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Prediction of the resilient modulus of flexible pavement subgrade soils using adaptive neuro-fuzzy inference systems

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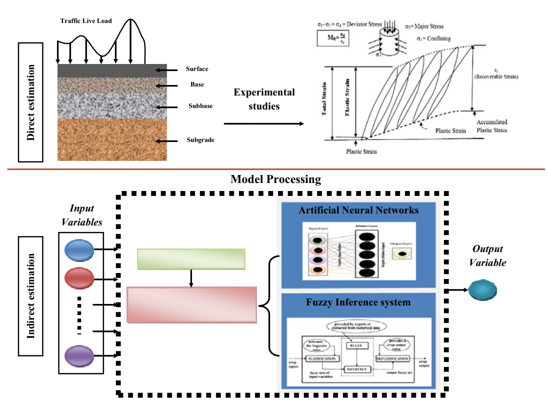
HIGHLIGHTS

- This study explores the application an artificial intelligence method, namely adaptive neuro fuzzy system (ANFIS) for prediction of resilient modulus of flexible pavement subgrade soils.
- The structure of ANFIS is described for utilizing in different complex prediction problems.
- Various validation and verification study phases are represented for evaluating the performance and accuracy of a model.
- The robustness of ANFIS, as a predictive tool, is confirmed for indirect estimation of resilient modulus of pavement subgrade soils.

GRAPHICAL ABSTRACT



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ABSTRACT

The resilient modulus (M_R) of pavement subgrade soils essentially describes the structural response of pavements for a reliable design. Due to the elaborate, expensive and complex experimental estimation of M_R factor, several models are proposed for indirect estimation of it which are mostly established based on statistical analyses e.g. regression analyses. The deficiencies of existing models in addition to the complexity of resilient behavior of soils indicate the necessity to develop better models. This study investigates the potential of a powerful hybrid artificial intelligence paradigm, i.e. adaptive neuro-fuzzy inference system (ANFIS), for prediction of M_R of flexible pavements subgrade soils. A comprehensive database which comprises a total of 891 experimental datasets conducted on different Ohio cohesive soils is taken from the literature for evolving models. In ANFIS modeling, $P_{\#200}$, LL, PI, w_{opt}, w_c, S_r, q_u, σ_3, σ_d are considered as input variables and correspondingly the output is M_R. Several statistical criteria, validation and verification studies are used for evaluating the performance capability of the obtained model. A sensitivity analysis is utilized to demonstrate the effectiveness of the considered input variables for characterizing M_R. Besides, the response of ANFIS based M_R model to variations of each input variable is examined using a parametric study and results are compared to those experimentally provided in the literature. Eventually, the obtained results approve the robustness of ANFIS approach for indirect estimation of M_R of subgrade soils.

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1. Introduction

The main purpose of a pavement design is to provide structural and economical combinations of materials so that it can serve the applied traffic loads for a specific duration of time. Flexible pavement structures commonly consist of four principal layers including surface, base and two unbound layers, i.e. sub-base and subgrade. As vehicles pass over the pavement surface, different dynamic and cyclic loads are applied to pavement layers. All pavements gain their ultimate support from the underlying subgrade which usually includes different combination of soils [1,2]. Subgrade soils play the role of being a flexible foundation via deformation, compaction and distortion. At the initial stage of vehicular traffic loadings, i.e. the deviator stress (σ_d), a considerable deformation happens in subgrade soil structure. As the number of stress repetitions increases, the plastic strain decreases until it becomes practically all recoverable. The elastic modulus based on the recoverable strain under repeated stresses is referred to as the resilient modulus (M_R). As illustrated in Fig. 1, M_R is considered as the ratio of applied deviator stress (σ_d) to the recoverable strain (ε_r) [3].

