Technologies for Monitoring the Technical Condition of Tunnels by the Critical Values of the Noise and its Correlation with the Useful Signal

Telman Aliev
Identification methods and control systems
Institut of Control Systems ANAS
Azerbaijan University of Architecture and Construction
Baku, Azerbaijan
telmancyber@gmail.com

Naila Musaeva
Information technologies and systems
Azerbaijan University of Architecture and Construction
*Institut of Control Systems ANAS*Baku,
Baku, Azerbaijan
musanaila@gmail.com

***Abstract*—It is noted that at the moment of initiation of malfunctions in the structures of the tunnel, the noise of the noisy signal coming from the corresponding sensor takes on critical values that correlate with the useful signal. The authors develop the algorithms for calculating the probability of admissible and critical values of the noise of the noisy signal, the relay cross-correlation function and the correlation coefficient between the useful signal and the noise. Technologies are proposed for early monitoring of the technical condition of tunnels by critical values of the noise and for determining the dynamics of the development of defects by the value of the correlation coefficient between the useful signal and the noise of the noisy signal.**

***Keywords*—useful signal, noise, noisy signal, probabilities of admissible and critical values of noise, correlation coefficient, tunnel, type of malfunction**

I. Introduction

Tunnels are known to be an important part of modern transport communication networks with heavy traffic. Tunnels are typically built through both soft clay and hard rocks. Therefore, they are subject to rock pressure, groundwater, vibration shocks due to moving vehicles, etc. As a result, deformations, cracks, corrosion, wear, breakdowns and other malfunctions occur in the structures of the tunnels, which can lead to an emergency state. To avoid this, it is necessary to ensure its stability during construction of the tunnel and to adequately manage the risks of accidents during operation.

Geodetic monitoring systems are created for uninterrupted and safe operation of the tunnel. For this purpose, a system of sensors gauging pressure, displacement, load on reinforcement and anchors, crack opening sensors, inclinometers, etc. is installed to measure, collect and process initial information. Based on the results obtained, a conclusion is made on the technical condition of the tunnel, the presence of defects and the degree of their danger for the operation of vehicles, as well as recommendations are given on how to eliminate the malfunctions. [1-3].

However, the existing monitoring and control systems do not allow detecting the early period of malfunctions in the tunnels. This is especially important for countries of seismically active regions, when, after frequent weak earthquakes or minor repeated landslides, microscopic changes in the technical condition of the tunnel appear, which can subsequently lead to serious damage. [1-4].

It is shown in [5-10] that in the normal technical condition of the tunnel, the noisy signal that comes from the corresponding sensor contains only the noise caused by the influence of external factors. At the moment of formation of even the smallest damage, additional noise appears, which correlates with the useful component of the noisy signal.

Therefore, the problem arises of determining the early stage of the initiation of a defect in the tunnels and the dynamics of its development by calculating the probability of the values of the noise getting into a certain critical interval, as well as the characteristics of the correlation between the useful signal and the noise.

II. Problem statement

It is known that in practice, real signals are the sum of useful signals $X(t)$ and noises $\mathrm{E}(t)$, i.e.,

$$G(t) = X(t) + \mathrm{E}(t). \quad (1)$$

Because useful signals $X(t)$ are contaminated with noise $\mathrm{E}(t)$, tangible errors emerge in determining the estimates of their correlation functions $R_{XX}(\mu)$.

Here, as shown in [1, 5-10], the sum noise $\mathrm{E}(t)$ is made up of the noise $\mathrm{E}_1(t)$ caused by external factors and the noise $\mathrm{E}_2(t)$ caused by the initiation of a defect during the operation of objects, i.e.,

$$\mathrm{E}(t) = \mathrm{E}_1(t) + \mathrm{E}_2(t). \quad (2)$$

Suppose that $G(t)$ is sampled stationary random signal with a normal distribution law, consisting of the useful signal $X(t)$ and the noise $\mathrm{E}(t)$ with a zero mathematical expectation m_{E}. Here, the formula for calculating the estimate D_G of the variance of the noisy signal $G(t)$ is written as [1,5-10]:

$$D_G = R_{GG}(0) = \frac{1}{N}\sum_{i=1}^{N} G^2(i\Delta t) =$$

$$= R_{XX}(0) + 2R_{X\mathrm{E}}(0) + R_{\mathrm{EE}}(0). \quad (3)$$

Therefore, the error of the obtained result is equal to

$$\lambda_{GG}(\mu=0) = 2R_{X\mathrm{E}}(0) + R_{\mathrm{EE}}(0) = D_{\mathrm{E}},$$

where $R_{X\mathrm{E}}(0) = \frac{1}{N}\sum_{i=1}^{N} X(i\Delta t)\mathrm{E}(i\Delta t)$ is the cross-correlation function between the useful signal and the noise; $R_{\mathrm{EE}}(0) = \sum_{i=1}^{N} \mathrm{E}(i\Delta t)\mathrm{E}(i\Delta t)$ is the variance of the noise $\mathrm{E}(t)$.

The formula for calculating the estimate of the correlation function $R_{GG}(\mu)$ at $\mu \neq 0$ can also be written as [1,5-10]:

$$R_{GG}(\mu) = \frac{1}{N}\sum_{i=1}^{N} G(i\Delta t)G((i+\mu)\Delta t) =$$

$$= R_{XX}(\mu) + R_{\mathrm{E}X}(\mu) + R_{X\mathrm{E}}(\mu) + R_{\mathrm{EE}}(\mu). \quad (4)$$

Since $R_{\mathrm{EE}}(\mu)$=0 at $\mu \neq 0$, the sum noise will be equal to

$$\lambda_{GG}(\mu) \approx \begin{cases} 2R_{X\mathrm{E}}(0) + R_{\mathrm{EE}}(0) & \text{when } \mu = 0 \\ 2R_{X\mathrm{E}}(\mu) & \text{when } \mu \neq 0 \end{cases}. \quad (5)$$

Hence the obvious inequality

$$R_{XX}(\mu) \neq R_{GG}(\mu). \quad (6)$$

For this reason, in practice, it is often impossible to ensure the adequacy of the results of the problem being solved using the estimate of $R_{GG}(\mu)$, since in this case part of the valuable information contained in the noise $\mathrm{E}(t)$ of the signal $G(t)$ is lost. In this regard, it is obvious that it is necessary to create algorithms and technologies for determining the estimate of the noise variance D_{E} and the cross-correlation function $R_{X\mathrm{E}}(\mu)$ between the useful signal and the noise.

At the same time, it is obvious [1,5-10] that the correlation between $X(t)$ and $\mathrm{E}(t)$ arises when the values of the noise are a certain critical interval. It is known that the probability $P(\alpha \le \mathrm{E}(t) \le \beta)$ of the noise $\mathrm{E}(t)$ being in a certain interval $[\alpha, \beta]$ can be calculated from the expression:

$$P(\alpha \le \mathrm{E}(t) \le \beta) = \int_{\alpha}^{\beta} f(\varepsilon)d\varepsilon, \quad (7)$$

where $f(\varepsilon)$ is the density distribution function of the noise $\mathrm{E}(t)$.

Since in most cases the stationary ergodic noise obeys the normal distribution law $N(\varepsilon, m_{\mathrm{E}}, \sigma_{\mathrm{E}})$, and its mathematical expectation m_{E} =0:

$$N(\varepsilon) = \frac{1}{\sigma_{\mathrm{E}}\sqrt{2\pi}} e^{-\frac{(\varepsilon - m_{\mathrm{E}})^2}{2\sigma_{\mathrm{E}}^2}}, \quad (8)$$

then the probability $P(\alpha \le \mathrm{E}(t) \le \beta)$ can be calculated as follows:

$$P(\alpha \le \mathrm{E}(t) \le \beta) = \int_{\alpha}^{\beta} N(\varepsilon)d\varepsilon. \quad (9)$$

Below, we propose algorithms and technologies for determining the early stage of the initiation of a defect in a tunnel and the dynamics of its development as a result of calculating the probability of the noise being in a certain critical interval $[\alpha, \beta]$, as well as relay cross-correlation function and correlation coefficient between the useful signal and the noise.

