SIMULATION MODELING OF PROCESS OF DAMAGING OF NETWORK PIPELINE STRUCTURES

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ABSTRACT

The approaches to assessment of the functional state of pipelines in the presence of continuous technological processes and complex industries are substantiated. Stability characteristics and a simulation modeling program for the process of damage to network structures of pipeline transport systems are calculated. It is shown that the ability to resist the process of progressive damage of such systems depends on their structure and composition. The developed software makes it possible to perform a comparative analysis of the properties of alternative structures and to take reasonable design decisions at the stage of formation of transport systems with specified properties.

<u>Keywords:</u> *pipeline transport, system, structure, simulation modeling.*

Background. *Pipeline transport systems are widely used in the conditions of modern industrial production. With their help at the enterprises of metallurgy, oil and gas complex, chemical plants raw materials, semi-finished products, finished products are delivered [1 2].*

The trouble-free functioning of such systems ensures the possibility of organizing continuous technological processes and complex productions. However, the delivery of various types of reagents and hazardous substances by the pipeline is associated with certain risks for the transport technological system itself and for the environment.

Thus, failures of individual elements of complex pipeline systems in a number of cases do not lead to a noticeable change in the functioning regimes due to excessive connections and the existence of alternative ways of delivering the product to consumers. At the same time, a series of consecutive failures or damage to pipelines may be accompanied by a partial or complete loss of system performance.

The causes of such events can be related to internal processes in the system (hydraulic shocks, corrosion damage and pipe depressurization, control errors) or external factors (fire spreading, seismic activity, landslide development, etc.) [3].

Such processes are characterized by the following series of features.

1. It is impossible to predict areas of damage to pipelines and the sequence of development of an emergency in advance.

2. It is not possible to compile a list of pipelines that will be damaged as a result of uncontrolled development of an emergency situation, and also to determine the sequence of such damages.

3. It is very difficult to predict the scale and consequences of the accident for the whole system. They can be associated with either a partial or complete cessation of the delivery of the target product to one or more consumers.

We believe it is legitimate to consider the process of successive transition to the inoperative state of the pipeline transport system as a result of the development of a series of uncontrolled failures as a progressive damage.

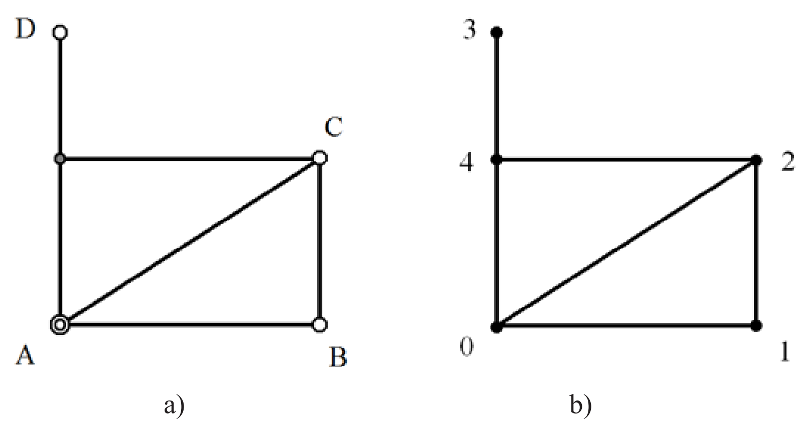
Objective. *The objective of the authors is to consider a simulation modeling of process of damage of network pipeline structures.*

Methods. *The authors use general scientific and engineering methods, graph construction, comparative analysis.*

Results. *A characteristic feature of progressive damage is motivated by the fact that the transition of individual pipelines to an inoperative state occurs in a random sequence. At the same time, due to excessive connections in the system, the development of damage at different stages can be accompanied by both a decrease in the volume of the product delivered to consumers and their subsequent shutdown, until the system completely ceases to function.*

The ability of the pipeline transport system to resist the development of this process depends primarily on its structure, composition and is closely associated with resistance to progressive damage.

