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Penetrability prediction of microfine cement grout in granular soil using Artificial Intelligence techniques

Ruhul Amin Mozumder, Aminul Islam Laskar*, Monowar Hussain

Department of Civil Engineering, National Institute of Technology, Silchar 788010, India

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ABSTRACT

In connection to permeation grouting present study is aimed to investigate the penetrability of microfine cement (MC) grout in granular soil. Series of laboratory based sand column grouting tests were undertaken to characterize the penetrability of MC grout in granular soil in terms of rheological properties of grout suspension (i.e. yield stress, τ_0 and plastic viscosity, μ), properties pertinent to sand and grout material such as fine sand content (FC), relative density of sand (RD) and uniformity coefficient of sand (C_u) and groutability ratio (N_2) and grouting procedure (i.e. grouting pressure, P), using permeation grouting technique. Ten (10) different sand types having d_{10} ranging from 0.17 mm to 2.53 mm and C_u ranging from 1.35 to 5.76 were grouted in laboratory with MC grout suspensions under two different relative densities (i.e. 30% and 70%). MC grout suspensions were prepared with four different water to cement (w/c) ratios viz. 0.8, 1, 2 and 3. Rheological tests of the MC grout suspensions prepared with different w/c ratios were performed to evaluate the flow properties (τ_0 and μ). Subsequently, artificial neural network (ANN) and support vector machine (SVM) based penetrability prediction models were developed to correlate penetrability with τ_0, μ, FC, RD, C_u, N_2 and P. Sensitivity analysis and neural interpretation diagram (NID) was employed to identify the key variables in penetrability prediction, to measure its effect and to explain and extract understandable knowledge from the proposed model.

1. Introduction

In deep soil stabilization, permeation grouting with microfine cement is a widely utilized approach for soil improvement in construction engineering. Permeation grouting is the process of filling voids in a soil or rock mass with a grout fluid at a low injection pressure to decrease the permeability and to improve the shear strength, while not destroying the original structure of the soil or rock (Bruce, 2005). Conventionally, groutability ratios such as N_1 and N_2, etc. have been used to predict the groutability of granular soils with particulate grouts (Burwell, 1958; Bell, 1993; Incecik and Ceran, 1995). Groutability ratios i.e. N_1 and N_2 are defined in Eqs. (1) and (2) as follows:

$$N_1 = \frac{d_{15}(\text{soil})}{d_{85}(\text{grout})} \tag{1}$$

$$N_2 = \frac{d_{10}(\text{soil})}{d_{90}(\text{grout})} \tag{2}$$

where d_{15} and d_{10} are the diameter of soil passing 15% and 10% of total soil mass respectively, d_{85} and d_{90} is the diameter of grout passing 85% and 90% of total grout mass respectively.

As per Eqs. (1) and (2), a soil is groutable when $N_1 > 25$ or $N_2 > 11$ and ungroutable if $N_1 < 11$ and $N_2 < 6$. But such criteria i.e. Eqs. (1) and (2) do not consider rheology of the grout, other relevant properties of grouted medium (i.e. relative density, fine sand content, gradation) and grouting pressure (Akbulut and Saglamer, 2002; Yoon and El Mohtar, 2013). Recently, a number of approaches were proposed to relate groutability with above mentioned parameters that provides reasonably good groutability estimations for cement based grouts (Akbulut and Saglamer, 2002; Yoon and El Mohtar, 2013; Markou et al., 2015). These approaches characterize fresh properties of cement grout suspension either in terms of w/c ratio or apparent viscosity of the grout (Akbulut and Saglamer, 2002; Yoon and El Mohtar, 2013; Markou et al., 2015). Grout w/c ratio does not reflect the effect of fineness of cement and superplasticizer whereas apparent viscosity is the viscosity corresponding to a certain shear rate. Cement grout as a fluid is most often assumed to behave like a Bingham fluid with good accuracy (Hakansson et al., 1992; Eriksson et al., 2004; Axelsson et al., 2009; Pantazopoulos et al., 2012; Markou et al., 2015) and its actual rheological behaviour can be represented only in terms of yield stress and plastic viscosity which are considered as fundamental flow properties. In addition, yield stress is a crucial parameter in grouting applications since it is related to stoppage of grout flow

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* Corresponding author.
E-mail address: aminul.nits@gmail.com (A.I. Laskar).

