ALGORITHMS FOR CONTROLLING THE ONSET OF ANTHROPOGENIC PROCESSES IN URBAN DEVELOPMENT AREAS IN SEISMICALLY ACTIVE REGIONS

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Abstract

It is noted that during changes in the geodetic state of urban development area, as well as the technical condition of the objects located there, the noisy signals coming from the corresponding sensors contain noise correlated with the useful signal. It is shown that the characteristics of the relationship between the useful signal and the noise are informative attributes of the beginning of anomalous natural phenomena, as well as changes in the stress-strain state of objects of the urban development complex. We have developed algorithms for calculating the estimates of the relay cross-correlation functions, normalized cross-correlation functions, as well as the correlation coefficient between the useful signal and the noise. It is noted that the use of the algorithms for calculating these characteristics in control systems allows detecting nascent anomalous processes, as well as defects of building structures at the initial latent stage and to prevent the possibility of accident situations.

Keywords: control, seismically active regions, noise, noisy signal, cross-correlation function, correlation coefficient

I. Introduction

It is known that the main objective of urban development is the design and development of cities, districts, complexes, residential and industrial zones, etc. Therefore, architectural and urban development objects are the territories where cities, villages, administrative districts, etc. are located. And buildings, structures, residential and industrial complexes, etc. are considered to be architectural and urban development objects.

At the same time, urban development areas are subjected to various kinds of natural and man-made impacts. For instance, man-made impacts are a result of the activities of industrial and military facilities, the movement of rail, road, sea, river transport, communications network, etc. Depending on the duration, cyclicity and degree of anthropogenic impacts are determined by the impact on civil and military complexes, residential buildings, national economy facilities, etc. Other dangerous effects on urban development areas are such natural processes as earthquakes, landslides, hurricanes, floods, etc. And one of the most dangerous natural phenomena are landslides, which lead to displacement of rocks as a result of seismic shocks, overwetting, washout of the slope and other processes. Such phenomena can occur on rocky terrain as well as on sand, clay, etc. Powerful landslides can cause an earthquake and vice versa, landslides can occur as a result of an earthquake.

In order to avoid the negative impact of natural and anthropogenic impacts on the state of objects, urban development monitoring is carried out. For this purpose, geodetic monitoring is first carried out, i.e., soil processes are studied, subsidence, displacement and subsidence of massifs are evaluated, groundwater is analyzed, possible seismically hazardous and landslide zones and areas are identified. At the same time at the stage of construction as well as during operation such defects of building structures and constructions as misalignments, cracks, shifts, displacements are identified and their stress-strained state is assessed. Thus, the current state and dynamics of changes in the technical condition of buildings and structures are assessed, possible accidents are predicted and appropriate recommendations are given.

In order to carry out such monitoring, appropriate sensors, such as displacement sensors, pressure sensors, reinforcement and anchor loads, crack aperture sensors, inclinometers, accelerometers, etc., are installed in the information locations of the analyzed area and building structures. The data on the geodetic state of the urban development complex as well as of the building structures and constructions are transmitted in the form of signals to the central monitoring station. The obtained digital information is recorded, processed, analyzed and conclusions are made about the geodetic condition of the urban development area and the stress-strain state of the building structures, the presence of defects and the degree of damage. In addition, conclusions are made about the causes that led to this or that defect.

However, existing systems of urban monitoring do not provide control of the latent period of change of the geodetic state of the territory under study, as well as the technical condition of the objects located there [1–2]. This is especially important for territories affected by seismic vibrations, landslides, dangerous vibrations and other natural processes, because after each weak but frequent earthquake or a small but repeated landslide, invisible and undetectable microscopic cracks, deformations, bends, etc., appear which subsequently can lead to serious damage that requires large costs [1–2].

In [1, 3-4] it is shown that changes in the geodetic state, as well as formation of even the smallest damages of objects of the urban planning complex is accompanied by the appearance of additive noise, which are correlated with the useful signals of noisy signals coming from the above sensors. The conducted studies have shown that the use of the technology for processing and analyzing noise and characteristics of the interrelation of noisy signals in the systems of noise monitoring of the urban development complex allows identifying the early latent period of defect and damage initiation, determining the dynamics of its development, and reducing the risks of accidents of urban development objects in seismically active and landslide-prone regions.

II. Problem statement

It is known that in practice, real signals are the sum of useful signals $X(t)$ and noise $E(t)$, i.e., $G(t) = X(t) + E(t)$. Because of the contamination of the useful signals $X(t)$ with the noise $E(t)$ there are tangible errors in determining the estimates of their correlation functions $R_{XX}(\mu)$. In this case, the total noise $E(t)$ is the sum of noise $E_1(t)$ from the influence of external factors and the noise $E_2(t)$, correlated with the useful signal, which arises when the geodetic state of the investigated area changes and a defect is generated during the operation of objects, i.e., $E(t) = E_1(t) + E_2(t)$.

