A Methodology to Build a Groutability Formula via a Heuristic Algorithm

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Abstract

The goal of this study is to provide a methodology to develop a groutability (N) formula of sandy silt soils using microfine cement grouts in a permeation grouting. Because the Fines Content (FC) of the sandy silt soils studied is relatively high, and the size of the grouts used is significantly smaller than the Portland cement, the existing empirical formulas cannot deliver a promising prediction of N. Support Vector Machines (SVMs) is an alternative tool used to predict N. However, SVMs do not provide an explicit formula, which creates an obstacle for practical engineers. Thus, a heuristic algorithm (the Tabu search, TS) was used to build the prediction formula. A total of 240 in-situ data samples were analyzed to ensure the accuracy of the proposed formula. The format of the existing empirical formula was adopted in the proposed TS-based formula. Four parameters were considered in our TS models: the effective soil particle size \((D_{10})\), the soil particle size \((d_{15})\), the water-to-cement ratio \((w/c)\) and the FC. The prediction accuracy of the TS-based formula was approximately 94.17%, indicating that the proposed formula is a suitable tool. Because the proposed formula has a similar format to that of formulas that are typically used, the proposed approach can be implemented readily in practical engineering settings. Note that the proposed formula was only verified by the collected data samples, the suitability of applying the built formula to other conditions needs more investigation.

Keywords: Tabu search, groutability, microfine cement, permeation grouting, SVMs

1. Introduction

With the development of microfine cement grouts and low-pressure grouting technology, permeation grouting has been successfully applied to engineering problems: rehabilitation projects for bridge structures (Khayat et al., 1997; Perret et al., 2002), environmental projects to isolate polluted sandy soil (Schwarz and Krizek 2006), remedial works of the defected earth fill dam (Chun et al., 2006) and retrofit projects to improve liquefaction resistance in sandy silt soils (Huang et al., 2007). One of the major challenges of using microfine cement grouts is estimating the groutability, N, within a reasonable level of error. Another challenge is whether an approach provides an easy evaluation process for practical engineers. Thus, this study aimed to develop an explicit prediction formula for sandy silt soils with a focus on microfine cement grouts used in permeation grouting.

Predicting the N with cement-based grouts is not an easy task. Many parameters affect N and must be evaluated systematically. For practical reasons, most researchers used the relative grain-size ratio between soils and grouts to predict N (Huang et al., 2007; Burwell 1985; Krizek et al., 1992; Incecik and Ceren 1995; Axelsson et al., 2009), as described in Eqs. (1) and (2).

\[
N_1 = \frac{(D_{15})_{soil}}{(d_{15})_{grout}}
\]

\[
N_2 = \frac{(D_{10})_{soil}}{(d_{10})_{grout}}
\]

A successful grouting should have \(N_1\) larger than 15 and \(N_2\) larger than 8 (Krizek et al., 1992), where \(D_{15}\) is the diameter through which 15% of the total soil mass passes and \(d_{15}\) is the diameter through which 85% of the total grout passes. Similar regulations are applied for \(D_{10}\) and \(d_{10}\).

The existing empirical formulas may fail to deliver a promising prediction of N when microfine cement grouting with a high water-to-cement ratio \((w/c)\) is used for sandy silt soils with high fines content (FC, size of soil particle < 0.074 mm) for several reasons. First, considering the effect of grout size, 70% of the microfine cements studied here have a grain size less than 1 µm, which is much smaller than that in traditional cement-based grouts (e.g., the Portland cement). Second, the FC of the sandy silt soils in this study is relatively high; that is, the effective soil particle size \((D_{10})\) and the soil particle size \((D_{15})\) have a very high probability of being less than 0.074 mm. This \(D_{10}\) or \(D_{15}\) will cause the relative grain-size ratio between soil and grout in the...
empirical formulas to be smaller than expected. Third, when \(w/c\) is larger than 3 like in this study, grouts often exhibit better flow properties, such as lower viscosity and higher infiltration rate. Thus, the empirical formulas may not be suitable to use only the relative grain-size ratio to determine \(N\).

Thus, in addition to the relative ratio between the soils and grouts, there are many other important factors that should be considered when predicting \(N\). For example, Zebovitz et al., (1989) stated that the FC in the sand may control the grouting operation. In some cases, even though the relative grain-size ratio between soil and grout was satisfied, the sample was not groutable when the fine sands contained 5% fines by weight. Ozugurel and Vipulanandan (2005) also concluded that the \(N\) of sand with acrylamide grout was influenced by the amount of FC.

More factors should be considered when constructing a prediction model. Thus, Akbulut and Saglamr (2002) included the FC and \(w/c\) in their prediction formulas.