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through a porous medium and the post grouting performance after a certain resting period (Cambefort, 1964; Gustafson and Stille, 1996; Axelsson, 2006; Liu and Neretnieks, 2006; Axelsson and Gustafson, 2007; Axelsson et al., 2009). Therefore, investigating groutability in the light of rheological parameters i.e. yield stress and plastic viscosity in particular and other relevant properties (such as properties of grouted medium i.e. gradation characteristics, relative density and fine sand content, grouting pressure besides effective grain size of grout and soil) in general, presents a research scope.

The term "groutability" typically refers to "penetrability" and "injectability" of a grout through a soil (Markou and Atmatzidis, 2002). "Penetrability" corresponds to the permeation distance the suspensions can travel during injection and is evaluated by monitoring the penetration distance of a grout at a predetermined maximum pressure (Markou and Atmatzidis, 2002; Santagata and Santagata, 2003). "Injectability" is related to the ability of the grout to enter into the voids of a given soil (Markou and Atmatzidis, 2002).

For successful implementation of any grouting project, estimation of penetrability of grout suspension is of key importance and should be done prior to grouting as it determines the efficacy of soil improvement as well as overall cost of the project. A reliable prediction of the penetrability of cement suspensions can help in selecting proper grouting materials and also enables one to assess the distance and sequence of grouting boreholes in a more realistic manner, thus minimizing, the uncertainties in the design and execution of grouting operations (Markou et al., 2015). However, groutability is affected by several parameters i.e. grout rheology, effective grain size of grout and soil, properties of soil media and grouting pressure. Therefore, due to high dimensionality of the grouting problem and complex interaction between the variables, estimation of groutability and hence penetrability is a difficult job. Nevertheless, in such situations, use of Artificial Intelligence (AI) techniques such as ANN and SVM for prediction of penetrability will be an interesting choice as these techniques have produced successful results in different knowledge domains (Liao et al., 2012), and in particular in the field of Geotechnical engineering (Shahin et al., 2004; Das and Basudhar, 2006; Narendra et al., 2006; Mozumder and Laskar, 2015; Goh and Goh, 2007; Samui, 2008; Kordjazi et al., 2014; Mozumder et al., 2017). In fact, development of AI technique based models using data collected from geotechnical works can serve as a useful basis for the design of future projects. The underpinning objective of using these techniques is that data contains useful trends and rules which can be extracted from the data through application of these techniques. Contrary to traditional statistical approaches, AI techniques have significant capacity/supremacy to deal with huge amount of data, characterized by high-dimensionality and intricacy. Furthermore, the developed models based on these techniques can be easily updated when new data are available. For brevity of the present study, details of AI techniques (i.e. ANN and SVM) are not discussed and can be found in DARPA (1988), Caudill (1988), Caudill and Butler (1992), Vapnik et al. (1996), Smola and Schölkopf (1998), Gunn (1998).

Typically injected pore volume of a grout at a given length of soil column in laboratory have been used to asses groutability by various researchers (Markou and Atmatzidis, 2002; Mittag and Savvidis, 2003; Ozgurel and Vipulanandan, 2005). In the present study, in addition to penetrability (which is assessed by measuring the permeation distance or length), emphasis is also given to quantify injectability and is obtained by measuring the injected pore volume of a grout. Although, primary objective of the present study is to investigate penetrability aspect of groutability, but due consideration has been also given to the injectability aspect while investigating penetrability, by applying correction factor to penetrability due to injectability, as further highlighted in subsequent sections.