III. Developing Algorithms for Calculating the Probability of Admissible and Critical Values of the Noise

From formula (7) it follows that to calculate the probability of the noise being in a given interval, it is necessary to determine the distribution density function $N(\varepsilon)$. Obviously, this requires calculating first of all the mean square deviation $\sigma_{\mathrm{E}} = \sqrt{D_{\mathrm{E}}}$ of the noise $\mathrm{E}(t)$. In works [1,15-10] it is shown that the estimate of the mean square deviation σ_{E}^* of the noise $\mathrm{E}(t)$ of the noisy signal $G(t)$ for real technical facilities can be calculated from the expression:

$$\sigma_{\mathrm{E}}^* = \sqrt{R_G(0) - 2R_G(\Delta t) + R_G(2\Delta t)}. \quad (10)$$

In addition, in [1, 15-10], a formula is derived for calculating the mean square deviation of the noise for the special case when the noise is white noise:

$$\sigma_{\mathrm{E}}^* = \sqrt{R_G(0) - R_G(\Delta t)}. \quad (11)$$

Then the density distribution function of the noise $\mathrm{E}(t)$, taking into account the fact that the mathematical expectation of the noise is $m_{\mathrm{E}} = 0$, will be determined from the expression:

$$N^*(\varepsilon) = \frac{1}{\sigma_E^* \sqrt{2\pi}} e^{-\frac{\varepsilon^2}{2(\sigma_E^*)^2}} \quad (12).$$

Obviously, the probability of the noise $E(t)$ being in some interval $[\alpha, \beta]$ can be determined from the expression:

$$P(\alpha \le E(t) \le \beta) = \int_{\alpha}^{\beta} N^*(\varepsilon) d\varepsilon . \quad (13)$$

Thus, knowing the probability with which the noise $E(t)$ takes admissible and critical values at different time instants, it is possible to determine the early latent period of the initiation of defects in a tunnel. The detection of the dynamics of malfunction development also requires calculating the value of the correlation coefficient between the critical values of the noise and the useful signal. This will allow determining the intensity of the emergency situation and prevent the occurrence of accidents in a timely manner.

IV. Algorithms and Technologies for Calculating the Relay Cross-Correlation Function and the Coefficient of Correlation Between the Useful Signal and the Noise

As shown above, during normal operation of the object, the noise $E(t) = E_1(t)$ emerges due to random external factors, which does not correlate with the useful signal $X(t)$. However, at the beginning of the latent period of changes in the technical condition of the object as a result of the initiation of various defects, the noise $E_2(t)$ emerges arises, whose critical values correlate with the useful signal. Therefore, from this moment on, the correlation between the useful signal $X(t)$ and the sum noise $X(t)$ is different from zero. Here, the initiation and development of malfunctions is essentially manifested in the estimates of the cross-correlation functions $R_{XE}(\mu)$ between $X(t)$ and $E(t)$ [1, 5-10]. Therefore, to control the beginning and dynamics of changes in the technical condition of tunnels, it is advisable to use the estimate of $R_{XE}(\mu)$.

It is known that the estimates of the relay correlation functions can be calculated from the formula [1]:

$$R_{XE}^r(\mu) = \frac{1}{N}\sum_{i=1}^{N} sgnX(i\Delta t) E((i+\mu)\Delta t).$$

Obviously, to use this formula, it is necessary to determine the samples of the noise $E(i\Delta t)$ and the useful signal $X(i\Delta t)$, which cannot be measured directly or isolated from the noisy signal $G(t)$ [1].

In this regard, we will consider one of the possible options for the approximate calculation of estimates of the relay cross-correlation function $R_{XE}^{r*}(\mu)$ between the useful signal $X(t)$ and the noise $E(t)$ as a result of calculating the relay correlation function $R_{GG}^r(\mu)$ of the noisy signal $G(t)$.

