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ScienceDirect

Soils and Foundations 57 (2017) 384–396

www.elsevier.com/locate/sandf

A new prediction method for the rheological behavior of grout with bottom ash for jet grouting columns

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Received 18 December 2015; received in revised form 4 October 2016; accepted 4 February 2017
Available online 16 May 2017

Abstract

Among the many variables involved in jet grout technology, dealing with the complex phenomena of grout flow, specifically related to the pumping pressure (shear stress), the pumping rate (shear rate) and the viscosity, mostly becomes a difficult task for grouting in practice. Thus, this study presents the capability of a new methodology in soft computing techniques, called gene expression programming (GEP), to predict the rheological behavior (i.e., the shear stress versus the shear rate and the viscosity versus the shear rate) of grout with bottom ash for jet grouting columns, as an alternative approach to traditional methods. For this purpose, shear stress and viscosity formulas, including the main input variables of the shear rate and bottom ash proportion, are derived using GEP modeling through the stages of production and testing. Then, the performances of the GEP formulas are compared with the measured data and the regression and conventional rheological models (De Kee and Robertson-Stiff) for use in practice. The results indicate that the GEP formulas are able to yield estimations with good precision resulting in better predictions ($R \geq 0.96$) compared to the regression model. A successful description of the pseudoplastic response of rheological behavior is given, and a response consistent with conventional rheological models is obtained. Moreover, the measured data (shear stress and viscosity) generally follow the GEP modeling well, but the level of satisfaction is more favorable at high proportions of bottom ash. In conclusion, the study reveals that the derived GEP formulas are relatively promising for estimating the pumping pressure, the viscosity and the pumping rate of grout with bottom ash for jet grouting columns, at least in assisting conventional methods for preliminary designs.

Keywords: Jet grouting column; Grout; Bottom ash; Rheological behavior; Gene expression programming

1. Introduction

The jet grouting technique is one of the most popular ground-improvement methods that offers relatively good soil quality for the engineering characteristics (i.e., bearing capacity, settlement, permeability, etc.) in a variety of applications (i.e., foundation reinforcement, retaining structures, impermeable barriers, etc.) for solving possible ground problems. The resulting product is a cemented-soil body called the jet column appropriately arranged in the subsoil (Croce and Flora, 2000). In brief, in this technique (Fig. 1), the grout (cement-based fluid mixture) is injected into the ground at the treatment depth at a very high flow (200–400 L/min) with a very high velocity of energy through small-diameter injection nozzles (1–10 mm) placed on a grout pipe or rod. The jet grout propagates radially with respect to the treatment axis from the borehole at a constant rate of rotation due to the road speed by separating the soil particles. The particles are then mixed and cemented with the jet grout. Then, the rod is slowly withdrawn toward the ground surface resulting in a homogeneous mass of a high-strength soil-cement body

Peer review under responsibility of The Japanese Geotechnical Society.
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http://dx.doi.org/10.1016/j.sandf.2017.05.006
0038-0806/

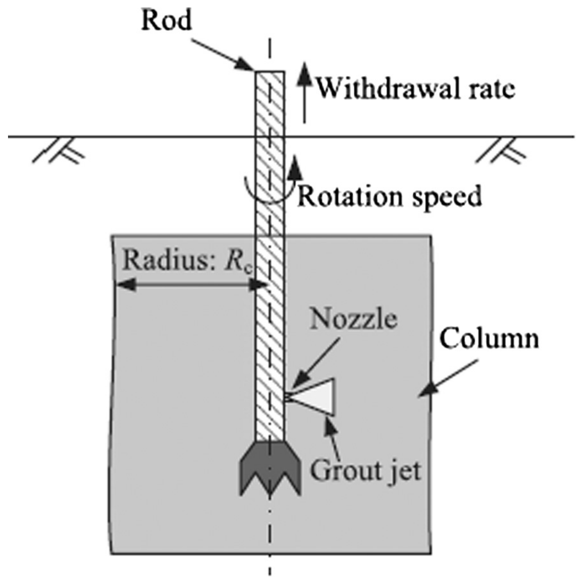

Fig. 1. Brief representation of jet grouting (Shen et al., 2013).

