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Measurement of stress dependent permeability of unsaturated clay

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ABSTRACT

Unsaturated permeability in soil is useful in assessment of water consumption by roots and suction distribution in slopes, which in turn, helps in design for the stability of slopes/covers. Stress factor is important in understanding the behavior of the unsaturated soils because it has a significant effect on its permeability as it brings micropores and minipores changes in the soil structure. Past studies have often neglected to measure its effect on the permeability property of the soil. The present study will introduce an optimization framework of genetic programming (GP) in developing the explicit relation of the permeability and the stress of the unsaturated clay. Experimental validation of the GP model will be done using the metrics such as the coefficient of determination, the root mean square error and the mean absolute percentage error. 2-D analysis of the model will be useful for experts to monitor the permeability property unsaturated clay.

1. Introduction

Unsaturated permeability is one of the essential input functions, which is often used in interpretation of behavior of crop water consumption, suction distribution in landfill covers and slopes [1–4]. It is well known to depend on the degree of saturation as well as void ratio [5]. In addition to this, stress, which is one of two constitutive variables that governs unsaturated soil behavior [6] could also influence permeability [7] by altering soil fabric (macropores, minipores and micropores) [8]. The influence of stress on the permeability is widely studied by various researchers [7,9–12]. Any influence of net stress on permeability is important for analyzing slope stability [7].

Different methods (Fig. 1) are available in literature for the indirect estimation of permeability. In most of cases, permeability is usually determined from soil water characteristic curve based on analytical approaches proposed by Genuchten [13] and Fredlund and Xing [14]. Alternatively, permeability can be also estimated from soil properties, which are commonly known as Pedotransfer functions [15], and are mainly utilized in agricultural and environmental science [16]. Besides these, soft computing methods (artificial neural network (ANN) and support vector regression (SVR)) were also used to develop models for predicting the permeability for various types of soil [17–25]. However, the models developed do not take into account any influence of stress on permeability of soil [26–28]. Therefore, considering the importance of stress effect on permeability and its influence on seepage modeling, there is a need to develop models which explains the phenomenon effect of permeability on soil particles. Also, the methods such as ANN and SVR do known for achieving good generalization but it is difficult to extract functional relationships between parameters [29,30].

Over the years, the evolutionary based optimization framework of Genetic programming (GP) has been applied extensively in modeling of the complex non-linear systems [31–34]. The advantages of using an optimization framework of GP is that it only needs experimentally collected data and settings of its parameters to formulate the model for the given system [35,36]. It is not based on statistical assumptions such as traditional regression methods nor it needs any human expertise to select the optimum settings [37,38]. Therefore, the present work will introduce an application of GP in deriving the relationship of the permeability and the two input parameters (suction and net stress) for Firouzkouh clay. Firouzkouh clay is a low plasticity clay mainly present in Firouzkouh (northern part in Iran). The models are evaluated statistically based on the root mean square error, coefficient of determination and mean absolute percentage error. 2-D analysis is then performed to find the main effects of suction and net stress on the permeability of the clay.

2. Experimental study to investigate effect of net stress on unsaturated permeability

Study of investigating the effect of net stress on the permeability under varying conditions of suction on residual soil is referred

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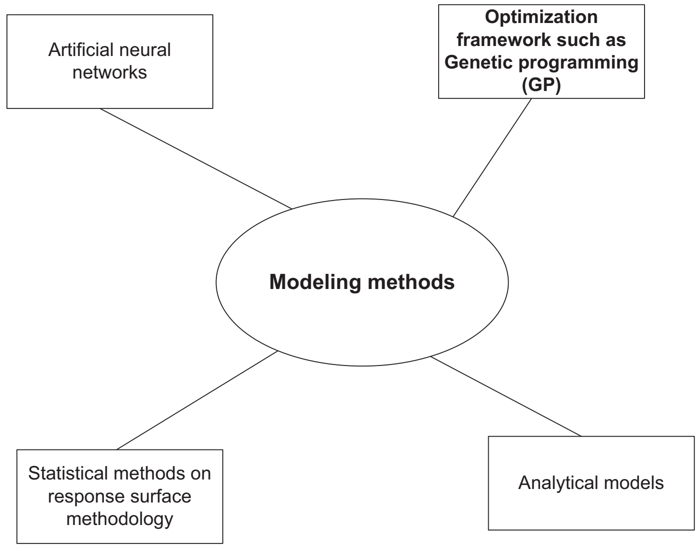