For this, we first adopt the following notation and conditions [1]:

$$sgnG(i\Delta t) = \begin{cases} +1 & when \ G(i\Delta t) > 0 \\ 0 & when \ G(i\Delta t) = 0 \\ -1 & when \ G(i\Delta t) < 0 \end{cases}.$$

Then the relay correlation function $R_{GG}^r(\mu)$ of the noisy signal $G(t)$ will be calculated from the formula [1]:

$$R_{GG}^r(\mu) = \frac{1}{N}\sum_{i=1}^{N} sgn\, G(i\Delta t) G((i+\mu)\Delta t).$$

Considering that [1]

$$\begin{cases} sgnG(i\Delta t) = sgnX(i\Delta t) \\ sgnG(i\Delta t) G(i\Delta t) = sgnX(i\Delta t) G(i\Delta t) \end{cases} \quad (14)$$

the expression for calculating the relay correlation function $R_{GG}^r(\mu)$ for $\mu = 0$ of the noisy signal $G(t)$ can be written as:

$$R_{GG}^{r*}(\mu = 0) = \frac{1}{N}\sum_{i=1}^{N} sgn\, G(i\Delta t) G(i\Delta t) =$$

$$\frac{1}{N}\sum_{i=1}^{N} sgn\, X(i\Delta t) X(i\Delta t) + \frac{1}{N}\sum_{i=1}^{N} sgn\, X(i\Delta t) E(i\Delta t)$$

$$= R_{XX}^r(0) + R_{XE}^r(0), \quad (15)$$

where $R_{XX}^r(\mu)$, $R_{XE}^r(\mu)$ are the relay correlation function of the useful signal and the cross-correlation function between the useful signal and the noise.

In the literature [1] it is shown that the estimates of the relay cross-correlation function $R_{XE}^{r*}(0)$ can be calculated from the expression

$$R_{XE}^{r*}(0) = R_{GG}^r(0) - 2R_{GG}^r(1) + R_{GG}^r(2) =$$

$$= \frac{1}{N}\sum_{i=1}^{N} sgnG(i\Delta t) G(i\Delta t) -$$

$$- \frac{1}{N}\sum_{i=1}^{N} 2\, sgn\, G(i\Delta t) G((i+1)\Delta t)$$

$$+ \frac{1}{N}\sum_{i=1}^{N} sgn\, G(i\Delta t) G((i+2)\Delta t). \quad (16)$$

In this case, if the conditions of stationarity and normality of the distribution law of noisy signals are satisfied, then the following equalities will be valid for the controlled objects [1]

$$\begin{cases} R_{XE}^{r*}(0) \approx \dfrac{1}{N}\sum_{i=1}^{N} sgn\, X(i\Delta t)\mathrm{E}(i\Delta t) \neq 0 \\ R_{XX}^{r*}(0) + R_{XX}^{*}(2\Delta t) - 2R_{XX}^{*}(\Delta t) \approx 0 \\ R_{XE}^{r*}(\Delta t) \approx \dfrac{1}{N}\sum_{i=1}^{N} sgn\, X(i\Delta t)\mathrm{E}((i+1)\Delta t) \approx 0 \\ R_{XE}^{r*}(2\Delta t) \approx \dfrac{1}{N}\sum_{i=1}^{N} sgn\, X(i\Delta t)\mathrm{E}((i+2)\Delta t) \approx 0 \end{cases} \tag{17}$$

and due to this, the right-hand side of expression (16) takes the form

$$R_{XE}^{r*}(\mu = 0) = R_{XE}^{r}(\mu = 0).$$

Thus, we can assume that the estimate obtained by formula (16) is an estimate of the relay cross-correlation function $R_{XE}^{r*}(\mu\Delta t)$ between the useful signal $X(t)$ and the noise $\mathrm{E}(t)$.

The relationship between relay and normalized cross-correlation functions for normally distributed random processes $X(t)$, $\mathrm{E}(t)$ here is expressed by the relationship [1]:

$$R_{XE}^{r}(\mu) = \sqrt{\frac{2}{\pi}}\rho_{XE}(\mu)\sigma_{\mathrm{E}}, \tag{18}$$

where $\rho_{XE}(\mu)$ is the normalized cross-correlation function between the useful signal $X(t)$ and the noise $\mathrm{E}(t)$, σ_{E} is the mean square deviation of the noise $\mathrm{E}(t)$.

