Methods, Technologies and Means of Control of Seismic Stability of Complexes of Construction Structures in Operation

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***Abstract*— Existing methods and corresponding equipment for determining seismic stability of high-rise buildings and construction structures have been analyzed. Robust noise technology has been developed, which allows performing concurrent monitoring of change in seismic stability of all control objects after each weak earthquake. A distributed robust system for monitoring of seismic stability of socially significant objects of cities located in seismically active regions.**

***Keywords*— control; noise monitoring; seismic stability; consruction structures**

I. Introduction

Simplest forms of seismic survey are known to have been carried out in ancient times. Simultaneously with earthquakes study, attempts were made to protect buildings and structures from them [1]. The first attempt to develop methods for calculation and design of seismically stable buildings and structures was made in 1900 by a Japanese scientist Omori, who suggested determining seismic forces from the following formula

$$S = k_C Q \ ,$$

where $k_C = w_0 / g$, w_0 is maximum earthquake acceleration of the foundation.

However, soon it became clear that behavious of a structure during an earthquake also depends on its dynamic properties. In 1920, another Japanese scientist, Mononobe, obtained a formula for determination of dynamic force

$$S = k_C \cdot \beta \cdot C \, .$$

This expression differs from Omori's formula by having an additional dynamic factor β, which for single degree of freedom systems takes the form

$$\beta = 1 \big/ \left(1 - T^2 / T_0^2\right),$$

where T is the period of proper oscillations of a structure; T_0 is the period of oscillations of the foundation during an earthquake.

The general basics of dynamic method for calculation of seismic stability of buildings and structures were laid by K.S. Zavriyev in 1927, who suggested considering seismic oscillations of soil as harmonic sustained oscillations that begin by cosine law with dynamic factor

$$\beta = \left(\cos \omega_0 t - \cos \omega t\right) \big/ \left(1 - \omega_0^2 / \omega^2\right).$$

Mononobe's and K.S. Zavriyev's works had important parts to play in establishment of dynamic approach to structural analysis.

In 1934, the American scientist Bio developed a method of assessment of seismic forces using instrument records of soil oscillations during an earthquake. Also important is the research made by Hausner, Martel and Alford, which demonstrated that system attenuation, previously ignored by Bio, influence greatly the magnitude of seismic forces. California Seismic Building Codes operating in the USA are based on the results of that research.

In Russia, development of Bio's method was reflected in the works by A.G. Nazarov, who used multi-pendulum seismometers specially developed by him, records of which allowed evaluate maximum values of seismic forces. S.V. Medvedev used seismograms processed by semigraphical methods known as 'method of phase planes and vector diagrams'.

I.L. Korchinsky's works are also a big contribution in the development of dynamic theory and have been practically applied in design of seismically stable buildings and structures. He suggested recording the law of soil motion as a packet of damped sinusoids based on the analysis of seismograms of weak earthquakes.

I.L. Korchinsky offered spectral curve of dynamic factor that is also a seismic standard now and developed formulas for practical determination of seismic loads affecting buildings and structures [1].

Simultaneously with spectral method, methods of probabilistic (stochastic) analysis of seismic forces were developed. Foreign scientist Bicroft, Goodman, Ermingen, Newmark, Rosenblueth, Okamoto and Soviet scientists Barstein, Bolotin, Goldenblat and others worked in this field.

Modern stage of development of seismic stability theory is characterized with the general trend of specification of design problem. It implies fuller and more detailed description of seismic effects and requires application of stricter calculation methods. Problem of interaction of structure and soil must be studied, with specifying the influence of nature of soils and conditions of embedment of structures in them on dynamic characteristics of structures. Further improvement of design schemes of buildings and structures comprehensively demonstrating their physical properties, spatial behavior, twisting, wave processes in soils and structures is an important trend [1].

Seismic risk theory developed by A.P. Sinitsin in Russia is very promising. This theory is based on the concept that every structure is exposed to risk in the process of operation and if this risk is excessive, the structure can be ruined. The notion of 'risk' allows one to estimate possible deviation from the target, for which the decision has been made. Application of the theory can lead to economy due to well-grounded reduction of expenses on anti-seismic measures.