Suppose that $G(t)$ is a sampled stationary random signal with normal distribution, consisting of the useful signal $X(t)$ and the noise $E(t)$ with mathematical expectation m_E=0. In this case the formula for calculating the estimate of the correlation function $R_{GG}(\mu)$ can be represented as [1, 3-4]:

$$R_{GG}(\mu) = \frac{1}{N}\sum_{i=1}^{N} G(i\Delta t)G\big((i+\mu)\Delta t\big) = R_{XX}(\mu) + R_{XE}(\mu) + R_{EX}(\mu) + R_{EE}(\mu)\,, \quad (1)$$

where $R_{XX}(\mu) = \frac{1}{N}\sum_{i=1}^{N} X(i\Delta t)X\big((i+\mu)\Delta t\big)$ is the autocorrelation function of the useful signal

$X(t)$; $R_{XE}(\mu) = \frac{1}{N}\sum_{i=1}^{N} X(i\Delta t)E\big((i+\mu)\Delta t\big)$, $R_{EX}(\mu) = \frac{1}{N}\sum_{i=1}^{N} E(i\Delta t)X\big((i+\mu)\Delta t\big)$ are the cross-correlation functions between $X(t)$ and $E(t)$; $R_{EE}(\mu) = D_E = \frac{1}{N}\sum_{i=1}^{N} E(i\Delta t)E\big((i+\mu)\Delta t\big)$ is the variance of the noise $E(t)$.

Given that $R_{EE}(\mu)$ =0 at μ≠0, the total error will be

$$\lambda_{GG}(\mu) = \begin{cases} 2R_{XE}(0) + R_{EE}(0) & when \quad \mu = 0 \\ R_{XE}(\mu) + R_{EX}(\mu) & when \quad \mu \neq 0 \end{cases}. \quad (2)$$

Because of this, the inequality $R_{XX}(\mu) \neq R_{GG}(\mu)$ takes place. It is clear from this that the basic information needed for monitoring is contained in the estimates of the noise characteristics $R_{XE}(\mu)$, $R_{EX}(\mu)$, $R_{EE}(0)$. Since the noise $E(t)$ cannot be isolated from the noisy signal $G(t)$, it is impossible to draw adequate conclusions about the geodetic state of construction objects on the estimate $R_{GG}(\mu)$ in urban development areas it is not possible to make adequate conclusions about the geodetic state and the stress-strain state of construction objects. In this regard, there is an obvious need to create algorithms and technologies to find the estimates of the noise variance D_E the and cross-correlation functions $R_{XE}(\mu)$, $R_{EX}(\mu)$ between the useful signal and the noise.

III. Algorithms for calculating the characteristics of the relationship between the useful signal and the noise

As shown above, in the normal geodetic state of the urban development area and objects located there, noise $E(t) = E_1(t)$ arises from random external factors that have no correlation with the useful signal $X(t)$. However, at the beginning of the latent period of change in the geodetic state of the area and the technical condition of objects, the noise $E_2(t)$ emerges which is correlated with the useful signal. Therefore, from this point on, the correlation between the useful signal $X(t)$ and the total noise $E(t) = E_1(t) + E_2(t)$ is non-zero. In this case, the initiation and development of malfunctions is essentially reflected in the estimates of the cross-correlation functions and the correlation coefficient between $X(t)$ and $E(t)$ [1, 3-4]. Therefore, for controlling the latent period of the origin and the dynamics of the development of natural anomalies and technical malfunctions, it is quite often more appropriate to use in monitoring systems the estimates $R_{XE}(\mu)$, $R_{EX}(\mu)$, as well as the correlation coefficient r_{XE} between the useful signal and the noise as a carrier of diagnostic information. In the following paragraphs, we show the possibility of using estimates of the relay cross-correlation functions, normalized cross-correlation functions, as well as the correlation coefficient between the useful signal and the noise as informative attributes.