Hence the normalized cross-correlation function $\rho_{XE}(\mu)$ can be calculated from the expression [1]:

$$\rho_{XE}(\mu) = \frac{R_{XE}^{r}(\mu)}{\sqrt{\frac{2}{\pi}}\cdot\sigma_{\mathrm{E}}}. \tag{19}$$

It follows from this formula that to calculate the normalized cross-correlation function $\rho_{XE}(\mu)$ between the useful signal $X(t)$ and the noise $\mathrm{E}(t)$, we need to know the relay cross-correlation function $R_{XE}^{r}(\mu)$ and the mean square deviation σ_{E} of the noise. Obviously, using formula (16), it is possible to calculate the relay cross-correlation function $R_{XE}^{r*}(\mu)$. At the same time, the mean square deviation σ_{E} of the noise can be calculated from expression (10).

Therefore, the calculation of the normalized cross-correlation function can be reduced to the form:

$$\rho_{XE}^{*}(\mu) = \frac{R_{XE}^{r*}(\mu)}{\sqrt{\frac{2}{\pi}}\cdot\sigma_{\mathrm{E}}^{*}}. \tag{20}$$

It is known here that the value of the normalized cross-correlation function $\rho_{XE}(0)$ at $\mu = 0$ is the correlation coefficient:

$$r_{XE} = \rho_{XE}(0) = \frac{R_{XE}^{r}(0)}{\sqrt{\frac{2}{\pi}}\cdot\sigma_{\mathrm{E}}}. \tag{21}$$

Therefore, it is possible to calculate the value of the correlation coefficient r_{XE} between the useful signal $X(t)$ and the noise $\mathrm{E}(t)$:

$$r_{XE}^{*} = \rho_{XE}^{*}(0) = \frac{R_{XE}^{r*}(0)}{\sqrt{\frac{2}{\pi}}\cdot\sigma_{\mathrm{E}}^{*}}. \tag{22}$$

Thus, using formulas (10), (11), (16), (18)-(22) , we can calculate the correlation coefficient between the useful signal $X(t)$ and the noise $\mathrm{E}(t)$.

V. Technologies for Monitoring the Technical Condition of Tunnels by Critical Values of the Noise and Its Correlation with the Useful Signal of the Noisy Signal

It is known that to prevent the risk of transport accidents in tunnels, it is necessary to carry out control of random signals that come from sensors gauging pressure, displacement, load on reinforcement and anchors, crack opening sensors, inclinometers, etc. in real time. Below we propose an algorithm for calculating the probability of development of tunnel defects, which makes it possible to significantly reduce the risk of transport accidents.

At the initial time period t_0, when the tunnel is in fully operational condition, the variance $D_{\mathrm{E},t0}^{*}$ of the noise $\mathrm{E}(t)$ is calculated from the expressions:

$$D_{\mathrm{E},t0}^{*} = \frac{1}{N}\sum_{i=1}^{N} G(i\Delta t)G(i\Delta t) - 2\frac{1}{N}\sum_{i=1}^{N} G(i\Delta t)G((i+1)\Delta t) + \frac{1}{N}\sum_{i=1}^{N} G(i\Delta t)G((i+2)\Delta t).$$

Then we calculate the probabilities of the admissible values of the noise $\mathrm{E}(t)$, i.e. the values of the noise, within the range of which the damage is considered inexistent, based on the condition $m_{\mathrm{E}} - k\sigma^*_{\mathrm{E},t0} \le \mathrm{E}(t) \le m_{\mathrm{E}} + k\sigma^*_{\mathrm{E},t0}$, where k is the selected coefficient. After that:

− taking into account the condition $m_{\mathrm{E}} = 0$, we calculate the minimum and maximum values of the noise $\mathrm{E}(t)$: $\varepsilon_{min} = -k\sigma^*_{\mathrm{E},t0}$; $\varepsilon_{max} = k\sigma^*_{\mathrm{E},t0}$;

− at a certain step $\Delta\varepsilon$ we set the values of the noise $\mathrm{E}(t)$ in ascending order from ε_{min} to ε_{max}:

$$\varepsilon(1) = \varepsilon_{min},\ \varepsilon(i+1) = \varepsilon(i) + \Delta\varepsilon,$$
$$\varepsilon(i+2) = \varepsilon(i+1) + \Delta\varepsilon,\ \ldots,\ \varepsilon(n) = \varepsilon_{max}, \quad (23)$$

and form a sequence of admissible values of the noise $\varepsilon(1)$, $\varepsilon(2)$, $\varepsilon(3)$, …, $\varepsilon(n)$, for which the condition $\varepsilon(i-1) < \varepsilon(i)$ is satisfied.

