Progressive damage to structural elements of pipeline systems and efficiency assessment of protection measures

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Abstract. The Aim of this paper is to evaluate the effect of transportation node protection on the resilience of pipeline systems to the development of damage by the mechanism of progressive blocking of nodes as well as the efficiency analysis of the employed protection measures. Damage to a point element of a system due to simultaneous transition into the down state of all the pipelines converging into it is called blocking. The process of progressive blocking of a transportation system’s nodes in a random order is considered to be progressive damage of a network structure. Progressive damage is a hazardous emergency development scenario that is associated with the disconnection of first some, then all end product consumers from the source. A system’s ability to resist progressive damage is estimated by the resilience indicator, the average share of the damaged nodes whose blocking in a random order causes the disconnection of all end product consumers from the source. Methods of research. A system’s indicator of resilience to progressive blocking of nodes was defined using computer simulation. The resilience indicator can only be used in comparative analysis of network structure properties if the analyzed systems are comparable. The condition of comparability of systems with protected point elements is the presence of equal numbers of disconnectable consumer nodes and damageable nodes. If the analyzed systems include protective peripheral clusters that represent interconnected sets of point elements, the following must be equal to enable the comparability of such systems:
– number of peripheral clusters with two and more consumer nodes on condition of equal number of such nodes within each system;
– most probable order of disconnection from the source of both individual consumers and peripheral clusters with equal numbers of end product consumers.

Results. A system’s resilience to progressive blocking can be improved by means of managerial and technical measures of transportation node protection. It has been established that the highest efficiency of protection of individual point elements is achieved in case of protection of a consumer node located at the shortest possible distance from the source of the end product. It is demonstrated that the peripheral cluster for protection of a transportation system should be synthesized by including consumers situated at the minimal possible distance from the source node.

Conclusions. The development of emergency situations by the mechanism of progressive blocking of nodes is a hazardous scenario of pipeline system damage. The resilience of a network structure to damage can be improved by means of measures of transportation system nodes protection. The highest efficiency of protection of individual point elements is achieved in case of protection of a consumer node located at the shortest possible distance from the source of the end product. The peripheral cluster for protection of a transportation system from progressive damage should be synthesized by including consumers situated at the minimal possible distance from the source node.

Keywords: system, pipeline, node, damage, protection, resilience.

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Pipeline transportation systems are used in various industries for the purpose of delivering fuel, raw materials and end products to consumers. Such complex engineering facilities may include larger numbers of structural elements that interact among each other and ensure the reproduction of the functional effect even in the presence of damaging factors [1-3]. The operation of such potentially hazardous technical systems is associated with the possibility of failure of individual structural elements both due to the effects of internal processes, and as the result of interaction with the environment [4-7].

Due to the presence of excessive connections within a network the transition of one or more structural elements into the down state can be usually compensated by immediate redistribution of traffic.

If, as an emergency unfolds, the network damage process continues, that will cause first some, then all end product consumers to be disconnected.

In this context, within a short period of time, some number of linear and point elements may transition into the down state [8-11]. Damage to a linear element (pipeline) means its inability to further handle traffic. If a structure’s point element is damaged, any traffic through such node will also be terminated.

Then, the blocking of an individual node of a system may be considered as the result of simultaneous transition into the down state of all the pipelines converging into it.

If the damage to a network structure occurs in the form of progressive blocking of individual system nodes in a random order, such scenario of emergency development is called progressive blocking.

Progressive blocking is accompanied by a rapid degradation of the transportation capacity of the system and may cause the disconnection from the source of all end product consumers.

A system’s resilience to progressive blocking can be improved by protecting individual point elements. Protection of a transportation node is understood as a set of measures to ensure guaranteed non-transition into the down state of all pipelines that converge into it.

It is obvious that node protection is an efficient tool of improving a whole system’s resilience to the development of progressive blocking, however, literary sources do not provide recommendations regarding the implementation of protection measures and selection of optimal protection architectures.

The Aim of this paper is to evaluate the effect of transportation node protection on the resilience of pipeline systems to the development of damage by the mechanism of progressive blocking, as well as to analyze the efficiency of the employed protection measures.

The effect of protection of individual system nodes on its resilience to the development of progressive damage

Let us examine the structure diagram of a pipeline system shown in Fig. 1. It has the source node A, as well as consumers B, C, D, E, F.

![Figure 1. Structure diagram of a pipeline system with protected transportation nodes](image)

Consumer nodes C and F are protected, as only protected linear elements converge into them. Node F is connected to the source that is protected by transportation connection AF, cannot be disconnected from it and thus is not disconnectable. Protected node C is considered disconnectable despite being protected, as in case of progressive blocking it can be disconnected from the source.

The following designations are used in the research of the process of progressive blocking:

- $U_0$, the total number of product consumers that may be disconnected from the source in case of progressive blocking development;
- $Q_0$, the share of the total number of disconnectable consumers that were disconnected from the source of product at the given instant of system time;
- $R_y$, the total number of damageable, i.e. unprotected transportation nodes that can be blocked;
- $r_y$, the current number of blocked nodes in the process of progressive damage;
- $Y$, the degree of damage of the unprotected part of a network structure observed at the given instant of system time ($Y = r_y / R_y$).