In addition to the existing formulas introduced earlier, Artificial Neural Networks (ANNs) or Support Vector Machines (SVMs) are potential tools that can be used to build a prediction model of \(N\). ANNs have been successfully applied to many geotechnical engineering problems, such as predicting the bearing capacity of strip footing (Kuo et al., 2009), predicting the lateral load capacity of piles in clay (Das and Basudhar, 2006), analyzing the slope stability analysis (Cho, 2009) and predicting the rock fragmentation due to blasting (Bahrami et al., 2011). ANNs also have been applied to the groutability problem. For example, the \(N\) of granular soils with cement-based grouts was estimated using an ANN model based on a database of 87 laboratory observations (Tekin and Akbas, 2011). The \(N\) of sandy silt soils with high FC was predicted via a Radial Basis Function Neural Network (RBFNN) (Liao et al., 2011). Both ANN models provided a good correlation between the observed and predicted outcomes.

The SVM is a useful technique for data classification. Constructing a SVM is often considered to be easier than building an ANN model. SVMs also have been applied to many engineering problems, such as predicting the blast-induced ground vibration (Khandelwal, 2011), detecting local damages in a building structure (Mita and Hagiwara, 2003), identifying the lateral flow occurrence (Lee and Kim, 2010), analyzing hand writing, which require pattern classification or are regression-based applications.

Neither ANNs nor SVMs provide a specific formula for engineers, although they have the potential to deliver a promising prediction. The concept and operation of an ANN or an SVM model is a black box for some practical engineers. On the other hand, an explicit empirical formula is often used in geotechnical engineering. Thus, this study aimed to develop a formula with a similar format to that in existing formulas that provides an easy evaluation procedure for predicting \(N\).

As mentioned earlier, the existing formulas, as described in Eqs. (1) and (2), may not be able to deliver a good prediction of \(N\) due to the size effects of soils and grouts. To improve the prediction accuracy, new threshold values for \(N_1\) and \(N_2\) in Eqs. (1) and (2) are needed. As discussed, other factors such as FC and \(w/c\), if considered, can provide better prediction accuracy. In the latter case, at least four new thresholds need to be determined. Assuming that there are 10 possibilities for each threshold, the size of the search domain is \(10^{12}\). For such a large design domain, the Tabu Search (TS) is a good solution tool because a TS can reduce the computational cost using a Tabu list. Moreover, TS usually avoids a local optimum and can be applied to both discrete and continuous solution spaces (Tung and Chou, 2002). Thus, TS was adopted to build a prediction formula in this study. Please note that the results of permeation grouting performed in the field and in the laboratory may be different; only data samples from the field were considered in this study.

The 240 in-situ data samples of permeation grouting with microfine cement grouts were collected in the cities of Taipei and Kaohsiung, Taiwan and were analyzed by the proposed TS-based models. Two TS models were investigated. The first model has the same format as that used in Eqs. (1) and (2). The second model includes two additional parameters, the FC and the \(w/c\). The effects of FC and \(w/c\) on \(N\) were examined thoroughly by comparing the results of these two TS models.

The results from the TS-based model were compared with those of some existing methods. The accuracy rates of our model were 91.25% and 94.17% for the first and the second model, respectively; these accuracy rates are much higher than the existing methods, which were only 45% to 68% accurate. These results indicate that the proposed method improves the prediction outcomes significantly. It is evident that the proposed TS-based model can be used for future soil improvement projects to avoid unnecessary or inefficient grouting, which reduces the engineering cost.

Although the SVM does not provide a formula for \(N\), it is often considered to be a robust tool for predicting \(N\). Thus, a SVM was conducted, and its results were used to validate the results obtained from the TS-based models.

2. Existing Approaches

2.1 The Empirical Formulas

Several relationships between soil grain-size and cement grout particle size have been defined to build a groutability prediction formula. For example, Burwell (1985) proposed Eqs. (1) and (2) to predict the \(N\). Grouting only succeeds when \(N_1\) is greater than 25 and \(N_2\) is greater than 11. Krizek et al. (1992) proposed another similar approach; they suggested the identical equations (i.e., Eqs. (1) and (2)) but with different thresholds: grouting only succeeds if \(N_1\) is greater than 15 and \(N_2\) is greater than 8. Similar groutability rules for soils in field grouting were also observed (Huang et al., 2007). They used \(N_1 > 9\) or \(N_2 > 4\) as a criterion to predict the \(N\) when microfine cement (MFC-GM8000) was used for the sandy silt soils.

Incecik and Ceren (1995) proposed an alternate equation as follow:

\[
N_1 = \frac{(D_{25})_{soil}}{(d_{10})_{grout}} \tag{3}
\]