The density function of the normal distribution is calculated:

$$N^*(\varepsilon(i))_{t0} = \frac{1}{\sigma^*_{\mathrm{E},t0}\sqrt{2\pi}} e^{-\frac{(\varepsilon(i))^2}{2\left(\sigma^*_{\mathrm{E},t0}\right)^2}}.$$

After that, for the time instant t_0, we calculate the probabilities of the values of the noise $\mathrm{E}(t)$ with the mean square deviation $\sigma^*_{\mathrm{E},t_0}$ being in the admissible intervals $\varepsilon(1) \le \mathrm{E}(t) < \varepsilon(2)$, $\varepsilon(2) \le \mathrm{E}(t) < \varepsilon(3)$, …, $\varepsilon(n-1) \le \mathrm{E}(t) \le \varepsilon(n)$:

$$P_{1,t0}\left(\varepsilon(1) \le \mathrm{E}(t) < \varepsilon(2)\right) = \int_{\varepsilon(1)}^{\varepsilon(2)} N^*(\varepsilon)_{t0} d\varepsilon,$$

$$P_{2,t0}\left(\varepsilon(2) \le \mathrm{E}(t) < \varepsilon(3)\right) = \int_{\varepsilon(2)}^{\varepsilon(3)} N^*(\varepsilon)_{t0} d\varepsilon, \ldots,$$

$$P_{(n-1),t0}\left(\varepsilon(n-1) \le \mathrm{E}(t) < \varepsilon(n)\right) = \int_{\varepsilon(n-1)}^{\varepsilon(n)} N^*(\varepsilon)_{t0} d\varepsilon. \quad (24)$$

The values of these probabilities are entered in the database of informative attributes as reference values corresponding to the fully operational condition of tunnels.

After a certain period of time at the instant t_1 at the points $\varepsilon(1)$, $\varepsilon(2)$, $\varepsilon(3)$, …, $\varepsilon(n)$, we re-calculate the density distribution function $N^*(\varepsilon)_{t1}$ for the noise $\mathrm{E}(t)$ with the mean square deviation $\sigma^*_{\mathrm{E},t1}$:

$$N^*(\varepsilon(i))_{t1} = \frac{1}{\sigma^*_{\mathrm{E},t1}\sqrt{2\pi}} e^{-\frac{(\varepsilon(i))^2}{2\left(\sigma^*_{\mathrm{E},t1}\right)^2}}.$$

Then, for the time instant t_1, we calculate the probabilities of the values of the noise $\mathrm{E}(t)$ with the mean square deviation $\sigma^*_{\mathrm{E},t_1}$ being in the admissible intervals $\varepsilon(1) \le \mathrm{E}(t) < \varepsilon(2)$, $\varepsilon(2) \le \mathrm{E}(t) < \varepsilon(3)$, …, $\varepsilon(n-1) \le \mathrm{E}(t) \le \varepsilon(n)$:

$$P_{1,t1}\left(\varepsilon(1) \le \mathrm{E}(t) < \varepsilon(2)\right) = \int_{\varepsilon(1)}^{\varepsilon(2)} N^*(\varepsilon)_{t1} d\varepsilon,$$

$$P_{2,t1}\left(\varepsilon(2) \le \mathrm{E}(t) < \varepsilon(3)\right) = \int_{\varepsilon(2)}^{\varepsilon(3)} N^*(\varepsilon)_{t1} d\varepsilon, \ldots,$$

$$P_{(n-1),t1}\left(\varepsilon(n-1) \le \mathrm{E}(t) < \varepsilon(n)\right) = \int_{\varepsilon(n-1)}^{\varepsilon(n)} N^*(\varepsilon)_{t1} d\varepsilon. \quad (25)$$