For this reason, a search for regularities that allow predicting behavior and assessing the durability of



Pic. 1. Network structure (a) and the corresponding marked graph of the pipeline transport system (b).

Calculated program module

Formation of matrices with incremental zeroing of elements of the adjacency matrix, carried out in a random order and characterizing the process of gradual damage to the structure of a given graph

```
Del(M) := | n ← rows(M) − 1
          | while M[i←round(rnd(n)), j←round(rnd(n))] = 0
          |   1
          | M[i,j] ← M[j,i] ← 0
          | [(i j) M]
```

Zeroing of a randomly chosen unit element of the matrix M

```
Doloj1(M) := | (n ← rows(M) − 1   k ← 0   a_k ← M   Ind_k ← «(i j)»)
             | while [ N ← Σ_{i=0}^{n} Σ(a_k)^⟨i⟩ ] > 0
             |   | k ← k + 1
             |   | (Ind_k  a_k) ← Del(a_{k−1})
             | (Ind  a)
```

Consecutive zeroing of all unit elements. At each step, one randomly selected element is zeroed.

$(n \leftarrow rows(M)-1 \quad k \leftarrow 0 \quad a_k \leftarrow M)$

Formation of reachability matrices based on the obtained set of adjacency matrices

```
NormExit(M, r) := | (Ind  b) ← Doloj1(M)
                  | str ← («№ damage» «Indices of damaged elements» «Result»)
                  | for k ∈ 0..last(b)
                  |   [ c_k ← Σ_{i=1}^{r} (b_k)^i   d_k ← c_k > 0   u^⟨k⟩ ← (d_k^T)^⟨0⟩   p_k ← k ]
                  | u ← stack[str, (p  Ind  u^T)]
                  | (b c d u)
```

b – ***adjacency matrices***
c – ***reachability matrices***
d – ***normalized matrices***
u – ***result***
p – ***№ output objects***

$(b \; c \; d \; u) := NormExit(Matsm, r)$

Pic. 2. Listing of the calculation part of PROG1.

various network structures with consequent damage to their linear elements (pipelines) is of particular interest.

The solution of this problem is assisted by the development of a simulation model of the process of progressive damage to the network structures of pipeline transport systems, including the creation of a computer program that allows assessing the damage resistance of such systems for the subsequent adoption of well-grounded design solutions.

Let's consider a pipeline system, the structural diagram of which is shown in Pic. 1a.

There are five nodes in the system, among them the source of the target product A and individual consumers B, C, D. In addition, the system contains N = 6 pipelines, which in the process of progressive damage turn into an inoperative state in a random sequence.

If, in order to stop supplying the target product to consumer B, an average of n pipelines is required to be damaged, then the ratio $\bar{W}_B = n / N$ is one of the characteristics of the process of progressive damage. Possible range for changing the values of the degree of damage: $0 \le \bar{W}_B \le 1$.

The indicator of the resistance of the network structure to the progressive damage F_W is the arithmetic average of the values of all degrees of damage established for the system under analysis. In this case:

$$F_W = \frac{\bar{W}_B + \bar{W}_C + \bar{W}_D}{3}.$$

The durability index characterizes the proportion of the total number of pipelines of the system, which on average need to be damaged to prevent the delivery of the target product to all consumers.

The task of determining the characteristics of the stability of the analyzed structure was solved by developing a specialized computer program. Listing of the calculation part of the simulation program for progressive damage PROG1, implemented in the MathCAD system, is shown in Pic. 2.