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

$$R^{r}_{XE}(\mu) = \frac{1}{N}\sum_{i=1}^{N} sgnX(i\Delta t)\, E\big((i+\mu)\Delta t\big), \quad (3)$$

where $sgnX(i\Delta t) = \begin{cases} +1 \;\; when \; X(i\Delta t) > 0 \\ 0 \quad when \;\; X(i\Delta t) = 0 \\ -1 \;\; when \;\; X(i\Delta t) < 0 \end{cases}.$

Obviously, to use this formula it is necessary to determine the samples of the noise $E(i\Delta t)$ and the useful signal $X(i\Delta t)$ that cannot be measured directly or extracted from the noisy signal $G(t)$ [1]. Let us consider one of possible variants of the approximate estimation of the relay cross-correlation function $R^{r*}_{XE}(\mu)$ between the useful signal $X(t)$ and noise $E(t)$ as a result of calculation of the relay correlation function $R^{r}_{GG}(\mu)$ of the noisy signal $G(t)$ [1]:

$$R^{r}_{GG}(\mu) = \frac{1}{N}\sum_{i=1}^{N} sgnG(i\Delta t)\, G\big((i+\mu)\Delta t\big), \quad (4)$$

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

It is shown in [1, 3-4] that the estimate of the relay cross-correlation function $R_{XE}^{r*}(\mu\Delta t)$ at different time shifts μ between $X(i\Delta t)$ and $E(i\Delta t)$ can be determined from the formula:

$$R_{XE}^{r*}(\mu) = \frac{1}{N}\sum_{i=1}^{N} sgnG(i\Delta t)\Big(G\big((i+\mu)\Delta t\big) - 2G\big((i+\mu+1)\Delta t\big) + G\big((i+\mu+2)\Delta t\big)\Big). \quad (5)$$

It is clear that with the normal geodetic state of the area and the technical condition of the objects due to the lack of correlation between $X(t)$ and $E(t)$ the estimate of the relay cross-correlation function $R_{XE}(\mu)$ between the useful signal and the noise will be close to zero. When various anomalies and defects occur, the value of the estimate of the relay cross-correlation function will vary depending on the degree of correlation between $X(t)$ and $E(t)$. And the distinctive feature of this algorithm is that if there is a correlation between $X(t)$ and $E(t)$, differences in the values of the estimates $R_{XE}^{r*}(\mu = 0)$, $R_{XE}^{r*}(\mu = \Delta t)$, $R_{XE}^{r*}(\mu = 2\Delta t)$, ... at different time instants unambiguously reflect the dynamics of malfunction development, which makes it possible to obtain reliable information about the risk of accidents.

In addition, to assess the latent period of the initiation of anomalous seismic processes and landslides, as well as the technical condition of objects in the urban development area, it is advisable to use estimates of the normalized cross-correlation function, as well as the correlation coefficient between the useful signal $X(t)$ and the noise $E(t)$.

In this case, using formula (5), the calculation of the normalized cross-correlation function can be reduced to the form [1]:

$$\rho_{XE}^{r*}(\mu) = \frac{R_{XE}^{r*}(\mu)}{\sqrt{\frac{2}{\pi}}\cdot\sigma_E^*}, \quad (6)$$

where the mean square deviation σ_E^* of the noise can be calculated from the expressions [1, 3-4]:

$$\sigma_E^* = \begin{cases} \sqrt{R_{GG}(0) - 2R_{GG}(\Delta t) + R_{GG}(2\Delta t)} & \text{for the general case} \\ \sqrt{R_{GG}(0) - R_{GG}(\Delta t)} & \text{for the special case} \end{cases}. \quad (7)$$

It is known that the value of the normalized cross-correlation function at μ=0 is the correlation coefficient. Therefore, the value of the correlation coefficient between the useful signal $X(t)$ and the noise $E(t)$ can be calculated from the expression:

$$r_{XE}^* = \rho_{XE}^{r*}(0) = \frac{R_{XE}^{r*}(0)}{\sqrt{\frac{2}{\pi}}\cdot\sigma_E^*}. \quad (8)$$

IV. Technologies for determining the latent period of changes in the geodetic state and technical condition of objects of the urban development area

To assess the geodetic state and technical condition of objects in the urban development area, the estimates of the relay and normalized cross-correlation functions, as well as the correlation coefficients between the useful signal $X(t)$ and the noise $E(t)$ for each of the monitored parameters should be calculated at different time instants t_1, t_2, t_3, ... t_k. The obtained values of the estimates are entered into the database of informative attributes, which can be represented in the form of matrices:

$$S1 = \begin{bmatrix} R^{r*}_{X_1E_1}(\mu)t1 & R^{r*}_{X_1E_1}(\mu)t2 & \dots & R^{r*}_{X_1E_1}(\mu)tk \\ R^{r*}_{X_2E_2}(\mu)t1 & R^{r*}_{X_2E_2}(\mu)t2 & \dots & R^{r*}_{X_2E_2}(\mu)tk \\ \dots & \dots & \dots & \dots \\ R^{r*}_{X_nE_n}(\mu)t1 & R^{r*}_{X_nE_n}(\mu)t2 & \dots & R^{r*}_{X_nE_n}(\mu)tk \end{bmatrix}, \tag{9}$$

