Inverse Analysis of Soil Parameters Based on Deformation of a Bank Protection Structure

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Abstract:

Deformation prediction is an important part of the structural stability analysis. Accurate acquisition of soil parameters is crucial to improve the accuracy of prediction. The deformation of bank protection structure is affected by many factors, such as structural stiffness, soil pressure and hydrostatic pressure and so on. In this work, we present an inverse analysis method of parameter determination which combines numerical simulation with BP (back-propagation) neural network. According to the data sets obtained by numerical simulation, the nonlinear mapping relationship between soil parameters and structure displacement is established. Finally, through the inversion analysis of the soil parameters of the bank protection structure, we proved the feasibility of the method. After the inversion, the comparison of the calculated with the measured values of the displacement shows a high accuracy and plausibility of the applied method.

Keywords: Deformation prediction, water-soil interaction, BP neural network, soil parameters, inverse analysis.

1. Introduction

Bank protection structure such as steel sheet pile, has been widely used in the wharf, deep foundation pit and cofferdam engineering due to its strong integrity, high strength and convenient installation. The stability of bank protection structure is of great significance to the river embankment safety. Deformation prediction is an important study to evaluate the structure stability. However, the deformation of bank protection structures is affected by many factors, such as structural stiffness, soil pressure and hydrostatic pressure and contains a complex mechanical process which is a grey, fuzzy, stochastic and nonlinear engineering problem.

In order to predict the deformation of the structure accurately, numerical simulation is a widely used effective method. However, this method is strongly dependent on the accuracy of in-put parameter because the mechanical parameters of soil which are normally obtained through laboratory experiments cannot represent the real situation on site. That is one of the reasons for the inaccuracy of simulation. In general, some parameter estimation software, such as PEST or UCODE, is often utilized to most forward model after modification. These software have limitations of single-physical process. The deformation of the bank protection structure as a result of the interaction between soil pressure and water pressure is a coupled nonlinear multi-physical problem. For this case, these inverse methods are no longer efficient[1].

Recently, with the continuous development of computer performance, nonlinear inversion methods of parameter, such as BPNN (back-propagation neural network), genetic algorithm and simulated annealing algorithm are widely used in geophysics and geotechnical engineering. These nonlinear inversion methods are based on a large number of measured data and have good prediction ability which is realized by establishing the nonlinear mapping between the input and output[2-3] data. However, these methods do not involve the mechanical mechanism of the deformation, and it is difficult to grasp the key factors in the deformation process. Thus, there is often difficulty in the deformation trend prediction. In this regard, numerical simulation method, based on the mechanical interaction in internal structure, has a good reliability, although it requires a high computational performance and accurate parameter determination.

In this paper, we present an inverse analysis method combining numerical simulation and BP neural network. According to the numerically coupled soil-water model, the data set that

consists of different parameter input and displacement output are constructed. Through the interface of Livelink for MATLAB, we can use the neural network toolbox to train the data samples and then establish the mapping relationship between the model parameter and resulting structural displacement.

2. Methodology

2.1 Soil-water interaction model

The deformation of bank protection structure is not only affected by the inner soil pressure but also by the hydrostatic pressure. On one hand, the river-water level fluctuation will cause a change in the hydrostatic pressure on the side of the structure. On the other hand, it will lead to the changes of seepage field in the river bank , which in turns, causes the redistribution of soil pressure and pore water pressure on the other side of this structure. Thus, the deformation of bank protection structure is the result of the interaction of soil and water.

In the riverbank, the seepage of groundwater can be described by Darcy's law as,

$$v_w = -K(\nabla p_w + \rho_w g \nabla D) \qquad (1)$$

where v_w is the groundwater velocity; K is the permeability coefficient; μ_w is the fluid dynamic viscosity; p_w is pore-water pressure. Considering that the deformation of structure mainly occurs along the horizontal direction (perpendicular to the river flow direction) and the displacement is small, the influence of soil consolidation on the permeability coefficient can be neglected.

