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(imię i nazwisko)

Abstract

The doctoral dissertation titled "Direct and inverse artificial neural networks as auxiliary tools in numerical solutions of selected problems of soil-structure interaction in geotechnical engineering" focuses on issues related to the use of artificial neural networks to solve the inverse problem in geotechnics and soil mechanics. The "direct" and inverse problems are also analyzed in the context of simplification of numerical models of geotechnical issues.

In geotechnical design, the basic mathematical model is formulated in a form of a boundary value problem, which simultaneously covers the building structure and the subsoil in mutual interaction. Its solution is usually obtained in an approximate form by applying the Finite Element Method to the formulated boundary value problem. While the constitutive behavior of building materials used in the field of building structure is quite well known, in geotechnical issues the soil medium has mechanical properties that are often difficult to recognize. The source of difficulties here is the need to carry out laboratory tests and in situ tests of the mechanical properties of the soil, natural heterogeneities of the soil and its non-linear behavior. These tests are usually expensive and their number is limited. Moreover, in geotechnical research, the mechanical parameters of the soil are determined indirectly by measuring values correlated with them. Accurate data on soil properties and the behavior of the soil-structure interface are therefore crucial to the quality of the numerical model and the quality of the design. The boundary problem, which is the mathematical basis for engineering design, requires specifying the material properties of the building structure and the ground medium. The data defining the constitutive relationships are here input data, their reliability is a condition for the applicability of the adopted mathematical model and the reliability of the engineering solution. In the dissertation, the boundary problem mentioned above will be called the "direct" problem, and the problem of identifying material parameters appearing in the constitutive equations will be called the "inverse problem". The term "inverse problem" is natural if we assume that the mathematical model of a physical experiment (laboratory or in situ) is a similar boundary value problem, with appropriately defined geometry and loads, in which the material parameters are unknown and the typical elements of the solution are known, i.e. the loads on the boundary and the corresponding displacements measured in the experiment.

While engineering methods for solving boundary value problems (when material properties are given) are well known, the inverse problem leading to determining the values of parameters characterizing materials leads (in general) to minimization problems with differential constraints, which are not typical and difficult engineering problems. The basic thesis of this work is to demonstrate that artificial neural networks are a particularly effective tool for solving the inverse problem. The thesis of the work, formulated in the first chapter, was justified by presenting a method of solving the inverse problem using artificial neural networks and applying this method in several convincing examples from the field of

geotechnics. A method of formulating a simplified problem based on numerical tools to solve the inverse problem is also presented.

The substantive part of the dissertation consists of 7 chapters. In Chapter 1, the author presents the subject matter, motivation for writing the work, as well as the issues and main goals of the work. Thesis statement of the dissertation is formulated here as it is mentioned above.

Chapter 2 of the doctoral thesis contains a literature study covering the historical development of artificial neural networks and a presentation of the theoretical and conceptual foundations of their structure. This is a detailed description of the artificial neural network algorithm and its elements. Particular emphasis was placed on presenting the properties of the artificial neural network as a universal approximator of function, functional or operator. In this role, artificial neural networks are used in all the examples presented in this thesis. In most of the problems described in this thesis, an artificial neural network is used as a substitute for the solution obtained using the finite element method. For selected elements of such a solution (displacements in a small number of points in the domain), the network trained with solutions obtained using FEM can effectively simulate these solutions for various material parameters.

Chapter 3 of this dissertation is devoted to the formulation of the "direct" problem and the inverse problem and the related to these problems - the "direct" solution and the inverse solution. While the "direct" problem is always interpreted as a structural design problem, the inverse problem can be interpreted as a model (theoretical and numerical) of an experiment. In the experimental procedure, we typically measure displacements for known stresses for a given sample geometry and imposed constraints. Information about the mechanical properties of the sample material is unknown and is to be obtained from these data. The importance of the inverse problem has until recently been underestimated in solving practical and theoretical problems in civil engineering. The inverse problem solves a fundamental problem in practical applications, namely: how to determine the mechanical parameters of the material for which experimental data on the structure's response have been obtained. In geotechnical engineering, it is usually impossible to design an experiment in such a way that the values of the soil's mechanical parameters can be trivially determined. Currently, in the era of development of numerical methods, determining material data adequate to the computational model should be an important element of the process of geotechnical calculations. A solution method for solving the inverse problem is presented, which is based on the use of artificial neural networks as an auxiliary tool. The inverse solution can be approximated by training an artificial inverse network (ANN^{-1}), using the same set of test solutions as for the direct problem, but in this case the first element of the training pair is used as a target for the output neurons, and the second - is presented on ANN input layer. Due to the fact that artificial neural networks are universal approximators, well-trained networks are excellent approximations of both direct and inverse solutions, also for input values never used in training. Although it may sound paradoxical, thanks to the use of neural networks, the inverse problem can be easily solved, even without the need to formulate it, based on well-known classical solutions to the "direct" problem.

