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Prediction of the diameter of jet grouting columns with artificial neural networks

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Abstract

The prediction of the diameter of columns is a fundamental step for the design of jet grouting applications, as harmful consequences may derive from an inadequate selection of the treatment setup. Starting from different perspectives, empirical or theoretical correlations between the mean diameter of columns, the treatment parameters and the mechanical properties of native soils have been provided in the literature. However, the margin of uncertainty with these relations is still relatively large, mostly because of arbitrary assumptions made in their formulation. In order to reduce as much as possible the role of preliminary choices, a method based on artificial neural networks (ANN) is proposed. It consists in training a computer code with a set of experimental observations and in using the established correlations between input and output variables to predict future occurrences. After a brief introduction of the principles and limitations of ANN's, the paper describes the logical procedure followed for the selection of the variables which better describe the mechanism of columns formation. A database of more than 130 case studies, where jet grouting parameters, properties of soil and diameters are simultaneously reported, has been collected from the literature to train the network. Systematic analyses have been then performed, parametrically varying the structure of the network and the use of data, in order to improve the accuracy of prediction. The comparison with other methods recently published in the literature confirms the good predictive capability of the proposed method. For its practical application, a set of design charts has been produced where the mean diameters of columns are expressed, for all injection systems and soil types, as functions of the soil penetration index N_{SPT} and the specific energy of treatment. Safety factors have been finally computed to take into account the inaccuracy of prediction.

Keywords: Jet grouting; Columns diameter; Neuron; Training; Validation; Reliability

1. Introduction

The jet grouting is one of the most popular ground improvement methods, being adopted worldwide for the solution of various geotechnical problems (foundation, earth retaining, waterproofing etc.). The technique basically consists in cutting and mixing in place the soil with cement grout, ejected with high speed from small nozzles, in order to form sub-cylindrical columns of cemented material (Yahiro and Yoshida, 1973). Possible alternatives to the basic solution (named "single fluid" system), where only cement grout is injected, consist in protecting the action of the injected grout with a coaxial jet of air ("double fluid" system) or in using a coaxial jet of air and water to initially cut the soil and a second jet of grout to infer cementation ("triple fluid" system) (Croce et al., 2014). For a successful performance

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of the jet grouted structures, either when they are formed by arrays of isolated columns (e.g. Modoni and Bzówka, 2012) or when they consist of continuous elements made of partially overlapped columns (Croce and Modoni, 2005; Eramo et al., 2012; Arroyo et al., 2012), it is fundamental to control the diameter of columns by tuning the power of injection in relation to the properties of native soils. In fact, if diameters are smaller than expected, as it may descend from an erroneous choice of the treatment parameters, the jet grouted elements (single columns or panels, circular shafts, tunnel canopies made by overlapped columns etc.) may be too weak or discontinuous, and hence the integrity and functionality of the overall structures may be threatened (e.g. Maertens and Maekelberg, 2001; Croce and Modoni, 2002; Lignola et al., 2008).

In general, the diameter of columns, depends on the ability of the jet to propagate its cutting/erosive action at larger distances from the nozzle, which is determined by the combination between the energy given with the injection and the resistance of soil (Bergschneider and Walz, 2003). The first is a function of the composition of the injected fluids, number and diameter of nozzles, injection flow rate, retraction speed of the monitor, whereas the latter depends on the mechanisms activated at the jet soil interface and is thus governed by the composition and initial state of the surrounding soil (Dabbagh et al., 2002).

In the past, the columns dimension has been controlled with different strategies. Former relations (e.g. Miki and Nakanishi, 1984; Botto, 1985; Tornaghi, 1989; Bell, 1993; Covil and Skinner, 1994; Croce and Flora, 2000) considered the dependency of diameters on soils properties and/or treatment parameters starting from site observation. The main limitations of such empirical studies stem from the reduced number of cases available to build relations but, moreover, from a non systematic analysis of the mechanisms taking place during injection. As a result, subjective and incomplete choices of the relevant factors turned into formulations lacking of generality. To fill this gap, an alternative strategy was undertaken by Chu (2005), Modoni et al. (2006) and Ho (2007), who analysed the mechanisms taking place during the diffusion of submerged jets and at the impact between jet and soil to formulate mathematical relations describing these phenomena. These functions are the basic components of theoretical models used to predict the diameters produced by single fluid jet grouting in cohesive soils (Chu, 2005) or in gravelly, sandy or clayey materials (Modoni et al., 2006).