Dependence $Q_0(Y)$ is the damage diagram of the structure and has the form of a staircase function. Thus, for the network entity shown in Fig. 1 the damage diagram is shown in Fig. 2.

![Figure 2. Damage diagram of a network structure](image)

Values $M[Y_B], \ldots, M[Y_E]$ are the mathematical expectations of the scopes of damage that trigger progressive disconnection of consumers B, \ldots, E from the source [12].

A system’s indicator of resilience to the development of progressive blocking of nodes is the area $F_y$ of the staircase figure shown in Fig. 2:

$$F_y = \{M[Y_B] + M[Y_C] + M[Y_D] + M[Y_E]\} / U_0$$
Thus, the resilience indicator represents the average share of a system’s damageable nodes whose blocking in a random order causes the disconnection of all disconnectable end product consumers from the source.

As pipeline transportation systems may differ in complexity and include various numbers of structural elements, the correct comparison of the values of their durability indicators is only possible if the corresponding dependences \( Q_0(Y) \) are similar to each other.

Matching of damage diagrams of systems with protected point elements is, in principle, only possible under certain conditions. Let us assume that the analyzed network structures have identical numbers of:
- consumer nodes that may be disconnected from the source in case of blocking process development;
- damageable nodes, i.e. nodes that may transition into the down state due to the lack of appropriate protection.

In this case, the considered systems are comparable, while the comparison of the values of their resilience indicators proves to be correct.

If the set of protected system nodes is interconnected, such network fragment is considered to be a protection cluster [13]. A cluster is called central if it contains a source node. Otherwise it is called peripheral.

The presence of protection clusters has a significant effect on the development of progressive blocking. For instance, if a peripheral cluster has several consumers, at a certain instant of system time they will be disconnected from the source of product simultaneously.

For that reason, besides the above list of comparability conditions, sufficient conditions must be specified, whose fulfillment enables correct comparability of expected values of \( F_Y \) in cases when the system has protection clusters.

So, if there are peripheral clusters, the network structures are comparable if they comply with the additional list of conditions and have the following features:
- identical numbers of peripheral clusters with two and more consumer nodes and identical number of such nodes within each;
- identical orders of disconnection from the source of both individual consumers and peripheral clusters with equal numbers of product consumers.

Thus, the above primary and additional sufficient conditions of comparability of network structure properties allow identifying the feasibility of comparison of their resilience indicator values.

The efficiency analysis of the protection measures taken as regards individual nodes of a transportation system took into account the results of computer simulation [14]. The resilience of a system was estimated both subject to the remoteness of the protected transportation node from the source, and its functionality.

In the general case, a transportation system can include the following types of point elements:
- source of the end product node;
- consumer nodes;
- hubs.

The above elements have different functionalities, and it can be assumed that their protection affects the resilience of systems to progressive damage to different extents. Additionally, the resilience of a network entity to damage also depends on the distance between the protected node and the source of the end product. The remoteness from the source is defined as the minimal number of transitions that must be made along the existing network in order to match the analyzed node with the active source.

The effects of the above factors on the development of progressive blocking of nodes were studied using a system whose structure diagram is shown in Fig. 3.

The choice of the above diagram is due to the following structural features:
- network nodes left and right of the source of product are symmetrical;
- each consumer node on the left can be associated with a hub on the right that is at the same distance from the source of product;
- all consumer nodes are at various distances from the source of the end product.

In the process of progressive damage simulation each calculation model included only one protected node. For
that reason, during each calculation procedure the number of damageable nodes in the system was 22, while the number of disconnectable consumers was 4.

The expected values of $F_r$ in such conditions are comparable and allow evaluating not only the effect of the type of a protected node, but also its remoteness from the source on the resilience of the network entity to progressive damage.

For clarity, the established values of $F_r$ are shown in Fig. 3 next to arrows that indicate the protected point element of the system. The analysis of the obtained results allows concluding the following:

- the most pronounced positive effect is achieved by protecting consumer nodes located at the minimal distance from the source of product;
- as the distance between the protected consumer and the source increases, the efficiency of the protection measures steadily declines;
- the efficiency of protection of hubs is lower as compared to that of the consumer nodes situated at the same distance from the source of product;
- protecting remote hubs practically does not change the values of the resilience indicator.

Thus, while evaluating the protection of individual point elements of a transportation system, it must be noted that the preferable solution consists in protecting a consumer node located at the shortest possible distance from the source of the end product.

As the distance between the protected consumer and the source increases, the efficiency of the protection measures decreases, which should be taken into consideration in the development of design solutions. Additionally, the protection of the source node should be recommended as an efficient measure, if such procedure is possible.

**Protective peripheral cluster and its effect on the resilience of network structures to damage**

The presence of a peripheral cluster within a transportation system has a significant effect on its resilience to the development of progressive blocking of nodes. In this context, of interest is the search for such cluster configuration that enables the maximum positive effect subject to the existing resource restrictions. In the most general terms, we can assume that the costs associated with the protection of transportation nodes are proportional to the number of protected linear elements. Then, the synthesis of the protection cluster should be considered as an optimization procedure associated with the search for the solutions that would enable the required level of protection under the minimal number of protected linear elements [15].

