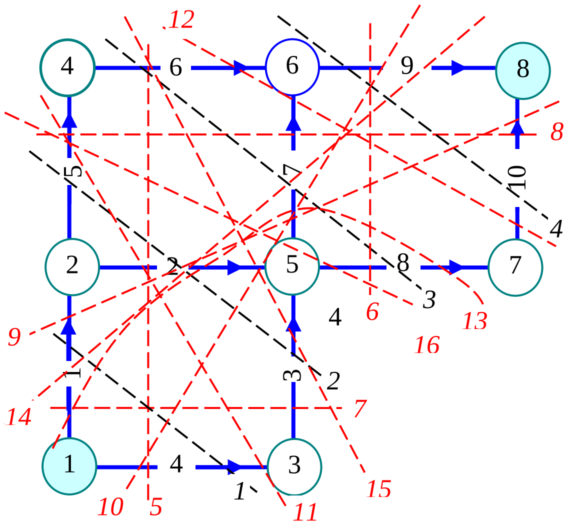

Fig. 3: The minimal cross-sections in the oriented graph are shown by dashed lines

The function (3) assumes the value 0 if all the elements of the minimal cross section are defective and otherwise are equal to 1, if at least one element of this section is operable. Thus, the function $\beta_k(x_1,x_2,...,x_n)$ is a structural function of the network in which all the elements belonging to the k section are connected in parallel. There can be several such minimal circuits in the ring network. The only minimal cross-section has only a purely parallel connection scheme for pipelines.
For an arbitrary circular network, one can write a structural function through minimal paths

$$f(x_1,x_2,...,x_n)=\bigcup_{1\leq j\leq n_\alpha}\alpha_j(x_1,x_2,...,x_n)=\overline{\bigcap_{1\leq j\leq n_\alpha}\overline{\alpha_j(x_1,x_2,...,x_n)}} \quad (4)$$

or through minimal sections

$$f(x_1,x_2,...,x_n)=\bigcap_{1\leq k\leq n_\beta}\beta_k(x_1,x_2,...,x_n). \quad (5)$$

It follows from equation (4) that in order to supply water from the source node to the drain node, it is necessary for at least one minimal path to exist in this network, i.e. $f(x_1,x_2,...,x_n)=1$.
The meaning of equation (5) is as follows. To implement water supply from the source node to the drain node, it is necessary that at least one faulty element (section) is present in each minimal section of the network. There is not a single gap in the network connecting the source to the drain.
Let each section of the ring water supply network correspond to an index of reliability, for example, p_i probability of failure-free operation.
Then the reliability of j minimal path is determined by the expression

$$P_j=\prod_{i\in A_j}p_i. \quad (6)$$

The parallel connection of the minimal paths gives the upper limit to the connection reliability of the source node and the drain node.

$$P^B\{f(x_1,x_2,...,x_n)\}=1-\prod_{1\leq j\leq n_\alpha}\left(1-\prod_{i\in A_j}p_i\right). \quad (7)$$

Expression (7) represents the parallel inclusion of all n_α minimal paths. Each minimal path is consistently incorporated sections, in the sense of reliability, that are elements of this path. The reliability of k minimal cross section can be represented in the form

$$P_k=1-\prod_{i\in B_k}(1-p_i). \quad (8)$$

The sequential connection of the minimal cross sections gives the lower limit of the reliability of the connection of the source and drain nodes.

$$P^H\{f(x_1,x_2,...,x_n)\}=\prod_{1\leq k\leq n_\beta}\left(1-\prod_{i\in B_k}(1-p_i)\right). \quad (9)$$

From the equations (7) and (9) we write the upper and lower limits for the probability of failure-free operation of such a system in the form of Ezari-Proshan [4]:

$$\prod_{1\leq k\leq n_\beta}\left(1-\prod_{i\in B_k}(1-p_i)\right)\leq P\{f(x_1,x_2,...,x_n)\}\leq 1-\prod_{1\leq j\leq n_\alpha}\left(1-\prod_{i\in A_j}p_i\right), \quad (10)$$

where $P\{f(x_1,x_2,...,x_n)\}$ is the probability of failure-free operation of a ring water supply network containing independent elements of different reliabilities.
The essence of the estimates (7), (9) consists in the following. One element may belong to several minimal paths or sections. Dependent elements, in various minimal paths and minimal cross sections, are replaced by independent ones. This leads to the following. Failure of any element does not mean the simultaneous failure of the element of the same name and in all the simple chains to which this element belongs. This leads to an overestimation of the upper assessment of the reliability of the network, calculated on the minimal paths. Replacing dependent elements with independent ones in cross-sections leads to a lowering of the lower reliability rating of the network calculated by minimal sections.