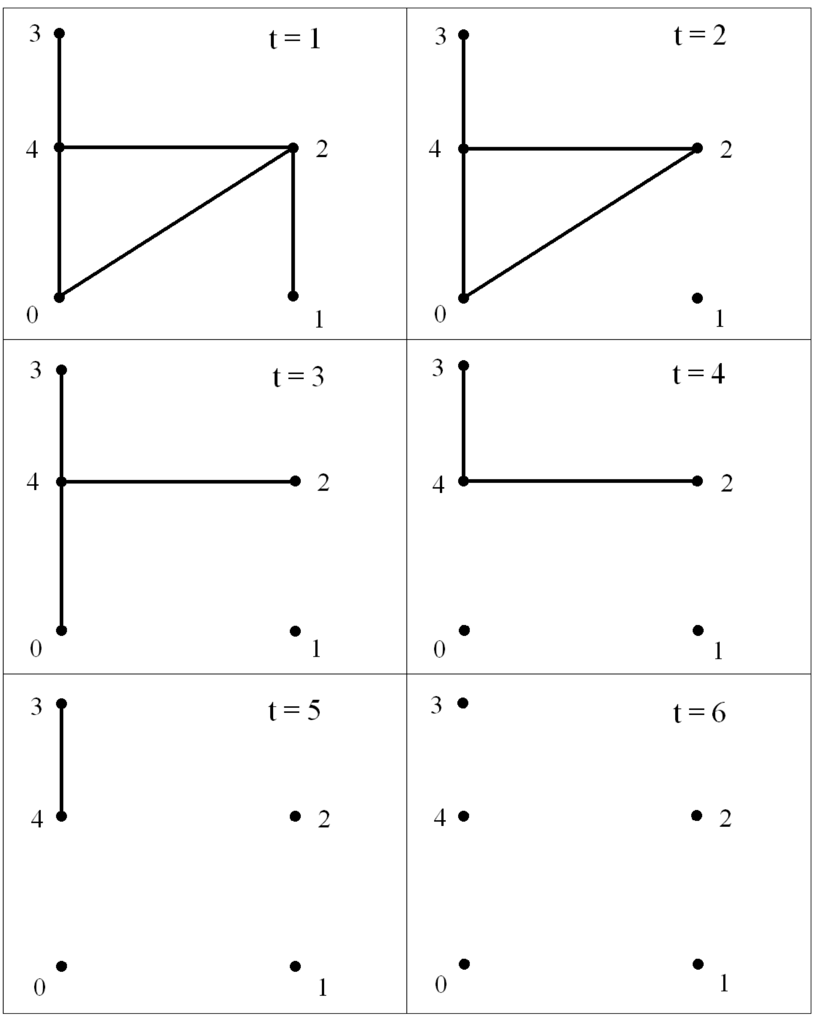
Initial data for calculations are a given number of nodes and linear elements (pipelines) in the system. In addition, the structure of the analyzed object is given by a graph which adjacency matrix Matsm is described in the block of input data.

The adjacency matrix of graph [4] is a rectangular table which number of rows and columns is equal to the number of its numbered vertices.

If there is a connection between the i-th and j-th vertices of the marked graph, then the elements of

$$u = \begin{bmatrix} \text{«№ damage»} & \text{«Indices of damaged elements»} & \text{«Result»} \\ \begin{pmatrix} 0 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \end{pmatrix} & \begin{bmatrix} \text{"(i j)"} \\ (0\ 1) \\ (2\ 1) \\ (4\ 0) \\ (0\ 2) \\ (4\ 2) \\ (4\ 3) \end{bmatrix} & \begin{pmatrix} 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 1 & 1 \\ 1 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix} \end{bmatrix}$$

Pic. 3. Listing of the form of presentation of the result of the performed calculations.



Pic. 4. The structure of the network object, corresponding to different points of the system time t when implementing the procedure of progressive damage.

the adjacency matrix are: $a_{i,j} = a_{j,i} = 1$. If there is no direct connection between the indicated vertices, then $a_{i,j} = a_{j,i} = 0$.

On the main diagonal of the binary adjacency matrix zeros are located. An exception may be the option of having a loop at the top of the graph.

