On the layered structures material properties definition

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Abstract. The article is devoted to the neural network construction that uses as input information the time domain response data of layered structure to diagnostic punch-load and represents the tool for the layers’ elastic properties reconstruction along the corresponding thickness coordinates.

Introduction
The number of practical problems in the field of construction, soil mechanics, structural strength is associated with the multilayered media properties determination. At the same time, the known methods for identifying of mechanical properties, such as shock indentation, ultrasound diagnostics, surface wave studies (MASW, SASW) give a satisfactory result only in well-studied ranges of changes in the media properties. It is also important to use the visual monitoring data for the structures, the defects presence assessment in corresponding areas, as well as the results of additional instrumental studies and the mathematical modeling methods. Thus, in order to expand the main selected method applicability range for the design properties diagnostics and to increase the reliability of the results given, the problem of using the available information entire volume and improving the existing knowledge base on the basis of newly received information is relevant.

In recent years, due to the computational abilities’ development and machine learning algorithms, there has been a new wave of interest in the use of neural network methods for non-destructive testing and the materials properties evaluation. This can be found, for example, in [1-3]. An overview of the use of machine learning in monitoring the condition of buildings and structures is given, for example, in [4-6]. One of the most important problems discussed in the monitoring buildings and structures methods study by studying changes in the subject’s dynamic characteristics is the uncertainty arising from the fact, that the registered signals contain both the response of the design and the external impact characteristics. Therefore, a significant part of the research is to protect the system from any false positives arising from changing in characteristics of external parameters and not to miss relevant information in signals caused by response in the design studied [7-8]. In addition, attempts are made to use neural networks to automate both the evaluation process and the decision on the state of the structure [9].

Problem statement
A multilayered elastic half-space characterized by layer thicknesses and material properties is considered: $E_i$ - is the modulus of elasticity, $\nu_i$ - is the Poisson coefficient, $\rho_i$ - is the density ($i = 1,2, ..., N$), constant within each layer.

The goal is to reconstruct the elastic modulus of material in response to the forced impact acting on
the surface of multilayered media on the basis of measured vertical components of displacements:

$$\mathbf{U}(t) = \{U_z(r_1, t),..., U_z(r_m, t)\}^t$$

(1)

$r_j$ - defines the distance from the impact point to the $j$-th observation point $(j = 1, 2, ..., m)$, $t$ - time.
The observation points approximate position (signal sensors) is shown on Figure 1:

![Figure 1. Position of sensors on the surface](image)

**Solution**

We use the results of measuring the dynamic characteristics of the structure surface response using a vibration measuring system. When using accelerometers, the transition to the values $\mathbf{U}(t)$ is carried out using the Fast Fourier Transform procedures, averaging, window and the data frequency filtering.

During the following processing procedures, the input information vector is selected for the further use in the neural network:

$$\mathbf{x} = \max_t \mathbf{U}(t)$$

(2)

and the normalization is carried out with the components mapping inside the segment $[0, 1]$.

The neural network outputs will be the layers elastic moduli normalized deviations from the maximum possible for a given design:

$$y_i = \frac{\max E_i - E_i}{\max E_i - \min E_i}$$

(3)

The basis is a multilayer neural network with three hidden layers and sigmoid activation function on each layer.

**Practical case**

The neural network learning procedure was carried out using the error back propagation method and with the training set obtained experimentally and on the basis of a mathematical model coordinated with the experiment. As an object, the pavement design, containing a coating layer and a base layer on the ground was considered. The coating elasticity dynamic modulus varied in the range from 1900 to 5500 MPa, for the foundation from 400 to 1000 MPa and for the soil from 30 to 150 MPa. The number of sensors on the coating surface was taken by 5. The optimal number of neurons in the hidden layers is $\{20, 30, 20\}$.

By testing the network on the test set, it was established that the greatest error in determining the elastic modulus is achieved for the coating. For example, in Figure 2 the reconstruction error of the elastic modulus for the top layer does not exceed 13% for fixed $E_2 = 650$ MPa, $E_3 = 46$ MPa.

Note that the neural network analysis use in this formulation is possible for multilayer structures of the selected type. For example, a decrease in the elastic modulus with a distance from the structure surface is the characteristics of road structures. For soils the opposite pattern is more common. The presence of defects, as well as the general condition of the structure during exploitation, can introduce a significant error when using experimental data as input to the neural network. Hence, the preliminary classification of the structure type is required, for example, by analyzing the frequency response.
Discussion

The existing normative documents in the group with scientific research on monitoring and assessment the state of building constructions and other structures involve the use of a number of information sources, in particular the collection of data from vibration sensors installed at critical points of bearing parts of buildings and structures; from sensors monitoring the opening of cracks; geotechnical monitoring sensors; from additional tools for monitoring deformation and displacement of bearing structures and soil; visual observations. The obtained rather heterogeneous information should become a source of integral characteristics and change indicators in the state of load-bearing structures of construction projects. However, it should be noted that there are practically ineffective methods describing the measured parameters and the methods of their processing for assessing the mechanical state of buildings and structures. As a result, it is possible to formulate the following problems necessary for the building monitoring system's effective development and implementation:

- The optimal criteria development for the dynamic deformation and strength characteristics measurement results assessment as applied to the problem of analyzing the state of the object and estimation of its material properties;
- the development of methods for evaluation indicators, including in real-time;
- development of software and hardware systems in the framework of the practical implementation of the developed criteria and methods for assessing the state of construction of the object in accordance with GOST R 22.1.12-2005;
- comprehensive risk assessment and determination of the bearing capacity of the construction object, including in cases of natural or techno-genetic emergencies.

In solving these problems, an important element is the construction of structures for integrated accounting of information, its aggregation and application to the creation of information and diagnostic systems. One of these tools can be neural networks.

The proposed approach is based on the synthesis of an intelligent monitoring system with a three-level hierarchical structure: the lower level is based on the subsystem of information collecting, including the use of sensor networks that control the main parameters of engineering objects; the middle level is the system of aggregation of information and its clustering using neural networks with large amounts of input information; at the top level there are the algorithms of intellectual support of the adoption of diagnostic solutions and corresponding user interfaces.

At the lower level, intelligent agents are relatively self-standing elements that have rules for processing of input information. For elements in the visual build information, such as opening of cracks and condition of the structural elements, a regulated-wide scales of measurement parameters are used. Thus, the structure of information flows for a neural network has heterogeneity both in origin, composition, and time characteristics (static, dynamic).
The structure of the middle-level neural network is focused on its learning without teacher in the presence of a large number of elements of the training sample. The task of the network is to identify internal patterns of information distribution and selection of the most significant features determined by the network outputs for the further use in the top-level diagnostics subsystem.

The problem solution for the structure state final diagnosis is carried out by a multilayer neural network, interfaced by outputs and inputs with a medium-level neural network. For corresponding learning, the expert standards with the application of existing regulatory assessments, expert opinions and the involvement of mathematical models for the buildings behavior in various states are used, as well as the methods for identifying defects in structures.

Summary
The paper demonstrates the possibility of using neural networks to determine the layered structures’ material properties, in particular road structures. An error estimate in the reconstruction of properties is given. The difficulties in the analysis application for the case of the structure arbitrary case, as well as in the overall assessment of the state of structures, are established. For a comprehensive assessment of the mechanical state the approach based on multi-level neural networks matched by inputs and outputs is proposed.

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