Equations (7) and (9) enable us to estimate the upper and lower boundaries of the reliability of the nodes of a bipolar network and solve problems of large dimension. Reliability indicators p_i can be different, which allows us to assess the reliability of ring water networks, taking into account the length and the diameter of each site.
By determining the intensity of failures λ_i and restoring each section μ_i of the network, you can use the readiness factor or operational readiness factor as reliability indicators.
The actual index of reliability $P\{f(x_1, x_2,..., x_n)\}$ can be obtained, if in the expressions for the upper or lower limits, by opening the parentheses and giving similar ones, all the exponents for variables p_i greater than 1 are replaced by 1 [14]. We denote such an operation by $E(f)$, where f is a polynomial. As a result, we obtain for minimal paths

$$P\{f(x_1, x_2,..., x_n)\} = E\left\{1 - \prod_{1 \le j \le n_\alpha}\left(1 - \prod_{i \in A_j} p_i\right)\right\}, \tag{11}$$

for minimal sections

$$P\{f(x_1, x_2,..., x_n)\} = E\left\{\prod_{1 \le k \le n_\beta}\left(1 - \prod_{i \in B_k}(1 - p_i)\right)\right\}. \tag{12}$$

Consider the network (Fig. 2). The number of minimal paths is 5. Let us write down the reliability of each minimal path.

$$\begin{aligned} &r_1 = p_1 p_5 p_6 p_9; r_2 = p_1 p_2 p_8 p_{10}; r_3 = p_1 p_2 p_7 p_9 \\ &r_4 = p_4 p_3 p_8 p_{10}; r_5 = p_4 p_3 p_7 p_9. \end{aligned} \tag{13}$$

These minimal paths form a hammock (Fig. 4).

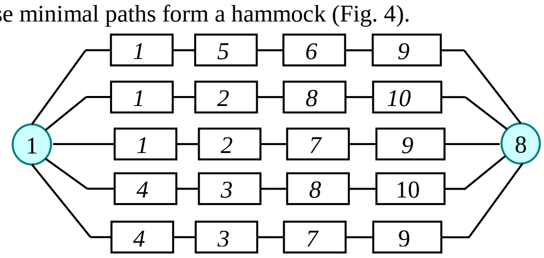

Fig. 4: Network reliability scheme for minimal paths - "hammock"

The number of repetitions of sites in the hammock is from 2 to 3. These sites will be dependent.
Among the ways (Fig. 4) there are independent ways. These are the following pairs of independent paths: r_1 and r_4, r_2 and r_5, r_3 and r_4 (Fig. 5).

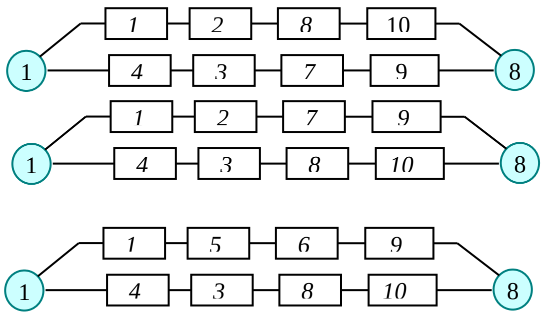

Fig. 5 - Pairs of independent paths in the "hammock"

The number of ribs in each hammock (Fig. 5) is 8. Two edges do not enter each of the hammocks. Reliability indicators for each hammock have the form

$$R_1 = 1 - (1 - p_1 p_5 p_6 p_9) \cdot (1 - p_4 p_3 p_8 p_{10}); \tag{14}$$

$$R_2 = 1 - (1 - p_1 p_2 p_8 p_{10}) \cdot (1 - p_4 p_3 p_7 p_9); \tag{15}$$

$$R_3 = 1 - (1 - p_1 p_2 p_7 p_9) \cdot (1 - p_4 p_3 p_8 p_{10}). \tag{16}$$

Values R as calculated by these formulas will differ for different values of p_i. Values R will give an underestimation of reliability, because each of these hammocks does not include a number of sections (edges).
We add to the independent paths, in the listed hammocks, partially dependent paths, which complement the missing 2 edges. To a hammock with independent paths 1-5-6-9 and 4-3-8-10 we will add partially dependent paths. The first such way is 1-2-7-9. It has two dependent edges and two independent edges. As a second option, you can select two partially dependent paths 4-3-7-9 and 1-2-8-10. Each of them has three dependent paths and one independent path. This is the minimal number of partially dependent paths that, together with independent paths, contain all edges of the digraph. Such estimates are smaller than the upper estimate and may be closer to an exact solution.
The upper limit of reliability is written in the form