The complexity of the task at hand consists in the fact that obtaining reliable information on the properties of network entities with various configurations of the peripheral cluster requires a preliminary estimation of the comparability of such structures’ properties.

First of all, the compared entities must have the same number of disconnectable consumers, as well as the same number of damageable nodes. Additionally, the systems’ peripheral clusters must include identical numbers of end product consumers.

The above conditions are indispensable for correct comparison of the properties of network structures. The condition of sufficiency is associated with the attainment of similarity of damage diagrams of comparable entities. For that purpose, the compared structures must have the same highest-probability consumer disconnection sequence.

The above sufficient condition, provided that the system has peripheral clusters of various configurations, usually is not achieved. In this case, instead of searching for specific values of $F_r$, attention should be focused on the analysis of the general patterns and dynamics of damage development in cases when the system has a protection cluster with several end product consumers. Let us note that if a peripheral cluster has several consumers, all of them are disconnected from the source of product simultaneously.

Let a system with 6 disconnectable consumers have a peripheral cluster that includes 3 consumers. Depending on the adopted configuration of the protection cluster the damage diagrams may differ. Let us assume that the cluster is situated not far from the source, and a simultaneous disconnection of its 3 consumers happens last. The damage diagram of such system will be as shown in Fig. 4a. If the cluster with three consumers disconnects first, the corresponding damage diagram is as shown in Fig. 4b.

![Fig. 4. Damage diagram of network structures with simultaneous disconnection from the source of the consumers that make the peripheral cluster last (a) and first (b)](image)

As $F_r$ is the area of a staircase figure on the damage diagram, it should be assumed that damage in the form shown in Fig. 4a proves to be the most preferable. In this case the conditions are objectively beneficial for the maximum possible value of $F_r$.

That means that it should be recommended to design the peripheral cluster in such a way as to primarily include consumers that are least remote from the source of the end product.
Let us verify that provision using a specific example. Let us examine the structure diagram of a pipeline system shown in Fig. 5a. Protection cluster C1 includes 4 consumers, that, in case of progressive blocking of nodes, will be disconnected from the source together and before all others.

The damage diagram for this case is shown in Fig. 6a. If 4 less remote consumers are included in the peripheral cluster (Fig. 5b), the damage diagram of such system will be as shown in Fig. 6b.

The obligatory requirements of compatibility of structures SIT1 and SIT2 are met in this case. The specified values of $F_Y$ can be compared subject to the reservation of impossibility of completely matching corresponding damage diagrams.

The defined resilience characteristics of structures designated SIT1 and SIT2 are shown in Table 1.

![Figure 5](image1.png)

Figure 5. Structure diagrams of SIT1 (a) and SIT2 (b) with a peripheral cluster situated more or less far from the source of the end product A

As it can be seen, the previously made assumption regarding the expected properties of items is completely confirmed. That means that design solution associated with the formation of the peripheral cluster should provide for the inclusion of consumers that are least remote from the source of the end product.

The matter of the practicality of inclusion of hubs into the peripheral cluster is of applied significance and must be examined in depth. Figure 7 shows structure diagrams of SIT3 (a) and SIT4 (b) that include clusters C3 and C4 that are different from cluster C2 of system SIT2 in the presence of additional hubs. Increasing the number of nodes in clusters C3 and C4 requires the inclusion of new damaged point elements in order to ensure the observance of the comparability requirements.

![Figure 6](image2.png)

Figure 6. Appearance of the damage diagram of network structures SIT1 (a) and SIT2 (b)

![Figure 7](image3.png)

Figure 7. Structure diagrams SIT3 (a) and SIT4 (b) with additional distributed nodes and protection clusters C3 and C4

Due to that the total number of point elements in SIT3 is 19 (Fig. 7a), while SIT4 has 20 such elements (Fig. 7b).

The defined values of $F_Y$ for the above network entities are shown in Table 1 and allow concluding that the inclusion of additional point elements into the peripheral cluster is only justified in case of decreasing distance to the source of the end product.

**Conclusions**

1. The development of emergency situations by the mechanism of progressive blocking of nodes is a hazardous scenario of pipeline system damage. The resilience of a network structure to damage can be improved by means of measures of transportation system nodes protection. The highest efficiency

| Network structure designation | Number of damageable nodes | Number of disconnectable consumer nodes of the system | Expected value $F_Y$ |
|------------------------------|---------------------------|------------------------------------------------------|---------------------|
| SIT1                         | 16                        | 6                                                   | 0.265               |
| SIT2                         | 16                        | 6                                                   | 0.296               |
| SIT3                         | 16                        | 6                                                   | 0.342               |
| SIT4                         | 16                        | 6                                                   | 0.401               |
of protection of individual point elements is achieved in case of protection of a consumer node located at the shortest possible distance from the source of the end product.

2. The peripheral cluster for protection of a transportation system from progressive damage should be synthesized by including consumers situated at the minimal possible distance from the source node.

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