It is highly relevant to develop methods for designing of buildings and structures with allowance for elastoplastic properties of the material, which is important for estimation of actual carrying capacity of structures during seismic effects. There are different methods that take into account the above-mentioned specifics of structure deformation, the strictest of which is the method developed by Sh.G. Napetvaridze, R.V. Dvalishvili and D.K. Ukleba, considering elastoplastic spatial seismic oscillations of 'soil-structure' system.

Estimated seismicity of a building is established in compliance with building standards in seismically active regions, depending on estimated seismicity of construction site. Estimated seismicity of construction site is determined in accordance with specified standards depending on the seismicity of construction region and category of soil in the foundation of the building or structure, or based on the results of seismic microzoning.

Selection of design schemes of buildings and structures in their design for seismic effects is one of the fundamental ones in seismic design. Reliability and strength of the structure depend on the adequate selection (development) of design scheme. Design scheme should show in sufficient degree physical properties of the real object, such as its topology, material, deformation conditions, etc. Design scheme is also a dynamic model, which is why dynamic characteristics of the design object obtained by means of it should correspond to that object and can be used to control the adequacy of selection of design scheme. Dynamic characteristics are specified experimentally if necessary.

Building of a strict design scheme of a building is an extremely complicated task, since one has to consider the following factors: inelastic behaviour of the structure, viscous damping, advance of inelastic waves in soil and building, elastoplastic properties of soils and their damping, possibility of rebuilding the structure of the design scheme in the process of seismic effect, etc. Each of those factors alone is a complicated scientific problem, which is far from completion. Simultaneous allowance for all of them is therefore hardly possible in the foreseeable future. In real design, a designer has to introduce simplifying hypotheses that put the real structure into knowingly less favourable conditions compared with actual ones. One of such crucial simplifications is introduction of the hypothesis of elastic behaviour of the structure, which leads to designing a building or structure for deliberately bigger seismic loads, excessive consumption of materials and subsequently to increase of construction costs. Rise in construction costs is thereby a price paid for insufficient knowledge of seismic stability problem [1].

The given analysis shoed that existing methods and corresponding equipment for determining seismic stability of high-rise buildings and construction structures are reasonable to apply in design or at the stage of beginning of construction of corresponding objects. Besides, the above-mentioned technologies are convenient and effective for determining of oscillations of individual construction objects or regions, towns, settlements, residential communities located in seismically passive areas. However, for towns located in seismically active regions, it appears practically impossible and unreasonable to control seismic stability of thousands, several thousands and more socially significant construction structures. Obtaining accurate information on the condition of the named construction complexes with application of known methods and technical means of control takes quite a long time, probably years. To this end, robust noise monitoring technology and distributed robust system for monitoring of seismic stability of socially significant objects in towns located in seismically active regions is considered below.

II. Problem Statement

It is known that currently used seismic systems do not allow forecasting the time of beginning of earthquakes [1]. There is also a lack of inexpensive and sufficiently reliable systems for control of seismic stability of construction objects. Combination of these two factors during earthquakes leads to numerous destructions with disastrous consequences [2-8].

In real life, after a certain period of time T_0 of normal operation of some construction objects in seismic regions, period of time T_1 of their latent transition into the emergency state begins due to different reasons. It is often a result of weak earthquakes, which leads to changes in their seismic stability. Subsequent weak earthquakes, hurricane winds with rain showers cause them to go into time interval of expressed emergency state T_2. [2-7].

Despite the difference in duration of T_0, T_1, T_2, monitoring problem in the cases in question comes to providing reliable indication of the beginning of time T_1 of the period of latent change in the seismic stability of the object or the beginning of the period of origin of anomalous seismic processes [2-7].