After that, we calculate the difference of the probabilities of the noise $\mathrm{E}(t)$ being in the intervals $\varepsilon(1) \le \mathrm{E}(t) < \varepsilon(2)$, $\varepsilon(2) \le \mathrm{E}(t) < \varepsilon(3)$, …, $\varepsilon(n-1) \le \mathrm{E}(t) \le \varepsilon(n)$ at the time instants t_1 and t_0:

$$P_{1,t1-t0}\left(\varepsilon(1) \le \mathrm{E}(t) < \varepsilon(2)\right) =$$
$$= P_{1,t1}\left(\varepsilon(1) \le \mathrm{E}(t) < \varepsilon(2)\right) - P_{1,t0}\left(\varepsilon(1) \le \mathrm{E}(t) < \varepsilon(2)\right)$$
$$P_{2,t1-t0}\left(\varepsilon(2) \le \mathrm{E}(t) < \varepsilon(3)\right) =$$
$$P_{2,t1}\left(\varepsilon(2) \le \mathrm{E}(t) < \varepsilon(3)\right) - P_{2,t0}\left(\varepsilon(2) \le \mathrm{E}(t) < \varepsilon(3)\right)$$
$$\ldots \quad (26)$$
$$P_{(n-1),t1-t0}\left(\varepsilon(n-1) \le \mathrm{E}(t) < \varepsilon(n)\right) =$$
$$P_{(n-1),t1}\left(\varepsilon(n-1) \le \mathrm{E}(t) < \varepsilon(n)\right) -$$
$$- P_{(n-1),t0}\left(\varepsilon(n-1) \le \mathrm{E}(t) < \varepsilon(n)\right).$$

The differences of the probabilities $P_{1,t1-t0}\left(\varepsilon(1) \le \mathrm{E}(t) < \varepsilon(2)\right)$, $P_{2,t1-t0}\left(\varepsilon(2) \le \mathrm{E}(t) < \varepsilon(3)\right)$, $P_{(n-1),t1-t0}\left(\varepsilon(n-1) \le \mathrm{E}(t) < \varepsilon(n)\right)$ the informative attributes of the initiation of defects in tunnels.

Then work is performed to detect the defect, and the values of probabilities (25) and difference of probabilities (26) are saved as reference sets for the occurrence of this type of defect.

After the values of the probabilities have also been obtained at the time instants t_3, t_4, …, t_k, the database of informative attributes takes the form:

$$TS = \begin{bmatrix} \sigma^*_{E,t0} & N^*\left(\varepsilon(i)\right)_{t0} & P_{1,t0} & P_{2,t0} & \cdots & P_{(n-1),t0} \\ \sigma^*_{E,t1} & N^*\left(\varepsilon(i)\right)_{t1} & P_{1,t1} & P_{2,t1} & \cdots & P_{(n-1),t1} \\ \sigma^*_{E,t2} & N^*\left(\varepsilon(i)\right)_{t2} & P_{1,t2} & P_{2,t2} & \cdots & P_{(n-1),t2} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \sigma^*_{E,tk} & N^*\left(\varepsilon(i)\right)_{tk} & P_{1,tk} & P_{2,tk} & \cdots & P_{(n-1),tk} \end{bmatrix} \quad (27)$$

After the appropriate training, one of the possible technical states of the tunnel is assigned to each line. In this case, a new column with one of the possible states is added to matrix (27):

$$TS = \begin{bmatrix} \sigma^*_{E,t0} & N^*\left(\varepsilon(i)\right)_{t0} & P_{1,t0} & P_{2,t0} & \cdots & P_{(n-1),t0} & 0 \\ \sigma^*_{E,t1} & N^*\left(\varepsilon(i)\right)_{t1} & P_{1,t1} & P_{2,t1} & \cdots & P_{(n-1),t1} & 1 \\ \sigma^*_{E,t2} & N^*\left(\varepsilon(i)\right)_{t2} & P_{1,t2} & P_{2,t2} & \cdots & P_{(n-1),t2} & 2 \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \sigma^*_{E,tk} & N^*\left(\varepsilon(i)\right)_{tk} & P_{1,tk} & P_{2,tk} & \cdots & P_{(n-1),tk} & k \end{bmatrix}, \quad (28)$$

where 0 is fully operational; 1 − operational without damage; 2 − partially operational with minor damage; 3 − limited operational, but the resulting minor damage develops intensively; 4 − non−operational; 5 − pre−emergency; 6 − emergency, etc. depending on the values of probabilities at a given time instant.

