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Determining the effective stress parameter in drying path by MGGP method

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ABSTRACT: The hydromechanical behavior of unsaturated soils depends on their state of stress. In recent years, the use of effective stress as a fundamental variable converting a multiphase medium to a continuum has appealed to researchers' attention. The determination of effective stress needs estimation of the so-called effective stress parameter, which is a function of other physical variables and essential parameters such as those of the soil water retention curve (SWRC). In the current study, multigene genetic programming (MGGP) has been employed to predict a relationship between the effective stress parameter of soils. The input variables are the net stress, suction, slope of the soil water retention curve, air entry value, and residual and saturated water contents. The comparison of the performance and accuracy of the obtained equation with the available equations as well as the values of effective stress parameters obtained from experimental tests indicate the reasonable adequacy and accuracy of the proposed equation. For this purpose, 101 data points of effective stress parameters from the literature were gathered and used. The high coefficient of determination obtained for the proposed equation, namely, 0.94, confirmed its reasonable accuracy. The parametric study revealed that an increase in the ratio of net stress to the air entry value will lead to an increase in the effective stress parameter for the same suction levels. However, a decrease in the effective stress parameter values was observed with the increase in the SWRC slope, and with the decrease in the ratio of residual to saturated water content.

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1- Introduction

More than two-thirds of the Earth's surface is covered with dry and semi-dry regions where soil layers are most often in unsaturated conditions. In unsaturated soils, σ´, denoting the effective stress has first been formulated by Bishop as follows (equation 1).

$$\sigma' = P + \chi(S) \quad (1)$$

where the parameter χ is the so-called effective stress parameter proposed by Bishop, suggested to be equal to the degree of saturation, P stands for net stress, and S specifies suction. However, his succeeding researchers have not found this approximation to be very appropriate and accurate. It should be noted that finding a suitable equation that accurately determines the value of the effective stress parameter in unsaturated soils is still an area of focus for researchers

The main goal of this study is to use a powerful machine learning approach called Multi-Gene Genetic Programming (MGGP), a branch of artificial intelligence (AI), to provide a suitable relationship for the effective stress parameter. The main advantage of the MGGP approach over regression and other soft computing techniques is its ability to predict equations without prior assumptions about the shape of the sought relationship. In this study, parameters related to soil water retention such as air entry pressure (bubbling pressure), residual volumetric water content, saturated volumetric water content, soil suction, and net stress are considered as independent variables. Another important advantage of this study over other studies that used artificial intelligence is the use of air entry suction as the boundary value between unsaturated and saturated zones and thus the development of a two-part relationship for the effective stress parameter using AI; Furthermore, the suggested general form is tailored so as to respect the continuity of the effective stress parameter value at the air entry suction.

2- Methodology

GPtips 2.0 software and programming in the MATLAB environment were used to implement multi-gene genetic programming for finding a suitable formula for the effective stress parameter. Each of the SWRC parameters or any combination of these parameters can be considered as a suitable candidate for model inputs. Therefore, six parameters

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Table 1. Final and optimized parameters of MGGP approach

Parameter	Value or type
Population size	400
Generations number	120
Tournament size	5
Elite percentage	0.15
Maximum tree depth	4
Optimized and final function set	Sqrt, Sum
Number of input variables	4
Maximum number of genes in each tree	8
Complexity metric	Expressional complexity

including net stress, suction, SWRC slope, air entry pressure, residual, and saturated volumetric water content were considered as model input variables. Then these variables were converted to dimensionless quantities appearing in equation (2) to serve as input variables of the model. The output variable was the effective stress parameter.

In this study, a set of 101 data was used for developing the model. After reviewing previous studies and finding those whose datasets included all target variables required for this study, data points were extracted from the relevant literature. These data were extracted based on the results of triaxial shear tests, from which the effective stress parameter values were determined and pressure plate, and filter paper experiments to determine the parameters of the soil water retention curve [1-10]. The dataset consists of seven unsaturated soil properties, namely, suction (S), air entry suction (h_b), net stress (P), residual water content (θ_r), volumetric water content at saturation (θ_s), soil water retention curve slope (λ), and the effective stress parameter (χ). Input variables were made dimensionless/normalized as: θ_r/θ_s, P/h_b and h_b/S and used together with λ. The dataset was divided into two separate groups: an 80% training dataset and the remaining data were selected for testing the accuracy and effectiveness of the model.