Table 1

Results of simulation modeling of the damage process

Generation № 1		Generation № 2	
«Indices of damages elements»	«Result»	«Indices of damages elements»	«Result»
$\begin{bmatrix} "(i\ j)" \\ (1\ 0) \\ (2\ 1) \\ (2\ 0) \\ (4\ 0) \\ (4\ 2) \\ (4\ 3) \end{bmatrix}$	$\begin{pmatrix} 1&1&1&1&1 \\ 1&1&1&1&1 \\ 1&0&1&1&1 \\ 1&0&1&1&1 \\ 0&0&0&0&0 \\ 0&0&0&0&0 \\ 0&0&0&0&0 \end{pmatrix}$	$\begin{bmatrix} "(i\ j)" \\ (2\ 4) \\ (2\ 1) \\ (1\ 0) \\ (0\ 2) \\ (3\ 4) \\ (4\ 0) \end{bmatrix}$	$\begin{pmatrix} 1&1&1&1&1 \\ 1&1&1&1&1 \\ 1&1&1&1&1 \\ 1&0&1&1&1 \\ 1&0&0&1&1 \\ 1&0&0&0&1 \\ 0&0&0&0&0 \end{pmatrix}$
Generation № 3		Generation № 4	
«Indices of damages elements»	«Result»	«Indices of damages elements»	«Result»
$\begin{bmatrix} "(i\ j)" \\ (0\ 2) \\ (2\ 1) \\ (1\ 0) \\ (3\ 4) \\ (4\ 2) \\ (4\ 0) \end{bmatrix}$	$\begin{pmatrix} 1&1&1&1&1 \\ 1&1&1&1&1 \\ 1&1&1&1&1 \\ 1&0&1&1&1 \\ 1&0&1&0&1 \\ 1&0&0&0&1 \\ 0&0&0&0&0 \end{pmatrix}$	$\begin{bmatrix} "(i\ j)" \\ (0\ 2) \\ (2\ 1) \\ (0\ 4) \\ (4\ 3) \\ (4\ 2) \\ (1\ 0) \end{bmatrix}$	$\begin{pmatrix} 1&1&1&1&1 \\ 1&1&1&1&1 \\ 1&1&1&1&1 \\ 1&1&0&0&0 \\ 1&1&0&0&0 \\ 1&1&0&0&0 \\ 0&0&0&0&0 \end{pmatrix}$
Generation № 5		Generation № 6	
«Indices of damages elements»	«Result»	«Indices of damages elements»	«Result»
$\begin{bmatrix} "(i\ j)" \\ (2\ 1) \\ (1\ 0) \\ (4\ 0) \\ (4\ 2) \\ (2\ 0) \\ (3\ 4) \end{bmatrix}$	$\begin{pmatrix} 1&1&1&1&1 \\ 1&1&1&1&1 \\ 1&0&1&1&1 \\ 1&0&1&1&1 \\ 1&0&1&0&0 \\ 0&0&0&0&0 \\ 0&0&0&0&0 \end{pmatrix}$	$\begin{bmatrix} "(i\ j)" \\ (4\ 3) \\ (0\ 2) \\ (0\ 1) \\ (4\ 2) \\ (2\ 1) \\ (0\ 4) \end{bmatrix}$	$\begin{pmatrix} 1&1&1&1&1 \\ 1&1&1&0&1 \\ 1&1&1&0&1 \\ 1&1&1&0&1 \\ 1&0&0&0&1 \\ 1&0&0&0&1 \\ 0&0&0&0&0 \end{pmatrix}$
Generation № 7		Generation № 8	
«Indices of damages elements»	«Result»	«Indices of damages elements»	«Result»
$\begin{bmatrix} "(i\ j)" \\ (3\ 4) \\ (4\ 2) \\ (2\ 0) \\ (0\ 4) \\ (0\ 1) \\ (1\ 2) \end{bmatrix}$	$\begin{pmatrix} 1&1&1&1&1 \\ 1&1&1&0&1 \\ 1&1&1&0&1 \\ 1&1&1&0&1 \\ 1&1&1&0&0 \\ 0&0&0&0&0 \\ 0&0&0&0&0 \end{pmatrix}$	$\begin{bmatrix} "(i\ j)" \\ (2\ 1) \\ (4\ 2) \\ (0\ 2) \\ (4\ 0) \\ (4\ 3) \\ (0\ 1) \end{bmatrix}$	$\begin{pmatrix} 1&1&1&1&1 \\ 1&1&1&1&1 \\ 1&1&1&1&1 \\ 1&1&0&1&1 \\ 1&1&0&0&0 \\ 1&1&0&0&0 \\ 0&0&0&0&0 \end{pmatrix}$

However, further we consider graphs without loops in their composition.