The main objectives of the present study are:

- To investigate the penetrability of MC grouting in granular soil considering the effect of parameters such as rheological properties of grout suspension i.e. yield stress and plastic viscosity, effective grain size of sand and grout, relative density of sand, fine sand content, gradation of sand and grout injection pressure;
- To develop ANN and SVM models to characterize penetrability in terms of yield stress and plastic viscosity of grout, effective grain size of sand and grout, relative density of sand, fine sand content, gradation of sand and grout injection pressure;
- To conduct sensitivity analysis to evaluate relative importance of experimental parameters in influencing the penetrability of MC grout in granular soil.

2. Materials and experimental methodology

In order to study the penetrability of microfine cement (MC) grout in granular soil, locally available sand with predominantly sub-rounded or nearly rounded grain shape was used in the present study for the preparation of different soil types. At first five different sand fractions with grain size range 4.75–2.36 mm, 2.36–1.18 mm, 1.18–0.600 mm, 0.600–0.300 mm and 0.150–0.300 mm denoted as R_1, R_2, R_3, R_4 and R_5 respectively were prepared. Using the above mentioned sand fractions by mixing them in various proportions, five different composite sand types (designated as CS_1, CS_2, CS_3, CS_4 and CS_5) were also produced. As a whole ten different clean dry sand types were prepared in the laboratory to study the effect of effective size, gradation and fine sand content of sand on the penetrability of cement grouts. The engineering properties of different sand types used in the study are presented in Tables 1 and 2. It may be observed that all the composite sand types i.e. CS_1–CS_4 except CS_5 corresponds to same grain size upper limit, but lower limit is varied to produce sand with different uniformity coefficients (Table 2), which are higher than the ones of sand fractions R_1–R_5 (Table 1). Grain size distributions of the five composite sands (Table 2) are presented in Fig. 1. More specifically, CS_1 and CS_2 contain only coarse and medium fractions (i.e. R_1, R_2 and R_3) without any medium fine or fine fractions (i.e. R_4 and R_5). Composite sand types CS_3 and CS_4 contain all the fractions i.e. R_1–R_5 and in particular CS_4 contains all sand fraction in equal proportion and thus have smoothest gradation with highest value of C_u. Fines proportion i.e. percentage R_5 in CS_3 and CS_4 are 10% and 20% respectively. Sand type CS_5 do not contain any coarse fraction unlike the remaining composite sand types which contain the coarser fractions and amount of fines content is highest (i.e. 30%) in CS_5 among the composite sand types. Exact proportions of the sand fractions comprising each composite sand type are shown in Table 2. All sands were grouted at a loose condition (at RD = 30%) and were dry prior to grouting. Sand CS_4 and R_4 was also grouted in a relatively dense condition (RD = 70%) to evaluate the effect of relative density (RD) of sand types on the groutability/penetrability of MC grout. Since all the sand samples were grouted in dry condition, therefore, effect of degree of saturation is not considered as a parameter in the present research.

Commercially available microfine cement (MC), a blend of Portland cement and slag powder was used as grout for injection purpose. Chemical composition and grain size distribution of MC used in the present study as supplied by the manufacturer are given in Table 3 and

Table 1
Engineering properties of sand fractions used in the study.

Range designation	Range size in mm	d_{10} in mm	d_{15} in mm	d_{50} in mm	e_{max}	e_{min}	C_u	C_c	USCS
R_1	4.75–2.36	2.53	2.64	3.65	0.89	0.45	1.484	0.83	SP
R_2	2.36–1.18	1.27	1.34	1.81	0.90	0.46	1.488	0.83	SP
R_3	1.18–0.60	0.64	0.67	0.92	0.90	0.47	1.516	1.01	SP
R_4	0.60–0.30	0.33	0.35	0.46	0.92	0.47	1.455	1.06	SP
R_5	0.30–0.15	0.17	0.18	0.22	0.94	0.49	1.353	1.02	SP