$$P^B = 1 - (1 - r_1) \cdot (1 - r_2)(1 - r_3)(1 - r_4)(1 - r_5). \tag{17}$$

Substituting in (17) the equalities (13) and performing the operation $E(f)$ by replacing p_i^x with p_i, we obtain the real value of the reliability

$$\begin{aligned} E(f) = {} & p_5 p_6 p_2 p_4 p_3 p_1 p_7 p_9 + p_1 p_2 p_7 p_9 - \\ & p_1 p_2 p_4 p_3 p_7 p_9 + p_4 p_3 p_7 p_9 - p_1 p_5 p_6 p_4 p_3 p_7 p_9 - \\ & p_5 p_6 p_2 p_7 p_1 p_9 + p_1 p_5 p_6 p_9 + p_1 p_2 p_8 p_{10} - \\ & p_8 p_{10} p_7 p_9 p_3 p_4 + p_4 p_3 p_8 p_{10} - \\ & p_5 p_6 p_9 p_2 p_8 p_{10} p_1 + p_1 p_5 p_6 p_8 p_{10} p_7 p_3 p_4 p_9 - \\ & p_1 p_5 p_6 p_9 p_4 p_3 p_8 p_{10} - p_8 p_{10} p_7 p_9 p_1 p_2 + \\ & p_5 p_6 p_8 p_{10} p_7 p_1 p_2 p_9 - p_5 p_6 p_8 p_{10} p_4 p_3 p_1 p_2 p_7 p_9 - \\ & p_1 p_2 p_4 p_3 p_8 p_{10} + p_5 p_6 p_9 p_2 p_4 p_3 p_1 p_8 p_{10} + \\ & p_1 p_2 p_7 p_9 p_4 p_3 p_8 p_{10}. \end{aligned} \tag{18}$$

After completing this operation, we eliminated all the dependent elements in equation (18). If any section goes into a state of failure, then all the terms in which this section enters are zero.
If we assume that every $p_i = const$, we get an expression in the form of a polynomial. For the upper limits

$$P^B = 5p^4 - 10p^8 + 10p^{12} - 5p^{16} + p^{20}. \tag{19}$$

The actual reliability values in the form of a polynomial are

$$E(f) = 5p^4 - 5p^6 - 2p^7 + 2p^8 + 2p^9 - p^{10}. \tag{20}$$

Graphical interpretation is shown in Fig. 6.

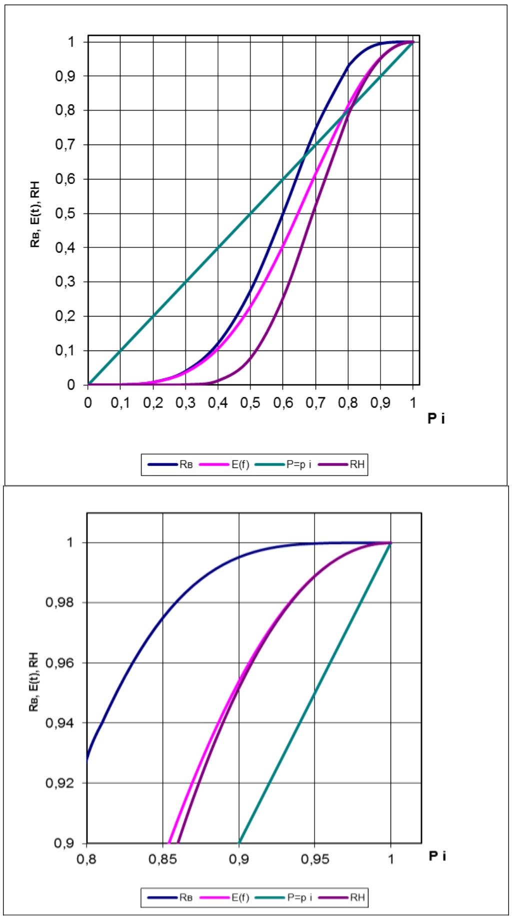

Fig. 6: Reliability of the connectivity of node 1 with node 8. The upper limit R_B, the lower limit R_H and the actual value of E (t) reliability

Let us consider the minimal cross-sections (Fig. 3). You can obtain the minimal cross-sections in several ways. One of such methods consists in constructing a dual network to the original one and calculating the minimal paths in it. The second is in the representation of the upper limit with the help of a conjunctive/disjunctive function with its subsequent replacement by a disjunctive/conjunctive function and obtaining a lower reliability estimate.