To understand the structure of the simulation modeling program, the listing shows the individual functional blocks that provide the required sequence of calculations. If necessary, it is possible to derive and determine the composition of matrices involved in intermediate calculations.

The dynamics of the damage to the network structure described by the Matsm matrix was estimated by generating a series of adjacency matrices with random pair zeroing of the units arranged symmetrically with respect to the main diagonal. In this case, the number of such matrices will correspond to the number of units located above the main diagonal of Matsm.

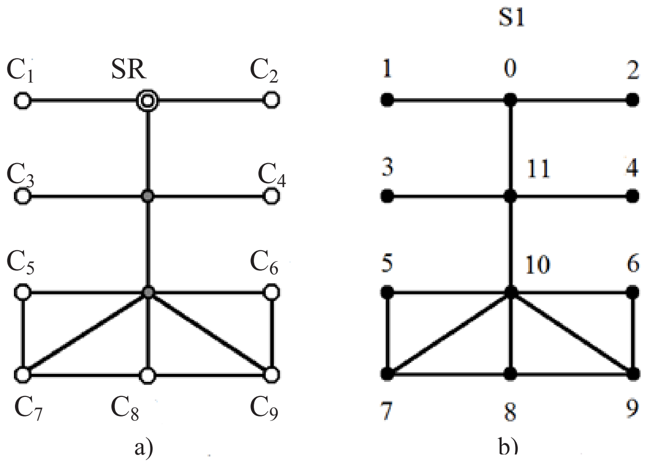
Each of the adjacency matrices thus obtained will characterize the graph of the damaged network structure at various points in the system time.

The next stage of program functioning involves the construction of a set of reachability matrices, each of which is formed on the basis of the corresponding adjacency matrix. The reachability matrix [5] characterizes the presence of messages between the

Table 2

Estimated characteristics of the process of network structure damage

Generation's number	Characteristics of damage process		
	W_B	W_C	W_D
1	0,333	0,667	0,667
2	0,5	0,667	0,833
3	0,5	0,833	0,667
4	1,0	0,5	0,5
5	0,333	0,833	0,667
6	0,667	0,667	0,167
7	0,833	0,833	0,167
8	1,0	0,5	0,667
Average value	0,645	0,688	0,542



Pic. 5. Structural diagram of the pipeline system with the position of the source in the node SR and consumers in the nodes C_1, C_2, … C_9 (a), and the marked graph S1 (b) corresponding to the original structure.

i-th and j-th vertices and the possibility of transition from one vertex of the graph to another taking into account the existing system of internal connections.

The simulation results are displayed in the form of a list of values of the system time, the notation of edges of the graph that are damaged in a random order, and the resulting matrix, which includes the first lines of the original and all constructed reachability matrices.

Analysis of the change in the content of the rows of the resulting matrix allows us to determine which of the consumers and at what time of the system time loses the connection with the source of the target product in the process of progressive damage.

Multiple restart of the program with fixing of values of the system time, at which the connection between the source and each of the consumers of the product is broken, makes it possible to create a database by which the characteristics of the stability of the network structure are evaluated.