$$S2 = \begin{bmatrix} \rho^{r*}_{X_1E_1}(\mu)t1 & \rho^{r*}_{X_1E_1}(\mu)t2 & \dots & \rho^{r*}_{X_1E_1}(\mu)tk \\ \rho^{r*}_{X_2E_2}(\mu)t1 & \rho^{r*}_{X_2E_2}(\mu)t2 & \dots & \rho^{r*}_{X_2E_2}(\mu)tk \\ \dots & \dots & \dots & \dots \\ \rho^{r*}_{X_nE_n}(\mu)t1 & \rho^{r*}_{X_nE_n}(\mu)t2 & \dots & \rho^{r*}_{X_nE_n}(\mu)tk \end{bmatrix}, \tag{10}$$

$$S3 = \begin{bmatrix} r^{r*}_{X_1E_1t1} & r^{r*}_{X_1E_1t2} & \dots & r^{r*}_{X_1E_1tk} \\ r^{r*}_{X_2E_2t1} & r^{r*}_{X_2E_2t2} & \dots & r^{r*}_{X_2E_2tk} \\ \dots & \dots & \dots & \dots \\ r^{r*}_{X_nE_nt1} & r^{r*}_{X_nE_nt2} & \dots & r^{r*}_{X_nE_ntk} \end{bmatrix}. \tag{11}$$

After appropriate training, the geodetic state and technical condition of the objects in the urban development area is identified. For instance, if the geodetic indicators of the noise characteristics have changed in some limited area, and the estimates of the noise characteristics of the technical condition have changed only for nearby objects, it can be regarded as the beginning of a hidden period of landslide occurrence. If the geodetic indices of noise characteristics have changed for quite an extensive territory, and the estimates of noise characteristics of technical conditions have changed for all objects simultaneously on this territory, this indicates the beginning of a latent period of preparation for an earthquake. It is possible to judge about the dynamics of geodetic processes by the intensity of changes in the noise characteristics. And the noise-characteristics will take different values depending on the type of terrain, e.g., rock, sand, clay, etc. At the same time it is necessary to carry out monitoring of technical condition of buildings, constructions, structures and other objects in the urban development already at the initial stage of occurrence of anomalous natural phenomena.

Depending on the values of the relay and normalized cross-correlation functions, as well as the correlation coefficients between the useful signal $X(t)$ and noise $E(t)$ at different time instants, conclusions are made about the geodetic state of the urban development area, for instance: 1 – ground waters are leaking; 2 – displacements and shifts in the soil are observed; 3 – subsidence of soil masses are observed; 4 – a source of vibrations is detected; 5 – a source of seismic vibrations is detected; 6 – a landslide zone is detected, etc. For each of these states the intensity of the process is defined: a – not developing; b – developing very slowly; c – developing slowly; d – developing with average intensity; e – developing intensively; f – developing very intensively; g – developing rapidly, etc. Then the matrices of the geodetic state of the urban development area take the form:

$$GS1 = \begin{bmatrix} R^{r*}_{X_1E_1}(\mu)t1 & R^{r*}_{X_1E_1}(\mu)t2 & \dots & R^{r*}_{X_1E_1}(\mu)tk \\ R^{r*}_{X_2E_2}(\mu)t1 & R^{r*}_{X_2E_2}(\mu)t2 & \dots & R^{r*}_{X_2E_2}(\mu)tk \\ \dots & \dots & \dots & \dots \\ R^{r*}_{X_nE_n}(\mu)t1 & R^{r*}_{X_nE_n}(\mu)t2 & \dots & R^{r*}_{X_nE_n}(\mu)tk \end{bmatrix} \begin{bmatrix} 1-a \\ 2-b \\ \dots \\ k-z \end{bmatrix}, \tag{12}$$

$$GS2 = \begin{bmatrix} \rho^{r*}_{X_1E_1}(\mu)t1 & \rho^{r*}_{X_1E_1}(\mu)t2 & \dots & \rho^{r*}_{X_1E_1}(\mu)tk \\ \rho^{r*}_{X_2E_2}(\mu)t1 & \rho^{r*}_{X_2E_2}(\mu)t2 & \dots & \rho^{r*}_{X_2E_2}(\mu)tk \\ \dots & \dots & \dots & \dots \\ \rho^{r*}_{X_nE_n}(\mu)t1 & \rho^{r*}_{X_nE_n}(\mu)t2 & \dots & \rho^{r*}_{X_nE_n}(\mu)tk \end{bmatrix} \begin{bmatrix} 1-a \\ 2-b \\ \dots \\ k-z \end{bmatrix}, \tag{13}$$