Chapter 4 presents an example illustrating the application of the introduced terminological convention and the effectiveness of the proposed inverse solution supported by an artificial neural network. This example considers the problem of estimating the load capacity of a pile based on an in situ experiment, namely - a static pile load test. The example assumes that the pile head displacement data obtained during the static load test can be approximated by the Meyer-Kowalow curve. The three parameters of this curve (understood as a simple constitutive relationship - displacement as a function of load) are unknown parameters of this relationship, determined as a solution to the inverse problem. This chapter shows how to train a network "directly" approximating the experimental curve obtained as a result of the test and how to train an inverse network whose output can predict the unknown parameters of the Meyer- Kowalow curve. One of these parameters is interpreted as the pile bearing capacity. An important element of the novelty proposed in this chapter is the presentation of the possibility of splitting the total load-bearing capacity into the load-bearing capacity of the shaft and the load-bearing capacity of the pile foot, based only on the data contained in the pile load-bearing chart obtained during the static test. This possibility appears thanks to the use of artificial neural networks to analyze the load-bearing curve understood as the subject of the inverse problem.

Chapter 5 presents the possibility of using artificial neural networks to interpret the dynamic surface deflection under the action of a falling mass in the FWD test. This test is used to assess the mechanical properties of pavement and substructure layers of roads, floors and airports. The numerical model of the stratified subsoil was formulated and solved using the finite element method. For displacements at typical observation points of the FWD test, a "direct" and inverse neural network were trained. Using the inverse network in the "recall" mode, for measured data directed to the network input, the network responds by assigning the Young's modulus values of subsequent layers to the network's output neurons. In this way, an appropriately trained inverse network provides a solution to the inverse problem, traditionally obtained through numerically expensive solutions to the problem of minimizing a functional with constraints. In the classical approach, the identified subsurface layers are represented by an elastic model of a laminated half-space. In the presented method, the ground model is limited only by the capabilities of the finite element program used to model the direct problem.

Chapter 6 presents the concept of reducing a complex geotechnical model containing the domain of the building structure in interaction with the domain of the soil medium. We limited ourselves to the classic models of Winkler and Pasternak, in which the action of the ground is replaced by a system of constraints whose reactions depend on the displacement of the structure. In these models (and in other similar models), the basic problem is to estimate the parameters of the introduced constraints, depending on the properties of the soil that has been replaced in this way. The concept is to build a complex neural network, the first element of which (the first hidden layers) is a fragment of the "direct" network trained with the "reference" model (the model to be simplified), and the second fragment (the subsequent hidden layers) comes from the inverse network trained with examples of solutions of reduced model. The method of constructing such a complex network is presented for two simple examples. The output of this network provides the parameters of the constraints of the reduced model as a function of the soil parameters, which replace these constraints in the reference model. The proposed procedure is automatic and can be used in the future to model more complex geotechnical issues.

Chapter 7 summarizes the results of the doctoral dissertation and presents prospects for future research. The author points out that the results can be easily verified or updated with additional research. The limitations of the method are also presented here. In particular, a case is presented in which it is difficult to build a reliable reduced model for a pile using the "Plaxis" program, as well as the prospects for calibrating such a model, which appear thanks to the proposed algorithms for solving the inverse problem. The doctoral dissertation ended with an indication of potential directions for further research work and a description of conclusions regarding tools and methods used as an auxiliary tool in the field of geotechnical engineering to numerically solve direct and inverse problems of soil-structure interaction.

Streszczenie dotyczące rozprawy doktorskiej pt. „Direct and inverse artificial neural networks as auxiliary tools in numerical solutions of selected problems of soil-structure interaction in geotechnical engineering".

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(podpis osoby ubiegającej się o nadanie stopnia doktora)