The number of minimal cross sections is 16. Let us write down the reliability of each minimal section.

$r_1 = 1-(1-p_1)(1-p_4)$;

$r_2 = 1-(1-p_5)(1-p_2)(1-p_3)$;

$r_3 = 1-(1-p_6)(1-p_7)(1-p_8)$;

$r_4 = 1-(1-p_9)(1-p_{10})$;

$r_5 = 1-(1-p_4)(1-p_2)(1-p_6)$;

$r_6 = 1-(1-p_8)(1-p_9)$;

$r_7 = 1-(1-p_1)(1-p_3)$;

$r_8 = 1-(1-p_5)(1-p_7)(1-p_{10})$;

$r_9 = 1-(1-p_1)(1-p_2)(1-p_7)(1-p_{10})$;

$r_{10} = 1-(1-p_4)(1-p_2)(1-p_7)(1-p_9)$;

$r_{11} = 1-(1-p_4)(1-p_2)(1-p_5)$;

$r_{12} = 1-(1-p_6)(1-p_7)(1-p_{10})$;

$r_{13} = 1-(1-p_1)(1-p_2)(1-p_7)(1-p_8)$;

$r_{14} = 1-(1-p_1)(1-p_2)(1-p_7)(1-p_9)$;

$r_{15} = 1-(1-p_3)(1-p_2)(1-p_6)$;

$r_{16} = 1-(1-p_5)(1-p_7)(1-p_8)$.

The lower limit of reliability will be written in the form

$$P^H = \prod_{k=1}^{16} r_k . \qquad (21)$$

For every $p_i = const$, it is possible to obtain the dependence of the change in the lower reliability limit on the reliability of the site (Fig. 6). This is the lower curve in the figure.

Example. Consider the network (Fig. 1.) The pipe material is steel. The network parameters are listed in Table 1. Determine the reliability of the connectivity of nodes 1 and 8 with respect to minimal sections and along minimal paths.

Table 1: Parameters of sections of the water supply network

Pipe number	Length, м	Diameter, мм	λ, [2] 1/km/year	$p_i = e^{-\lambda_i l_i t}$
1	450	500	0,114	0,9500
2	600	500	0,114	0,9340
3	320	500	0,114	0,9642
4	570	500	0,114	0,9372
5	250	400	0,131	0,9677
6	650	400	0,131	0,9181
7	310	400	0,131	0,9601
8	500	300	0,158	0,9242
9	450	300	0,158	0,9315
10	345	300	0,158	0,9471

The reliability of each minimal path is

$$r_1 = p_1 p_5 p_6 p_9 = 0{,}7863;$$
$$r_2 = p_1 p_2 p_8 p_{10} = 0{,}7766;$$
$$r_3 = p_1 p_2 p_7 p_9 = 0{,}7935;$$
$$r_4 = p_4 p_3 p_8 p_{10} = 0{,}7909;$$
$$r_5 = p_4 p_3 p_7 p_9 = 0{,}8081.$$

The upper reliability rating will be

$$P^B = 1-(1-r_1)\cdot(1-r_2)(1-r_3)(1-r_4)(1-r_5) = 1-(1-0{,}7863)\cdot(1-0{,}7766)\cdot(1-0{,}7935)\cdot(1-0{,}7909)\cdot(1-0{,}8081) = 0{,}9996 \qquad (22)$$