(jet column) due to the solidification of the injected cement-based grout (Croce and Flora, 2000; Modoni et al., 2006; Nikbakhtan et al., 2010). Most jet grouting applications have been based on the subjective rules of thumb firstly by means of trial and error at the site for jet grouting. The grout is ejected from the small nozzles with at very high speeds, but the experimental determination of the velocity mechanism is very difficult. Thus, at the design stage of the jet grout columns, there still appears a relative degree of uncertainty coming from the grout variables (the grout composition, binder content, particle size, particle shape, particle distribution, temperature, mixing, etc.) that play a significant role in grout rheology. The uncertainty during the injection process is also a major problem. Thus, it is necessary to adjust the operational injection parameters (Croce and Flora, 2000; Modoni et al., 2006, 2016; Ochmański et al., 2015; Ribeiro and Cardoso, 2016). Relevant to the velocity considerations of grout are the uncertainty related to the pumping pressure (shear stress), the pumping rate (shear rate) and the viscosity of the grout involved with rheological behavior (i.e., flow behavior) that significantly affect the hardened properties of the grout (Warner, 2004). This issue encourages engineers to develop more satisfactory design methods from the viewpoint of the prediction of rheological behavior in jet grouting.

In terms of jet-soil interaction, the jet-grout column can be reasonably considered through the typical features of the seepage and erosion. These features can be useful for modeling gravelly soils, and sandy and clayey soils, respectively (Modoni et al., 2006; Shen et al., 2013), where the rheology plays a significant role in their modeling. Through the mechanisms of jet grouting (Dabbagh et al., 2002) a bellshaped crater is formed at the soil-jet interface with a cutting front advancing at a progressively slower rate with the increased rate from the nozzle. For jet grouting of very pervious soils (gravels and sandy gravels), the seepage velocity is very large near the nozzle. However, it decreases sharply as the grout penetrates further into the soil (Modoni et al., 2006). From the viewpoint of grout rheology, it may be inferred that the injected flow propagates in the jet column under turbulent conditions in the inner region and under laminar conditions in the outer region. The diameter of jet grout column increases considerably with the soil permeability through the mechanism of seepage in the case of very pervious materials (i.e., gravelly soils). On the other hand, decreases in the column diameter obtained for sands and clays depends upon the shear strength of the soil. When the injected grout impacts the soils with lower permeability compared to gravel, the grout seepage is largely inhibited. Then, it turns back dragging the soil aside from its initial position through the erosion mechanism. This erosion mechanism of the flow results in the growth of the jet columns together with the replacement of the soil particles by the grout. The column diameter, involved with the flow behavior, can be simulated on the basis of the erosive action of the injected flow which depends upon the resistive action of the soil (Modoni et al., 2006, 2016). The extension of jet erosion for the jet grouting column results from the balance between the soil resistance and the jet cutting energy (Flora et al., 2013). It has been reported that the dependence of the column diameters for all soil types during the grouting process can generally be attributed to the parameters that include the diameter of the distance from the nozzle, the number of nozzles, the lifting speed of the monitor, the velocity along the cross-sectional profile, the kinematic viscosity of the grout and the flow rate of the grout or the fluid velocity (Modoni et al., 2006; Flora et al., 2013). Regarding clayey soils, jet grouting is found effective only when the performance is improved by high flow rates and low monitor withdrawal speeds. However, the increase in volume of the injected fluid for an appropriate flow rate could increase the amount of spoil. This results in a reduction in the economical efficiency of the ground improvement (Modoni et al., 2006). One of the existing methods for estimating the column diameter through the design stage of jet grouting is the empirical approach (Shen et al., 2013). In the proposed formulations for the empirical approach (Shibazaki, 2003; Mihalis et al., 2004), it is observed that the variables of jetting pressure and the flow rate of the grout play primary roles compared to the other variables (the number of passes of the jet, the velocity of the nozzle, the withdrawal rate of the rod) (Shen et al., 2013). It has been reported that any adverse effect due to the interactions with the variables during the jet grouting process may cause detrimental effects to the foundations of buildings or utilities as well as to the anticipated displacements in the subsoil and ground surface (Wang et al., 2013). When the jet grouting involves the injection of large volumes of grout that could need high pumping pressure, a considerable lateral movement of the soil with significant ground improvement can be expected. This could have a possible impact involving the hydraulic fracturing of the ground