III. Intelligent Distributed System of Noise Monitoring of Seismic Stability of Construction Objects

As Fig. 1 shows, the system under consideration includes the monitoring center (MC), seismic-acoustic station for robust noise monitoring of anomalous seismic processes (RNM ASP) and local devices for noise monitoring of seismic stability (LDNS) $L_{11}, L_{12}, ..., L_{1n}, ..., L_{nm}$ installed at all controlled construction objects. In Fig. 1, the totality of LDNS with transmitting antennas is the distributed system for noise monitoring of seismic stability of construction objects [2-7].

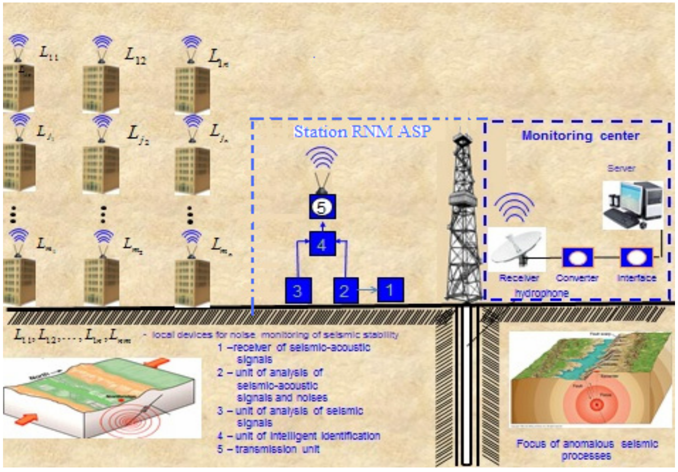

Figure 1. Intelligent robust distributed system of noise monitoring of seismic stability of construction objects.

Creation of the system implies that every socially significant and strategic object is equipped with LDNS built on the basis of controllers and corresponding sensors installed in most vulnerable structures of the object.

LDNS operate independently. In the process of operation of the monitoring system, characteristics of signals $g_1(i\Delta t),\ g_2(i\Delta t),\ ...,\ g_m(i\Delta t)$ received from the corresponding sensors are used to form the combination of estimates of noise correlation $R_{X\varepsilon\varepsilon}(0)$, cross-correlation function $R_{X\varepsilon}(0)$ between the useful signal $X(i\Delta t)$ and the noise $\varepsilon(i\Delta t)$, relay cross-correlation function $R^*_{X\varepsilon}(0)$ between the noise and the useful signal, noise variance D_ε [2-8], which will be equal to zero in the original normal seismic stability of the object. When the original state of seismic stability changes in the beginning of period T_1, they will be different from zero. Similarly, they will be different from zero at the moment of ASP origin in the beginning of period T_1 as well. Thus, in the period of time T_0, sets of informative attributes $W_{X\varepsilon}$ used as convenient and reliable indicators are formed from the above-mentioned estimates in the LDNS of each object:

$$W_{X\varepsilon} = \left\{ \begin{matrix} R_{X_1\varepsilon_1\varepsilon_1}(0) & R_{X_2\varepsilon_2\varepsilon_2}(0) & \ldots & R_{X_j\varepsilon_j\varepsilon_j}(0) & \ldots & R_{X_m\varepsilon_{m3}\varepsilon_m}(0) \\ R_{X_1\varepsilon_1}(0) & R_{X_2\varepsilon_2}(0) & \ldots & R_{X_j\varepsilon_j}(0) & \ldots & R_{X_m\varepsilon_m}(0) \\ R^*_{X_1\varepsilon_1}(0) & R^*_{X_2\varepsilon_2}(0) & \ldots & R^*_{X_j\varepsilon_j}(0) & \ldots & R^*_{X_m\varepsilon_m}(0) \\ D_{\varepsilon_1} & D_{\varepsilon_2} & \ldots & D_{\varepsilon_j} & \ldots & D_{\varepsilon_m} \end{matrix} \right\}. \tag{1}$$

If seismic stability of the object changes, certain elements of those sets will be different from zero. Such a moment will be registered and sent via radio channel of corresponding LDNS to the server of the monitoring center.