Borrowing the concepts of the Modoni et al. model, Shen et al. (2013) formulated a theoretical solution applicable to cohesionless and cohesive soils treated with single, double and triple fluid systems. In this formulation the diameter of column D is obtained adding to the diameter of the monitor (D_r) the double of the erosion distance effectively covered by the jet. The latter is computed as product between its ultimate value x_L, i.e. the distance which would be obtained for an unlimited action time of the jet, function of the soil properties and jet grouting parameters, and a reduction coefficient dependent on the injection time (η).

$$D = 2 \cdot \eta \cdot x_L + D_r \tag{1}$$

An alternative approach was proposed by Croce et al. (2011) who tried to reduce the mathematical complexity of the Modoni et al. model, which requires to iteratively integrate cascade equations, proving its equivalence with the following simpler power function:

$$D = A \cdot s^{\alpha} \cdot {E'_n}^{\beta} \tag{2}$$

where the diameter of columns (D) is related to the resistance of soil (s which is expressed by the undrained shear strength for cohesive materials, the product between vertical stress and tangent of friction angle for cohesionless soils) and to the specific energy at the nozzle E'_n. The latter, which represents the energy given per unit length of columns, has the advantage of grouping all the relevant treatment variables into a unique parameters expressed by the following relations:

$$E'_n = \frac{1}{2}\frac{m \cdot v_0^2}{L} = \frac{\pi}{8} \cdot \frac{M \cdot \rho \cdot d^2 \cdot {v_o}^3}{v_r} \tag{3}$$

where M and d represent respectively the number and diameter of nozzles, ρ the density of grout, v_o the exit velocity of the grout at the nozzle, v_r the retraction rate of the monitor. Croce and Flora (2000), wrote the following relation between the specific energy at the nozzle and the specific energy at the pump, considering a 10% loss in the injection plant:

$$E'_n \approx 0.9 \cdot E'_p \tag{4}$$

$E'_p = \frac{p \cdot Q}{v_r}$ where p' is the pressure at the pump and Q is the flow rate of the injected fluid.

The method was then extended to double and triple fluid systems by Flora et al. (2013) who proposed the following more complete equations:

$$D = D_{\text{ref}} \cdot \left(\frac{\alpha_E \cdot \Lambda^* \cdot E'_n}{7.5 \cdot 10}\right)^{\beta} \cdot \left(\frac{q_c}{1.5}\right)^{\delta}$$

$$\text{(for fine grained soils, } E'_n \text{ in MJ/m and } q_c \text{ in MPa)} \tag{5.a}$$

$$D = D_{\text{ref}} \cdot \left(\frac{\alpha_E \cdot \Lambda^* \cdot E'_n}{7.5 \cdot 10}\right)^{\beta} \cdot \left(\frac{N_{\text{SPT}}}{10}\right)^{\delta}$$

$$\text{(for coarse grained soils, with } E'_n \text{ in MJ/m)} \tag{5.b}$$

where q_c represents the unit tip resistance measured with Cone Penetration Tests (expressed with MPa) and N_{SPT} the blow counts number measured with Standard Penetration Tests. Λ^* depends on the cement–water ratio (Ω) by weight of the cutting fluid ($\Lambda^* = 7.5$ for $\Omega = 1$, 16 for water injected in the triple fluid system). The parameter α quantifies the effects of the shrouding air jet in double and triple fluid systems (it is equal to 1 for single fluid system, to 6 for double and triple fluid), the parameters β and δ are found by calibration with the data obtained from literature and from the personal experience of the authors ($\beta = 0.2$ and $\delta = -0.25$). Finally, the parameter E_{ref} quantifies the role of grain size composition of the original soil, being equal to 0.5, 0.8 and 1.0 for respectively fine grained soil, coarse grained soil with and without a significant amount of fine material.

The influence of the finer fraction on the resistance of soil to erosion is also acknowledged by Shen et al., who quantify the resistance to erosion of fine and coarse grained soils with