Method for determining effectiveness of prediction of failure of elements of pipeline systems

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Abstract. The importance and relevance of the development of effective methods for predicting the state of pipeline systems are substantiated. The set of analyzed parameters, containing both deterministic and random components, and being the functions of time is presented as a vector-column. As an indicator of the effectiveness of accident detection, the conditional probabilities of correct detection or omission of a hazard are offered. The formulas and the algorithm of two-alternative detection of emergency situations in pipeline systems are given. It is proposed to use the average risk of forecasting errors, which is the expectation of the average "fee" for the error, as a general indicator of the forecasting efficiency.

1. Introduction

The timely detection of hazardous sections of pipelines and their replacement during preventive repairs requires much lower costs than the elimination of accidents. This is especially important under the conditions of limited budget of the operating organizations. In this regard, the problem of developing the effective models for predicting the state of various technical systems is relevant and is considered by many researchers [1-9].

Determining the actual condition of underground pipelines is a complex multi-factor problem [10,11]. One of the possible ways to solve it is based on the analysis of accumulated statistical data on the damage detected during the operation of pipelines [12-15].

The lack of accurate data on the degree of impact of various factors on the rate of destruction of the pipeline makes it difficult to create a theoretical model of this process. Therefore, the search for ways to improve the efficiency of the prediction methods used is very important and is often found in the works of many authors [16-20].

The pipeline systems are composed of individual elements. The element should be understood as a part of the pipeline of the same reliability.

Any damage to the pipeline, causing the need to turn it off from work to eliminate the damage, is considered a failure. The occurrence of failures can be influenced by two types of factors – deterministic and random.

The deterministic factors include: pipe and insulation materials, properties of the transported medium (chemical composition, temperature), hydrogeological conditions (soil corrosion, average groundwater level) [21,22].
2. **Processing of the analyzed parameters**

The set of analyzed parameters containing both deterministic and random components and being functions of time forms a column vector:

\[
\tilde{y}(t) = \begin{bmatrix}
    y_1(t) \\
    y_2(t) \\
    \vdots \\
    y_M(t)
\end{bmatrix}
\]  

Total implementation \( \tilde{y}(t) \) may be caused by the actual hazard signal and the interference:

\[
\tilde{y}(t) = A\tilde{x}(t, \tilde{a}) + \tilde{n}(t, \tilde{v})
\]

where \( A \) – is the multiplier (1 or 0) which takes into account the presence or absence of the hazard signal; \( \tilde{x}(t, \tilde{a}), \tilde{n}(t, \tilde{v}) \) – are the vectors of the realization of the hazard signal and the interference, respectively; \( \tilde{a} \) – is the vector of the informative parameters of the signal; \( \tilde{v} \) – is the vector of random parameters of the interference (the interference means the random values of indirect parameters which take, for example, the form of the hazard signal but do not directly entail a real hazard of an accident or, on the contrary, conceal the actual danger).

The signal processing should give the estimate of the discrete parameter:

\[
\bar{A}[\tilde{y}(t)|\tilde{a}, \tilde{v}] = \begin{cases} 
1 & ("yes") \\
0 & ("no")
\end{cases}
\]

which will be considered dependent on \( \tilde{y}(t) \), that is, the functional of the implementation \( \tilde{y}(t) \).

When nothing but the equation (3) is assumed, the detection of danger is called two-alternative.

3. **The parameter discretization**

To optimize the two-alternative detection of the the emergency hazard, it is possible to discretize the indirect parameters as functions of time. It allows:

- to replace the random functions \( \tilde{y}(t) \) to the random multidimensional quantities \( \tilde{y} \);
- to consider the parameters of the set of realizations as functions of many variables and to enter the densities of their probability. Time discretization gives an opportunity to move to the digital processing of the information.

Let each of the scalar functions \( y_i(t) \) include \( L \) time discretes determined in accordance with the Kotelnikov's theorem (Figure 1).

![Figure 1. Expansion of scalar functions \( y_i(t) \) into temporal discrete.](image)
The total number of discrete during processing will be \( m = L \cdot M \) and the decision in this case is taken by the \( m \)-dimensional vector-column:

\[
y = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_m \end{bmatrix}
\]

The solving functional of the equation (2) becomes the decisive function of \( m \) scalar variables:

\[
\hat{A}(y|\alpha, \nu) = \begin{bmatrix} 1 \\ 0 \end{bmatrix}
\]

4. The forecast performance indicators

The inaccurate fixation of the danger signals and false signals (interference) leads to the fact that the random solutions of the two-alternative detector \( \hat{A} = 1 \) or 0 (events \( \hat{A}_1, \hat{A}_0 \)) may not meet the conditions of the presence or absence of a real emergency \( A = 1 \) or 0 (events \( A_1, A_0 \), respectively). There are four possible situations of combining random "solution" and "condition" events for a particular section of the pipeline network:

1) \( \hat{A}_1 A_1 \) - correct prediction of danger;
2) \( \hat{A}_1 A_0 \) - emergency skip;
3) \( \hat{A}_0 A_1 \) - false alarm;
4) \( \hat{A}_0 A_0 \) - correct elimination of danger.

The probabilities of combination of the events \( P(\hat{A}_i A_k) \), \( i, k = 0, 1 \), can be considered as possible indicators of the efficiency of the detection. Each of the alignment probabilities is reduced to the product of the conditional probability of the solution \( P(\hat{A}|A_k) \) by the probability of the condition \( P(A_k) \) [23]:

\[
P(\hat{A}_i A_k) = P(\hat{A}_i | A_k) \cdot P(A_k)
\]

The probability of the conditions of presence \( P(A_1) \) or absence \( P(A_0) \) of the pipeline accident hazard, called a priori, are usually unknown. But the conditional probabilities of the solutions \( P(\hat{A} | A_1) \) can be estimated experimentally or by calculation. In the presence of an emergency, it is possible to introduce conditional probability of the correct detection of the hazard:

\[
D = P(\hat{A}_1 | A_1)
\]

and the omission of the accident:

\[
\bar{D} = P(\hat{A}_0 | A_1) = 1 - D
\]

In the absence of an emergency predisposition, the conditional probability of a false alarm is introduced:

\[
F = P(\hat{A}_1 | A_0)
\]

as well as the conditional probability of the correct elimination of danger:
\[ \hat{F} = (\hat{A}_0 | A_1) = 1 - F \] (10)

A more general indicator is the average risk of forecasting errors-the average "fee" for errors, its mathematical expectation \( \tau = M(\tau) \).

For the two-alternative detection of the hazardousness of the pipeline, the mathematical expectation of the average risk of the prediction error is determined by the equation:

\[ \tau = M(\tau) = \tau_{01} \cdot P(\hat{A}_0, A_1) + \tau_{10} \cdot P(\hat{A}_1, A_0) \] (11)

where \( \tau_{01} \) and \( \tau_{10} \) – are respectively the cost of the accident omission and the false alarm, taking into account the degree of importance and economic costs to eliminate the consequences of erroneous solutions \( \hat{A}_0, A_1 \) and \( \hat{A}_1, A_0 \). The right solutions \( \tau_{00} \) and \( \tau_{11} \) have zero fee.

5. Conclusion

The proposed indicator of the pipeline systems prediction efficiency, which is based on the mathematical expectation of the average risk of forecasting errors, is quite universal and can be used for pipelines of various purposes.

The obtained results can be used in the development of algorithms and the creation of programs to predict the condition of pipelines in incomplete information, as well as to estimate the effectiveness of forecasting.

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