The deformation of the riverbank is governed by the ideal elastic-plastic constitutive model matched the Mohr-Coulomb yield criterion. In this mathematical model, changes of soil mechanical parameters caused by groundwater fluctuations will also be considered. This means the bulk density and shear strength of soil will be adjusted according to the calculated groundwater level, e.g. the shear strength parameters (cohesion c and friction angle φ) below the groundwater level are modified by [4],

$$c_s = c \cdot \alpha_c \qquad \varphi_s = \varphi \cdot \alpha_\varphi \qquad (2)$$

where α_c and α_φ are the reduction coefficient of shear strength parameters.

2.2 BPNN inverse analysis model

As for bank protection structure, the inverse analysis of soil parameters is generally a mathematical process, through which the soil mechanics parameter vector $b = (E, K)$ is inverted with n measured horizontal displacement vector $x_k = (x_1, x_2, \ldots, x_n)$ at a different depths. According to the measured displacement and combined with the above-mentioned coupling numerical model, inversion of soil parameters can be performed.

Numerical calculations based on the given soil parameter vectors $b_i = (E, K)_i (i=1, 2, \ldots, m)$, can obtain a corresponding number of simulated displacement vector $x_i' = (x_1', x_2', \ldots, x_m') (i=1, 2, \ldots, m)$. According to this set of simulated displacement vector, a mapping relationship between the parameter vector b_i and the simulated displacement vector x_i' can be established as,

$$b_i = f(x_i'). \qquad (3)$$

Once the mapping relationship is determined, the inversion of the model soil parameters can be achieved based on the comparison of measured and calculated displacement data.

However, the soil-water interaction model is based on a coupled multi-physics partial differential equations which requires a nonlinear mapping function. An analytical solution of cannot be directly obtained.

BPNN, as a commonly used neural network model, has the good predictive capability by establishing the nonlinear mapping between input and output. It has been proven to have good performance in many back propagation analysis of parameters cases[2].

2.3 Inverse Analysis Method of Soil Parameters

After establishing the data set of forward modelling and the nonlinear mapping relationship of inversion modelling, for any given soil parameters, we can receive a system response value x_k' by extension prediction ability of neural network. Comparing the response value x_k' and measured value x_k, the optimal parameters can be obtained by minimizing the difference between x_k' and x_k with the following objective function:

$$f(X) = \sum_{i}^{k} |\, (x_k' - x_k)\,|$$ (4)

where k is the number of measured values.

A brief overview of the above-mentioned inverse analysis method is shown as the flow chart in **Figure 1**.
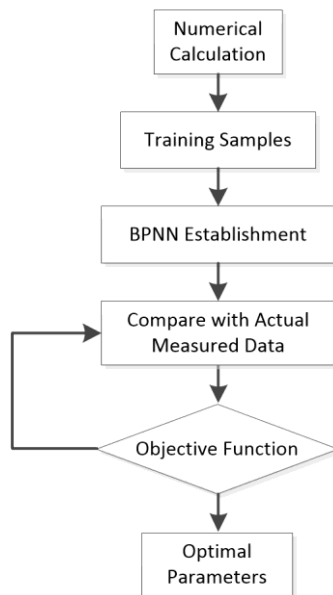

Figure 1. Flow chart of the analysis method.

3. Use of COMSOL Multiphysics® Software

In this work, an inverse analysis is implemented in two steps by using COMSOL® and MATLAB®. Firstly, we established a forward model to calculate the soil displacement by coupling the physics of Darcy's Law and Solid Mechanics. The numerical case is based on the steel sheet pile structural model of Hu and Xing (2016)[5]. Through the parametric scanning of soil parameters, e.g. elastic modulus (E) and permeability coefficient (K), the corresponding horizontal displacement values at different depths are obtained. As the river bank soil is divided into three layers and in each layer three displacement monitoring points are implemented, we can obtain 25 data sets through orthogonal experimental design, each containing 6 inputs and 3 outputs.

Subsequently, through the LiveLink for MATLAB module, required parameters are loaded and displacement results are calculated. Based on the neural network toolbox, the sample data can be trained, tested, and validated in the BPNN model. Subsequently, the mapping function of soil parameters and displacements are constructed. Finally, through the definition of the objective function, the optimal parameters of soil can be estimated by the joint inversion method. The data interaction process between COMSOL Multiphysics® and MATLAB® is sketched in **Figure 2**.
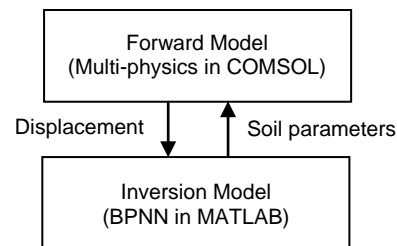
Figure 2. The sketch of the data interaction process between COMSOL Multiphysics® and MATLAB®.