Fig. 1. Types of modeling methods being used for modeling the permeability of the soil.

from Mirzaii and Yasrobi [7]. Soil investigated was Firouzkouh clay, which is clay of low plasticity. Liquid limit and plastic limit are 30% and 9% respectively. Unsaturated permeability for this clay was measured at three different suction values (at 30 kPa, 100 kPa and 180 kPa) and under three different applied net stress i.e., 20 kPa, 150 kPa and 300 kPa. Permeability tests were conducted using a flexible wall permeameter apparatus. The apparatus configuration is similar to that previously developed flexible wall permeameters [39,40]. For soil samples preparation, following steps were adopted. Initially dried soil was first moistened to Standard Proctor optimum water content, then was passed through a sieve No. 10 to reduce the size of clods. Soil samples were prepared inside a steel mold with internal diameter of 7 cm by statically compacting of a known mass of pre-prepared soil to target void ratio at a final sample thickness of 1 cm. The compression rate of 1 mm/min was used for all samples. Clay samples were statically compacted soil samples at optimum water content of 14.1% corresponding to maximum dry density of 18.06 kN/m^3. Total soil volume changes were deduced based on the volume of de-aired water exchanged by the cell. The thickness of the metallic cell wall was (i.e., two centimeters) considered to be rigid enough for accurate measurement of soil volume changes. Three volume change transducers were used for automatic measurements of water flow rates and sample volume changes during the tests. When steady state is reached, permeability corresponding to a certain suction value and applied stress, was measured using Darcy's law [7].

For the training of the models, two input process variables (suction (x_1) and net stress (x_2)) and output process variable (permeability (y)) is considered. A total of 145 data points (Table 1) were obtained from the experiment conducted by Mirzaii and Yasrobi [7]. The complete procedure of modeling the permeability of the clay is shown in Fig. 2. This study chooses 80% of the total samples randomly as training which is fed into framework of the GP in formulation of the model. The remaining data points (testing data) are used for evaluating the statistical performance.

3. Proposed optimization framework

In this study, the optimization framework based on Genetic programming (GP) is proposed to evaluate the effect of the stress and suction inputs on the permeability of the soil. The framework is based on same mechanism of genetic algorithms but the former one is used for structural optimization [41]. GP had been applied extensively in the past to model the complex systems when there is uncertainty about behavior of the system [42–44].

Table 1
Nature of data collected from the experiment shown by descriptive statistics.

Statistical parameter	Suction (x_1, kPa)	Net stress (x_2, kPa)	Permeability ($y \times 10^{-10}$, m/s)
Mean	91.47	160.62	67.94
Standard error	3.78	9.60	3.33
Median	84.15	150	65.5
Standard deviation	45.53	115.63	40.14
Variance	2073.25	13371.13	1611.93
Kurtosis	−0.93	−1.53	−0.43
Skewness	0.43	0.03	0.31
Minimum	23.78	20	0.78
Maximum	184.28	300	184

The implementation of GP (Fig. 3) is based on the settings of the parameters such as the elements in the terminal and functional set, the population size, the number of generations, the user-defined objective function, the type of genetic operations used and their probabilities and the termination criterion set. Simulations are performed in the MATLAB and the GPTIPS toolbox of Searson et al. [45,46] is referred to implement GP algorithm.

The elements of the two sets (functional and terminal) is defined by the user experience. In this study, the elements for the functional set includes the arithmetic signs whereas for the terminal set, it includes the set of the two inputs (suction and the stress). The models are formed from the combination of elements from these two sets. The set of these models are represented by the population size. This is also set by the user. In this study, it is chosen at value of 200 based on the trial-and-error approach. The number of generations is the iterations performed. One generation represents a single population of the models. The number of generations chosen is 100 in this study. The performance/objective values of the models are evaluated based on the structural risk minimization objective function [47]. This objective function is well known for generalization and penalizing the complexity of the larger size models. The genetic operations used are mutation, crossover and reproduction with probabilities set for crossover at 90%, mutation at 7% and reproduction at 3%. This implies that 90% of the total initial population will undergo crossover, 7%