The actual reliability value calculated by (11) is equal to

$$E(f) = p_5p_6p_2p_4p_3p_1p_7p_9 + p_1p_2p_7p_9 - p_1p_2p_4p_3p_7p_9 + p_4p_3p_7p_9 - p_1p_5p_6p_4p_3p_7p_9 - p_5p_6p_2p_7p_1p_9 + p_1p_5p_6p_9 + p_1p_2p_8p_{10} - p_8p_{10}p_7p_9p_3p_4 + p_4p_3p_8p_{10} - p_5p_6p_9p_2p_8p_{10}p_1 + p_1p_5p_6p_8p_{10}p_7p_3p_4p_9 - p_1p_5p_6p_9p_4p_3p_8p_{10} - p_8p_{10}p_7p_9p_1p_2 + p_5p_6p_8p_{10}p_7p_1p_2p_9 - p_5p_6p_8p_{10}p_4p_3p_1p_2p_7p_9 - p_1p_2p_4p_3p_8p_{10} + p_5p_6p_9p_2p_4p_3p_1p_8p_{10} + p_1p_2p_7p_9p_4p_3p_8p_{10} = 0{,}9850 \qquad (23)$$

This value shows the actual reliability value of the connectivity of nodes 1 and 8 of the oriented graph of a ring water network.

The relative error of the upper limit is

$(0{,}9850-0{,}9996)/0{,}9850\cdot 100\% = -1{,}48\%$.

This error is due to the fact that the reliability indicators of individual sections are significant and exceed 0.9. At lower reliability values of individual sections, the error will increase (Fig. 6).

Figure 6 shows the graph of the actual reliability value, calculated from equation (11).

To compare the results, the upper limit of the network reliability and the lower reliability limit calculated according to the minimal paths and cross sections are shown.

The upper limit of reliability in the range of values p_i from 0 to 0.5 approaches well the actual values.
For values p_i from 0.8 to 1.0, the lower limit of reliability approaches the actual values p_i calculated from (11). At values p_i from 0.55 to 0.75, the greatest coincidence yields the arithmetic mean of the probability, calculated from the minimal paths and minimal cross sections.
By selecting nodes 2, 3, 4, 5, 6, 7 as node-drains, you can determine the probability of their connectivity with the source node. This will provide an opportunity to assess the reliability of the ring water supply network as a whole.
The diagonal line on (Figure 6) intersects three S-shaped curves: the upper reliability limit, the actual reliability value and the lower reliability limit. These intersection points show the influence of the topology of the water supply network and the reliability of the element on the reliability of the entire system. The intersection point determines the borderline reliability of the system element. If the reliability of the elements of which the system consists is less than the borderline value, the reliability of the entire system will be less than the reliability of the individual element. Otherwise, the reliability of the system will be greater than the reliability of the elements entering into it. Equating the value of the polynomial (19) to the value p, we obtain the borderline value of the reliability of the element

$$5p^4 - 10p^8 + 10p^{12} - 5p^{16} + p^{20} = p\ .$$

Whence $p = 0{,}66628$.
For the actual reliability value from the polynomial (20)

$$5p^4 - 5p^6 - 2p^7 + 2p^8 + 2p^9 - p^{10} = p\ .$$

Here $p = 0{,}7825$.
These values p are approximate. The polynomials (19) and (20) are obtained for networks with the same reliability indices $p_i = const$ of all sections.
Equation (23) determines the actual reliability value, taking into account p_i for each network segment.
With the help of this method of reliability assessment, it is possible to analyze the influence of the connection point of water lines to the network, as well as the devices of duplicate lines of the network and water conduits. As parameters p_i, you can also take the availability factor or the operational readiness factor. To calculate the upper and lower estimates of connectivity reliability of the source and sinks of ring water networks, a computer program has been developed. This program makes it possible to calculate the real reliability of ring water supply networks by equations (11) and (12).

3. Conclusions

Using the method of minimal paths and minimal cross-sections, it is possible to estimate the reliability of the connectivity of the nodes of the ring water supply network and calculate the actual reliability value.
Using the upper and lower estimates of the reliability of a two-pole network graph, it is possible to calculate the borderline reliability estimates for annular water supply networks with any diameters and lengths of sections.
The method of minimal cross-sections and minimal paths makes it possible to estimate the reliability of the connectivity of all nodes (consumers) of the ring water network with arbitrary probability values of failure-free operation of each section.
The proposed reliability assessment method can be used both at the design stage of new ring networks and at the stage of reconstruction and expansion of existing ones.
Analysis of the topology of ring water networks makes it possible to obtain estimates of the reliability of such networks as a whole and assessments of the reliability of providing consumers with water at grid nodes.
The actual value of reliability calculated by formulas (11) and (12) makes it possible to solve the tasks of increasing the reliability of ring water supply networks both in the design of new water supply systems and the reconstruction of the existing ones.

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