In addition to matrix of the technical condition (28), a matrix of the dynamics of damage development is also built, which consists of estimates of the correlation coefficients r^*_{XE} between the useful signal $X(t)$ and the noise $E(t)$ at the time instants t_0, t_1, t_2, t_3, …, t_k. After training, each value of the coefficient of correlation r^*_{XE-t0}, r^*_{XE-t1}, … r^*_{XE-tk} is associated with a certain degree of the dynamics of the failure development: no defect; defect exists but does not develop; defect develops insignificantly; defect develops; defect develops rapidly; defect quickly leads to a catastrophic situation, etc. As a result, we get the following matrix of the dynamics of damage development:

$$DR = \begin{bmatrix} P_{1,t1-t0} & P_{2,t1-t0} & \cdots & P_{(n-1),t1-t0} & r^*_{XE,t1-t0} \\ P_{1,t2-t1} & P_{2,t2-t1} & \cdots & P_{(n-1),t2-t1} & r^*_{XE,t2-t1} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ P_{1,tk-t(k1)} & P_{2,tk-t(k1)} & \cdots & P_{(n-1),tk-t(k1)} & r^*_{XE,tk-t(k1)} \end{bmatrix}. \quad (29)$$

Thus, using matrices (28), (29), it is possible to determine the probability of the initiation of defects in tunnels, as well as to determine the dynamics of the development of these defects over time, which is a prerequisite for determining the probability of transport accidents in tunnels.

VI. Conclusion

Studies have shown that one of the possibilities for identifying the initial latent period of the initiation of damage and defects in tunnels and determining the dynamics of their development is the calculation and analysis of the probabilities with which the nose takes admissible and critical values, as well as the values of the correlation coefficient between the useful signal and the noise. The algorithms and technologies proposed in the paper allow solving both of these problems. The use of the proposed technologies in monitoring and control systems will make it possible to identify damaged sections of tunnels at an early stage, which allows determining the probability of transport accidents.

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References

[1] Aliev T. A., Noise control of the Beginning and Development Dynamics of Accidents, Springer, 2019, 201 p. DOI:10.1007/978-3-030-12512-7

[2] Shvidkyi V.Ya., Gres A.A. Checkup of deformations when tunneling under the runways-in-use of Sheremetyevo airport. Transport construction, 2019, no. 3, pp. 23-25 (in Russian).

[3] Shevchenko A.A., Kobetskiy A.D., Boev A.O. Experience in application of automated systems for monitoring of metro tunnels. Transport construction, 2019, no. 2, pp. 26-28 (in Russian).

[4] Weihong (Grace) Guo, Jionghua (Judy) Jin, S. Jack Hu. Profile Monitoring and Fault Diagnosis Via Sensor Fusionfor Ultrasonic Welding // Journal of Manufacturing Science and Engineering. 2019. Vol. 141, Issue 8, pp. 081001-1- 81001-13. https://doi: 10.1115/1.4043731

[5] Aliev T.A., Musaeva N.F., Suleymanova M.T., Gazizade B.I., Journal of Automation and Information Scien¬ces. 2015, vol. 47(8), no 4, pp.24-40. //DOI: 10.1615/JAutomatInfScien.v47.i8.30

[6] Aliev T.A., Musaeva N.F., Gazizade B.I., Journal of Automation and Information Sciences, 2018, vol. 50, no 6, pp.1-13. DOI: 10.1615/JAutomatInfScien.v50.i6.10

[7] Aliev, T.A. & Musaeva, N.F. & Suleymanova, M.T., Automatic Control and Computer Science. 2018, vol. 52, issue 3, pp. 231–242. DOI: 10.3103/S0146411618030021

[8] Aliev T.A., Musaeva N.F., Journal of Automation and Information Sciences. 2019, vol.51, no.9, pp. 12-23. doi: 10.1615/JAutomatInfScien.v51.i9.20

[9] Aliyev T. A., Musaeva N.F., Rzayeva N.E., Mammadova A.I., Measurement Techniques, Springer, 2020, no 6, pp. 421-430. DOI: 10.32446/0368-1025it.2020-6-9-16

[10] Aliev, T.A., Musaeva, N.F., Rzayeva, N.E., Mamedova, A.I., Journal of Automation and Information Sciences, 2020, vol. 52, no 5, pp. 1-12. DOI: 10.1615/JAutomatInfScien.v52.i5.10