Planning of Operational and Technological Measures based on Logical and Graphical Modeling

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Abstract. The article presents the results of a study of the principles of planning additional measures for the engineering protection of buildings in urbanized areas with a potential risk of deformation processes based on logical and graphic modeling. We analyzed statistical data on cases of activation of exogenous geological processes in Russia, affecting buildings. The relevance of the study is justified by the need to ensure the operational reliability of water-carrying communications, which are sources of potential flooding and activation of deformation processes. The purpose of the study was to substantiate the frequency of operational measures for hidden communications to reduce the risk of leaks. On the basis of the constructed failure tree, an economic feasibility study was carried out for the optimal periods of scheduled inspections at different intervals of repair. The results obtained by the author can be used in the development of regulations for the maintenance and repair of engineering communications.

1. Introduction

The modern standard for the development of built-up areas, developed by the Ministry of Construction of Russia, is based on the principles of sustainable development of territories and is aimed at improving the quality of the environment. Now a significant part of the exploited building has significant physical wear and tear and is functionally outdated. Therefore, one of the key areas for the formation and transformation of territories is not only the reconstruction of existing buildings, but also the demolition of old and construction of new buildings.

As a rule, new construction is complicated by the increase in the number of storeys of buildings, as well as their deepening under the ground. Both underground construction and the construction of the buried part of buildings are accompanied by increased risks associated with the specific soil conditions in Russia. Thus, according to the data of Glavgosexpertiza, karst rocks are distributed in almost 50% of the territory of Russia, and active karst deformations are recorded in more than 10% of the territory. At the same time, anthropogenic and technogenic factors aggravate exogenous geological processes in urbanized areas, which negatively affects the safety and security of both reconstructed and newly erected buildings. A review of numerous studies indicates that the potential for the manifestation of karst and suffusion-karst processes often causes significant difficulties in the performance of prospecting, design, expert and environmental work [1-5]. Figure 1 shows the results of the analysis of statistical data of the Ministry of Natural Resources and Environment of the Russian Federation, provided by the Center for State Monitoring of the State of Subsoil and Regional Works of the Federal...
State Budgetary Institution Gidrospetsgeologiya, which confirm the problem of the manifestation of a considerable number of cases of activation of karst and suffusion processes that significantly affect buildings.

1.1. Relevance and scientific significance
An analytical review of regulatory documents in the field of engineering protection of territories and buildings [6-9] made it possible to systematize information about the main and additional anti-karst measures. A review of scientific research confirms [10-15] that the technologies of the main measures of engineering protection of territories have been worked out in detail. However, in the event of the occurrence of negative deformation phenomena on already operated buildings, their implementation is very costly. Therefore, according to the author, the fundamental principle of maintaining the safety of buildings in operation in areas with the potential to activate suffusion-karst processes are additional engineering protection measures, since they are of a control and preventive nature.

One of the significant factors in the activation of negative deformation processes is flooding, including due to leaks of industrial and domestic water. Therefore, studies of the peculiarities of planning maintenance and repair of water-carrying communications as a factor in increasing the reliability of protective technological and operational measures are becoming more relevant.

1.2. Objectives of the study
The hypothesis of the study is that the technical condition of pipelines laid in the ground, especially free-flow ones, due to the lack of direct access to them, as well as poorly developed diagnostic tools, is poorly controlled and manageable. Therefore, additional research is required in the field of methodology for assessing the likelihood of malfunctions leading to leaks from communications and activation of deformation processes in order to optimize the planning of their maintenance and repair. Consequently, the purpose of this study was to substantiate the periodicity of operational measures to ensure the operational reliability of hidden communications. The main objectives of the study were:

- systematization of data on the typical causes of damage to water-carrying communications;
- construction of a tree of failures of water-carrying communications based on the event-logical approach;
- calculation justification of the optimal periods of scheduled inspections with different frequency of repairs based on the use of logical and probabilistic reliability assessment methods.