$$GS3 = \begin{bmatrix} r^{r*}_{X_1E_1t1} & r^{r*}_{X_1E_1t2} & \dots & r^{r*}_{X_1E_1tk} \\ r^{r*}_{X_2E_2t1} & r^{r*}_{X_2E_2t2} & \dots & r^{r*}_{X_2E_2tk} \\ \dots & \dots & \dots & \dots \\ r^{r*}_{X_nE_nt1} & r^{r*}_{X_nE_nt2} & \dots & r^{r*}_{X_nE_ntk} \end{bmatrix} \begin{bmatrix} 1-a \\ 2-b \\ \dots \\ k-z \end{bmatrix}. \tag{14}$$

Similar conclusions are made about the presence or absence of latent damage and the dynamics of their development for structures and objects of the urban development area, for instance: 0 - technical condition is serviceable; 1 - operational without damage; 2 - limited operational with minor damage; 3 - limited operational with minor damage developing intensively; 4 - non- operational; 5 - pre-emergency; 6 - emergency, etc., depending on the values of the noise characteristic estimates at a given time instant. Then the matrices of the technical condition of structures and objects take the form:

$$TS1 = \begin{bmatrix} R^{r*}_{X_1E_1}(\mu)t1 & R^{r*}_{X_1E_1}(\mu)t2 & \dots & R^{r*}_{X_1E_1}(\mu)tk \\ R^{r*}_{X_2E_2}(\mu)t1 & R^{r*}_{X_2E_2}(\mu)t2 & \dots & R^{r*}_{X_2E_2}(\mu)tk \\ \dots & \dots & \dots & \dots \\ R^{r*}_{X_nE_n}(\mu)t1 & R^{r*}_{X_nE_n}(\mu)t2 & \dots & R^{r*}_{X_nE_n}(\mu)tk \end{bmatrix} \begin{bmatrix} 1 \\ 2 \\ \dots \\ k \end{bmatrix}, \quad (15)$$

$$TS2 = \begin{bmatrix} \rho^{r*}_{X_1E_1}(\mu)t1 & \rho^{r*}_{X_1E_1}(\mu)t2 & \dots & \rho^{r*}_{X_1E_1}(\mu)tk \\ \rho^{r*}_{X_2E_2}(\mu)t1 & \rho^{r*}_{X_2E_2}(\mu)t2 & \dots & \rho^{r*}_{X_2E_2}(\mu)tk \\ \dots & \dots & \dots & \dots \\ \rho^{r*}_{X_nE_n}(\mu)t1 & \rho^{r*}_{X_nE_n}(\mu)t2 & \dots & \rho^{r*}_{X_nE_n}(\mu)tk \end{bmatrix} \begin{bmatrix} 1 \\ 2 \\ \dots \\ k \end{bmatrix}, \quad (16)$$

$$TS3 = \begin{bmatrix} r^{r*}_{X_1E_1t1} & r^{r*}_{X_1E_1t2} & \dots & r^{r*}_{X_1E_1tk} \\ r^{r*}_{X_2E_2t1} & r^{r*}_{X_2E_2t2} & \dots & r^{r*}_{X_2E_2tk} \\ \dots & \dots & \dots & \dots \\ r^{r*}_{X_nE_nt1} & r^{r*}_{X_nE_nt2} & \dots & r^{r*}_{X_nE_ntk} \end{bmatrix} \begin{bmatrix} 1 \\ 2 \\ \dots \\ k \end{bmatrix}. \quad (17)$$

IV. Discussion

The conducted analysis shows that using the matrices of noise characteristics (9)-(11), (12)-(14), (15)-(17), it is possible to identify an early stage of occurrence of changes in the geodetic state of an urban development area, as well as the technical condition of the objects located there. At the same time the objective of geodetic monitoring is to identify the latent period of the emergence of hazardous natural phenomena. The main objective of technical monitoring is to detect latent defects in the roof, facade, microcracks in the walls, the possibility of deformations, etc. This can be done by calculating the characteristics of the relationship between the useful signal and the noise. The combination of geodetic and technical control makes it possible to objectively assess the condition of the urban development complex; to prevent in a timely manner the risk of the risk of destruction of buildings, structures and constructions in seismically active regions; to identify the causes and sources of risks both for individual buildings and for the entire complex; to reduce the cost of maintenance and major repairs; to alert personnel to the possibility of destruction of objects with catastrophic consequences.

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