4. Results and Discussions

According to the analysis on the deformation mechanism of the structure, elastic modulus E and permeability coefficient K are considered as the main influencing factors to the stress field and seepage field, respectively. Therefore, elastic modulus E and permeability coefficient K of three layers are chosen as parameters to be inversed. The detail levels of inverse-analyzed parameters are listed in **Table 1**. According to orthogonal experiment design and numerical calculation, a training sample set containing 25 data sets is obtained.

**Table1：** The levels of inverse-analyzed parameters

Soil layer	E (MPa)	k (m/d)
1	1.0 1.5 2.0 2.5 3.0.	4 4.5 5 5.5 6
2	6.0 6.5 7.0 7.5 8.0	8 10 12 14 16
3	3.2 3.7 4.2 4.7 5.2	3 3.5 4 4.5 5

Using this sample set, a neural network model consisting of six inputs and three outputs is set up. After several tests, the network structure of 6-4-3-1 BPNN model (containing two hidden layers) is determined owing to its better performance on the stability of the calculated results. The regression results of BPNN training, validation and test are shown in **Figure 3**. The correlation coefficient R representing the fitting of observed value vs. calculated value is very close to 1, that means in our case the model has been well trained.
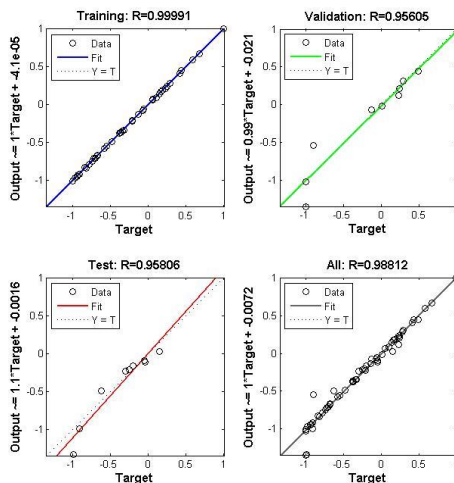

Figure 3. Regression result of training, validation, test and all data set.

Figure 4 shows the convergence curve of the mean square error in the parameter optimization process with the introduced objective function. The final optimized parameters of elastic modulus and permeability coefficients in the three layers are 2.76MPa, 6.67MPa, 4.92MPa, 5.4m/d, 10.5m/d and 4.1m/d, respectively.
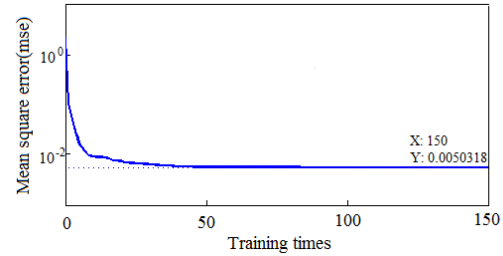
Figure 4. Regression result of training, validation, test and all data

According to these optimized parameters, the displacement field of bank protection structure is shown in **Figure 5**. Comparing the measured value and the calculated value of the displacement at each monitoring point, the results show that the relative errors are below 15%. which indicates a high computational accuracy.
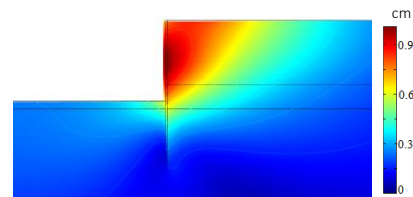
Figure 5. The calculated displacement field of bank protection structure using optimized parameters

5. Conclusions

In this work, we present a coupled method for the displacement prediction of river bank based on numerical simulation and BP neural network by using COMSOL Multiphysics® software. By comparing the calculated values with the measured values of the displacement, the results show that this coupled method has a high computational accuracy and plausibility.

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