Figure 1. Cases of activation of exogenous geological processes on the territory of Russia affecting buildings and structures according to the data of the FSBI Gidrospetsgeologiya.
2. Materials and methods

The object of research was the process of troubleshooting water-bearing communications in the conditions of probable karst deformations. The subject of the research was to study the possibility of applying the methods of logical-graphic modeling to assess the probability of failure and develop measures to prevent leaks from water-carrying communications. In the study of logical-probabilistic methods, high scientific and practical results were achieved [16-21], on the basis of which the following assumptions were made in this work:

1) safety studies consider failures resulting from deliberate actions leading to an unfavorable situation, while reliability considers random failures;
2) safety failures are mainly caused by human fault, therefore, they cannot simulate or give them a numerical estimate based on probabilistic methods;
3) safety, as opposed to reliability, does not take into account the maintainability and the possibility of the object functioning after a failure;
4) safety analysis includes analysis of "weak" links or types of risk, analysis of the causes of risks, analysis of the consequences of risks, determination of their probabilities, assessment of damage from risks, proposals for reducing risks (reducing probabilities, reducing damage).

To describe the process of functioning of communications as a complex system, a scenario of a dangerous state is drawn up. Failures of one or more system elements are taken as initiating conditions and events, which are assigned a logical variable that has two permissible states: operable or failure. Based on the formalization of functional binary events and the construction of a fault tree, a logical function of operability is compiled.

For a quantitative assessment of the probability of a dangerous state occurring, the logical function is converted into a calculated mathematical model in the form of a polynomial of the probability function \( P(t) \). In this case, the calculation is performed from the condition of the occurrence of failures during the period of normal operation as random events:

\[
P(t) = e^{-\alpha t}
\]

where \( t \) is the observation period; \( \alpha \) is the failure rate, defined as the reciprocal of the MTBF.

Thus, on the one hand, the method is a mechanism for formalizing the set of dangerous states of the system, and, on the other hand, a theoretically substantiated approach to quantitatively assessing the risk of disrupting the reliability of the system’s functioning.

Planning of operational and technological measures based on logical graphical modeling involves the development of a plan for maintenance, inspections and repairs with minimal losses associated with the implementation of control checks and the occurrence of failures:

\[
M_w = \begin{cases} 
n \cdot C & \text{for } t > T \\ 
n \cdot C + w \cdot (T - t) & \text{for } t_c < t \leq T 
\end{cases}
\]

where \( M_w \) is the mathematical expectation of the total operating costs for the adopted planning strategy, rubles; \( n \) is the actual number of checks; \( C \) is the cost of monitoring system performance, rubles; \( w \) is losses associated with the system being in a state of failure, rubles; \( t \) is time to failure, children \( t_c \) is frequency of checks, years; \( T \) is frequency of restoration measures (maintenance, repair), years.

3. Results and discussion

The results of the study are presented on the example of the operation of the water supply system. It has been established that possible threats that must be taken into account when analyzing risks can be grouped into 3 large groups of operational risk:

- natural (for example, loss of system survivability at extremely low temperatures);
- man-made (for example, an increase in the probability of failure in case of subsidence caused by undermining of the foundation due to accidents in the associated communications);
anthropogenic (for example, a decrease in durability caused by improper operation and use of the system for its intended purpose).

Based on the analysis of data on the operation of the water supply system, the first task of the study was solved to systematize data on the characteristic causes of damage (Table 1).

**Table 1.** Violations at various stages of the life cycle of the water supply system, leading to a head event - leaks ($Y_s$).

| Design faults ($Y_1$)                                    | Construction faults ($Y_2$)                        | Operational faults ($Y_3$)                      |
|----------------------------------------------------------|----------------------------------------------------|------------------------------------------------|
| Errors in the initial data - violations in the quality and accuracy of surveys ($X_{11}$) | Low qualification of workers ($X_{21}$)             | Violation of operating modes and conditions ($X_{31}$) |
| Incorrectly selected materials ($X_{12}$)                | Errors during installation ($X_{22}$)               | External influences of a natural and man-made nature ($X_{32}$) |
| Errors in calculations with irrational design ($X_{13}$) | Violation of work technology ($X_{23}$)              | Untimely performance of operational measures ($X_{33}$) |
|                                                          | Incorrect storage and damage to material ($X_{24}$) |                                                 |

In accordance with the above assumptions, the sources and risk factors for disruption of the water supply system were identified and the second task of the study was solved to build a fault tree based on the event-logical approach (Figure 2).