Besides, to increase accuracy of monitoring results, it is also reasonable to form sets of indicators from robust estimates of auto- and cross-correlation functions of signal $g_1(i\Delta t), g_2(i\Delta t), \ldots, g_m(i\Delta t)$ in the following form:

$$W_{g_ig_j} = \left\{ \begin{matrix} R^R_{g_1g_1}(\mu') & R^R_{g_1g_2}(\mu') & R^R_{g_1g_3}(\mu') & R^R_{g_1g_4}(\mu'),\ldots,R^R_{g_1g_j}(\mu'),\ldots R^R_{g_1g_m}(\mu') \\ R^R_{g_2g_2}(\mu') & R^R_{g_2g_1}(\mu') & R^R_{g_2g_3}(\mu') & R^R_{g_2g_4}(\mu'),\ldots,R^R_{g_2g_j}(\mu')\ldots R^R_{g_2g_m}(\mu') \\ R^R_{g_3g_3}(\mu') & R^R_{g_3g_1}(\mu') & R^R_{g_3g_2}(\mu') & R^R_{g_3g_4}(\mu'),\ldots,R^R_{g_3g_j}(\mu'),\ldots,R^R_{g_3g_m}(\mu') \\ \vdots & \vdots & \vdots & \vdots \\ R^R_{g_jg_j}(\mu') & R^R_{g_jg_1}(\mu') & R^R_{g_jg_2}(\mu') & R^R_{g_jg_3}(\mu'),\ldots,R^R_{g_jg_{j+1}}(\mu'),\ldots,R^R_{g_jg_m}(\mu') \\ \vdots & \vdots & \vdots & \vdots \\ R^R_{g_mg_m}(\mu') & R^R_{g_mg_1}(\mu') & R^R_{g_mg_2}(\mu') & R^R_{g_mg_3}(\mu'),\ldots,R^R_{g_mg_j}(\mu'),\ldots,R^R_{g_mg_{m-1}}(\mu') \end{matrix} \right\}. \tag{2}$$

where μ' is time shifts between $g(i\Delta t)$ and $g(i+\mu')\Delta t$, when estimates $R^R_{g_ig_j}(\mu')$ in the period of time T_0 will be equal to zero.

At that moment of violation of seismic stability, even one element of those sets being different from zero is perceived as the beginning of time T_1 in LDNS of each object. In that case, numbers of the set, column and line of the nonzero informative attribute can be used to identify the location and nature of deformation in the object. At the same time, LDNS also alarms the server of the monitoring center.

Furthermore, in each cycle, readings of signals $g_1(i\Delta t), g_2(i\Delta t), \ldots, g_m(i\Delta t)$ in each LDNS of each object are used to form files, which are transmitted to the modem of the server of the monitoring center via modems and wireless communication together with sets (1), (2). In the operation process, in addition to sets (1), (2), robust normalized correlation matrices [2-8] form during the period of time T_0 at the server for each object. It is also possible to form a set consisting of position-binary and spectral indicators on the server. The technologies of their formation are given in detail in [2-8]. Thus, pattern sets and correlation matrices form in the training process, which carry information on the state of original seismic stability of all controlled objects.

In the operation process, current readings of signals $g_1(i\Delta t), g_2(i\Delta t), \ldots, g_m(i\Delta t)$ in each cycle of monitoring mode are used to determine current estimates of elements of the mentioned sets and matrices and compare them with the estimates of corresponding pattern sets and matrices set in the training process. If their difference does not exceed the permissible minimum range, seismic stability and technical condition of the object are regarded as unchanged. Otherwise, the signal forms from the result obtained on the server, which shows the beginning of change in seismic stability of the object. In repetitive cycles, if current estimates differ from patterns again, the decision is made on the server to refer the object to the group that requires involving of mobile control and diagnostic systems to perform the final analysis and decision-making.

If deviation from the normal state of seismic stability is detected simultaneously at closely-spaced groups of objects, a landslide alarm is formed on the server.

The system also provides for safety threat control. For instance, in case of elevator failure, short circuit in power supply, etc. in monitoring object, a corresponding alarm is formed on the server with specification off the nature of failure and object number.

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