M_R can be defined as the structural response of pavements. It is a measure of the elastic modulus of recognizing nonlinear stress-strain characteristics of subgrade materials [4]. M_R takes into account the significant effects of traffic loading, deviator, cyclic and confining stress states. M_R can be determined by conducting various in-situ and cyclic tri-axial load, torsional shear and resonant column laboratory testing methods [5–11]. But, experimental estimation of the M_R is definitely expensive, elaborate and complex [12]. On the other hand, various codes such as Mechanistic-Empirical Pavement Design Guide (M-E PDG), American Association of State Highways and Transportation Officials (AASHTO) and National Cooperative Highway Research Program (NCHRP) have recommended considering M_R for structural analysis and design of multi-layered pavement systems [9,11,13–15]. Regarding to M-E PDG procedure for determining M_R value through a numerical model, numerous properties of unbound layers materials must be taken into account for describing the resilient behavior of pavement. Nevertheless, it is crucial to understand the factors affecting M_R for a precise estimation due to the changes in traffic patterns and environmental properties [16–18]. Accordingly, numerous studies have been conducted and several constitutive models have been suggested for estimation of M_R in terms of applied loads, stress states and soil physical and hydrological properties [5,17,19–24]. These models are often obtained via regression analyses. General forms of some constitutive M_R equations of subgrade soils which are made by regression analysis are represented in Table 1.

Regarding to the equations represented in Table 1, main variables are related to stress states such as σ_d and σ_3 which vary in laboratory tests for different soil samples to obtain a new M_R value. k_1, k_2 and k_3 are obtained by using either linear or nonlinear regression analyses to fit the prediction model to laboratory-generated M_R test data. Coefficient k_1 cannot take a negative value since M_R cannot be negative. Besides, k_2 should be positive since increasing the bulk stress or confining stress should produce stiffening effect on the material, which leads to higher M_R. In contrast, k_3 must take a negative value because increasing the shear or deviator stress should produce softening effect on the material [14,23,24]. Afterwards, a second set of regression analyses are carried out to relate these k-coefficients with the soil physical properties such as moisture or water content (w_c), specimen dry density (γ_d), maximum dry density ($\gamma_{d\ max}$), liquid limit (LL), plasticity index (PI), uniformity coefficient (C_U), coefficient of curvature (C_C), percent passing #200 sieve ($P_{\#200}$) and etc. A summary of obtaining these models can be found in the previously published literatures, including [7,17–20,23,24,27].

It can be realized that aforementioned analysis procedure is definitely complicated. Moreover, there are other disadvantages. Although the model developed by regression analysis performs reasonably well on selected data sets, the capability of them is thoroughly restricted to the range of utilized datasets used for the analysis; besides, they are not validated and not tested on new data.

The deficiencies of existing models in addition to the complexity of M_R behavior indicate the necessity to develop better prediction models for indirect estimation of M_R of pavement subgrade soils.

During past two decades, many computational intelligence techniques such as artificial neural networks (ANNs), fuzzy inference system (FIS), genetic programming (GP), support vector machines (SVM) and such methods are proposed based on biological theories and activities for tackling real world problems. These computing techniques have a lot of features that have made them attractive choices for using in different problems. The main feature is that they are data-driven self-adaptive methods. They can automatically learn from data to determine the structure of a prediction model. Besides, these techniques have been successfully employed to solve various problems in civil engineering domains [28–46].

Despite extending promotions in such artificial intelligence (AI) methods, there are few attempts in the literature for using them in predicting the M_R of pavement subgrade soils.

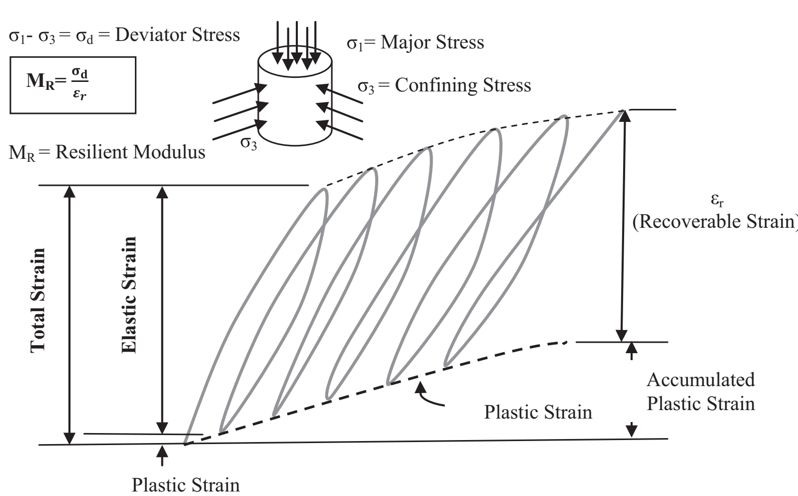

Fig. 1. Resilient modulus of subgrade soils under repeated traffic loading (Huang, 2004).