**Figure 2.** Example of a water system failure tree leading to leaks.

Let us represent as simple binary events on the performance of functions or failure of a system element in $X_i$. For $Y$, we will take intermediate events leading to the implementation of a dangerous state and obtained as a combination of two or more initiating events. Then $Y_s$ is a head event leading to the failure of the entire system.

Let’s consider an example of calculating the performance function for branch $Y_3$. The original form of the health function:

$$Y_s = X_{31} \lor X_{32} \lor X_{33}$$

To switch from a logical function to a probabilistic one, we use the orthogonalization method, which allows us to reduce a logical function to an orthogonal disjunctive normal form:

$$Y_3^F = K_{31} \lor K'_{31} \cdot K_{32} \lor K'_{31} \cdot K_{32} \cdot K_{33}$$

where $K_i$ is the designation of simple binary events for the performance of functions or failure of a system element for an equivalent function.
After evaluating the probabilities $P_{ij}$ of the realization of hazardous states, including after identifying the measure of the influence of threats on the realization of hazardous states according to formula (1), the obtained functions of the object's operability were transformed into such a form that it was possible to replace the logical variables with probabilities, and the logical operations with arithmetic:

$$P_3(t) = P_{31} + (1 - P_{31}) \times P_{32} + (1 - P_{31}) \times (1 - P_{32}) \times P_{33}$$

where $P_i(t)$ is the probability of failure-free operation of the system; $t$ is the duration of operation.

The functions of operability for the Y1 and Y2 branches were considered in a similar way. Knowing the intensity of manifestation of hazardous factors of influence, it is possible to predict the probability of failure-free operation of the system (Figure 3).

After studying the statistical data on failures of the water supply system, an assessment was made of the probable losses accompanying emergencies and at the assigned frequency of repairs using formula (2), the mathematical expectation of the total operating costs was determined for a different number of scheduled checks (Figure 4).

![Figure 3](image1.png)  
**Figure 3.** An example of the distribution of the probability of failure-free operation of the water supply system for different periods of routine maintenance.

![Figure 4](image2.png)  
**Figure 4.** An example of calculating the cost of operating a water supply system for a given period of routine maintenance and the frequency of scheduled inspections.

4. Conclusions

During the study of the features of planning operational and technological measures for the engineering protection of territories, the following results were obtained:

1. It has been established that underflooding is a significant factor in the activation of deformation processes in urbanized areas, including due to leaks from water-carrying communications. Therefore, an essential principle of ensuring the safe operation of buildings in areas with the potential to activate suffusion-karst processes are preventive measures to control the technical condition and repair engineering communications.

2. The scientific novelty of the research lies in the fact that the application of logical-graphic methods for assessing the likelihood of damage for inaccessible communications is proposed, which makes it possible to optimize the frequency of their maintenance and repair. The advantages of the method include:
   - relative simplicity of constructing and identifying causal relationships;
   - identifying the most significant risk factors for failure;
   - symbolic representation and justification of decisions made;
   - the possibility of processing by computational means and obtaining a quantitative assessment of the studied phenomena.
3. A tree of failures was compiled using the example of a water supply system based on the systematization of violations at various stages of the life cycle, leading to leaks from communications.

4. The calculation of the probability of failure-free operation of the water supply system with different MTBF has been carried out. It was found that it is within the design values significantly less than the standard service life of communications, which justifies the need for control measures.

5. The calculation of the total operating costs at different frequency of scheduled inspections has been performed. The possibility of choosing the number of checks, which corresponds to the minimum loss and damage, has been established, which substantiates the practical significance of the study.

5. References

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