Thus, the structure of the transport system considered earlier, shown in Fig. 1a is characterized by a marked graph, shown in Pic. 1b. For the accepted order of designating the vertices of a graph, its adjacency matrix:

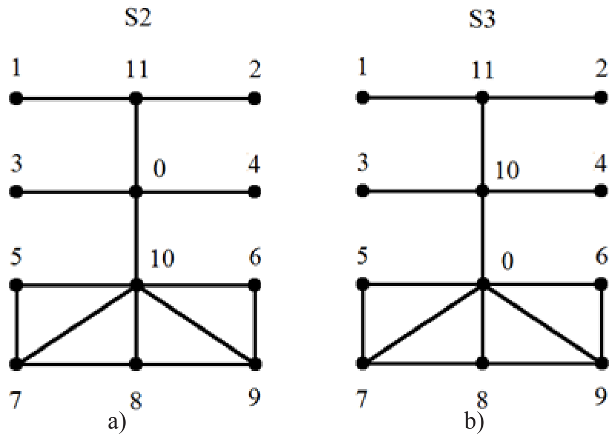
$$Matsm := \begin{pmatrix} 0 & 1 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \\ 1 & 0 & 1 & 1 & 0 \end{pmatrix}$$

The result of modeling the process of progressive damage is presented in the form shown in Pic. 3.

The dynamics of the process of progressive damage to the structure of the graph corresponding to the solution obtained is shown in Pic. 4.

When assessing the properties of the analyzed structure, the process of damage was repeated 8 times, which is not enough to form a full-fledged statistical database, but it allows to demonstrate the functioning of the computer program and to assess the feasibility of the simulation modeling procedure.

The results of the progressive damage process are shown in Table 1.



Pic. 6. The marked graphs S2 (a) and S3 (b) of alternative structural diagrams of the pipeline system with the location of the product source in the nodes to which the vertices with the designation 0 correspond.

The processing of the obtained data helps to establish the stability characteristics of the analyzed structure, the values of which are given in Table 2.

The simulation results allow us to conclude that to disconnect the consumer B from the source of the target product it is necessary to damage approximately 65 % of all pipelines of the system. To disconnect consumers C and D, an average of 69 % and 54 % of pipelines, respectively, should be damaged.

The estimated value of the durability index for the network structure under consideration is $F_w = 0,625$. This means that to stop the delivery of the target product to all consumers it is necessary to damage an average of about 63 % of the total number of pipelines of the system.

Let's consider the possibilities of the developed computer program in solving a practical problem. Suppose, for the pipeline system, the initial block diagram of which is shown in Pic. 5a, it is necessary to determine the location of the source of the target product, in which it is ensured that it achieves the greatest resistance to the process of progressive damage.

A marked graph of the original structural scheme with the location of the source of the target product at the vertex 0, and consumers at the vertices 1,2 … 7 is shown in Pic. 5 b. The resulting value of the stability index of the structure S1: $F_w = 0,467$.

Alternative variants of forming the structure of the pipeline transport system with a change in the position of the source of the target product are shown in Pic. 6.

The values of the durability indicators for alternative variants of forming the network structure with the marked graph S2: $F_w = 0,508$ and graph S3: $F_w = 0,544$., determined as a result of computer simulation.

This result means that damage to the structure S1 by the mechanism of progressive damage is associated with the transition to an inoperative condition of about 46 % of the pipelines of the base version. From the considered alternative variants the best indicator is possessed by the network structure S3. With its use, the damage to the system is explained with the transition to an inoperative condition of approximately 55 % of the total number of all pipelines.

Thus, when making a design decision, the last option of forming a network structure should be given preference. It should be noted that the level of costs for designing and manufacturing each of the systems considered is approximately the same, since all the structural differences are related only to changes in the location of the source of the target product.

Conclusions.

1. The durability characteristics and the program of simulation modeling of the process of progressive damage to the network structures of pipeline transport systems have been developed.

2. Calculation of the expected characteristics of the damage resistance of such systems allows us to make sound design decisions when comparing alternative options. Thus, a comparison of the indices of stability for the structures S1, S2 and S3 gives grounds to conclude that the most suitable properties are possessed by the system constructed on the basis of the structure S3, for which the calculated value Fw = 0,544 is established.

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