For the effective stress parameter, the following general form was considered, where function f has been obtained through multi-gene genetic programming.

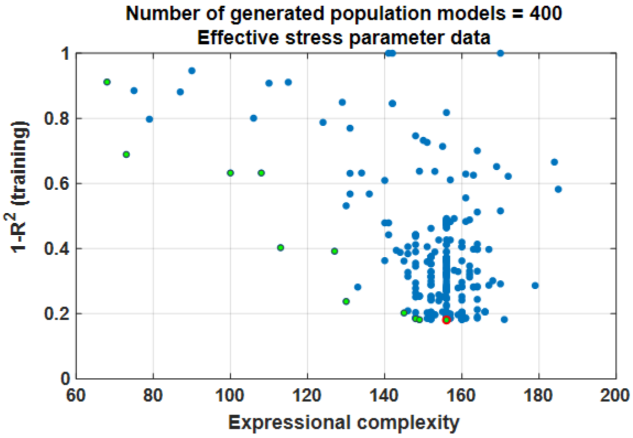

Fig. 1. Selection of the optimum models based on the complexity and accuracy

$$\chi = \begin{cases} 1 & \left(\frac{S}{h_b}\right) < 1 \\ 1 + f\left(\frac{h_b}{S}, \frac{P}{h_b}, \lambda, \frac{\theta_r}{\theta_s}\right)\left(\frac{h_b}{S} - 1\right) & \left(\frac{S}{h_b}\right) \geq 1 \end{cases} \tag{2}$$

3- Results and discussion

Figure 1 shows the selection of the optimal model based on the accuracy and complexity measures. As seen, the green points have the lowest complexity measure among different generations of simulations produced by the multi-gene genetic programming. The program has selected the equation that has both the lowest error and the lowest complexity measure simultaneously.

The obtained equation for function f reads as follows:

$$\begin{aligned} f\left(\frac{h_b}{S}, \frac{P}{h_b}, \lambda, \frac{\theta_r}{\theta_s}\right) &= 4.2265\left(\frac{h_b}{S}\right) - 0.047935\left(\frac{P}{h_b}\right) - 0.68201\left(\frac{\theta_r}{\theta_s}\right) \\ &-8.6725\sqrt{0.016667\left(\frac{P}{h_b}\right) + 1.4011\left(\frac{\theta_r}{\theta_s}\right)} + 4.4548\sqrt{1.0260\sqrt{\left(\frac{h_b}{S}\right)} + 0.29086\sqrt{\lambda}} \\ &+18.066\sqrt{0.016667\left(\frac{P}{h_b}\right) + 1.4011\left(\frac{\theta_r}{\theta_s}\right) + 1.9634} \\ &-0.69224\sqrt{0.0083333\left(\frac{P}{h_b}\right) + 1.0526\left(\frac{h_b}{S}\right)} \\ &+4.0152\sqrt{0.0083333\left(\frac{P}{h_b}\right) + 0.084602\lambda} \\ &-0.69224\sqrt{1.0526\left(\frac{h_b}{S}\right) + 1.4011\left(\frac{\theta_r}{\theta_s}\right)} \\ &+4.0857\left(0.0083333\left(\frac{P}{h_b}\right) + 1.4011\left(\frac{\theta_r}{\theta_s}\right)\right)^{1/4} \\ &-6.4011\sqrt{\frac{h_b}{S}} - 1.6731\sqrt{\lambda} - 0.26253\lambda^{1/4} - 25.300 \end{aligned} \tag{3}$$

4- Conclusions

In this research, a multi-gene genetic programming approach was used to arrive at the effective stress parameter equation for unsaturated soils. The derived equation had reasonable accuracy compared to laboratory data containing 101 test points, and also performed well compared to the other relationships in the literature. The parametric study of the proposed equation indicated a significant influence of air entry suction and the net stress ratio on changes in the effective stress parameter with suction. The effect of the water retention curve slope and the ratio of residual to saturated volumetric water content on the effective stress parameter variation with suction was less pronounced than the other (aforementioned) variables.

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