REVIEW

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A review of jet grouting practice and development

Pierre Guy Atangana Njock [1,2] · Jun Chen [1,2] · Giuseppe Modoni [3] · Arul Arulrajah [4] · Yong-Hyun Kim [5]

Abstract

The jet grouting technique was originally initiated in the UK and progressively developed following the needs for larger geometries, ease of implementation, economic rationality, and better mechanical properties. This paper presents a comprehensive review of the development and practice of jet grouting through some fundamental concepts and relevant case studies. Subsequently, a laboratory testing program is performed to investigate the factors affecting the efficacy of the twin grouting system. The principal objective of this study is to define the suitable conditions for the jet grouting efficacy regarding economic rationality as well as quality control. For the first phase, a particular emphasis is placed on the properties of jet columns, site geological conditions, implementation methods, and the justification of each selected treatment option, while the second phase mainly focuses on the unconfined compressive strength (UCS) tests. It follows that the mono-fluid jet grouting system presents a valuable flexibility in dealing with complex configurations; yet, the double- and triple-fluid systems are more indicated for cases of mass treatments for which large portions of space must be treated and overlapping is fundamentally important for the reliability of the treatment. Furthermore, it was established that the efficacy of the twin-jet method primarily relies on the proper adequacy of some critical parameters, namely, the cement content, the water-cement ratio, and cement slurry-water glass ratio. In spite of some uncertainties inherently related to the technique, the UCS test represents the quintessential laboratory index for evaluating the mechanical properties of grouted elements, deriving jet grouting efficacy and the economics of jet grouts.

Keywords Jet grouting · Unconfined compressive strength · Diameter prediction · Twin-jet · Remediation method

Introduction

Jet grouting has generated considerable recent research interest in the realm of geotechnical engineering. It is a soil consolidation technique that has been adopted extensively worldwide (Shibazaki 1996; Shen et al. 2012a, b; Yoshida 2012; Wang et al. 2013a), for a wide variety of applications including foundation reinforcement (Modoni and Bzòwka 2012),

construction of excavation waterproof barriers and slabs (Xu et al. 2014, 2017; Wu et al. 2015a, b, c, 2017; Zhang et al. 2015; Tan et al. 2016; Tan and Lu 2017a, b; Tan et al. 2017), prevention of short- and long-term ground movements (Chai et al. 2004, 2018; Shen and Xu 2011; Yin et al. 2011a, 2013a, 2014a; Shen et al. 2014b; Xu et al. 2012a, b, 2016), and protection against ground dewatering effects (Ma et al. 2014; Shen et al. 2013d, 2015a, b, 2017b; Wu et al. 2015d),

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as well as solidification of contaminated soils (Du et al. 2012, 2014a, b). The method consists of creating in situ rigid elements using a jet of fluid with high kinetic energy to disaggregate the soil and mix it with cement slurry. The earliest milestone of this high-pressure grouting technique dates back to the 1950s in the UK, with specialized applications in the oil industry (Essler and Yoshida 2004), though it is officially patented in Japan as Chemical Churning Pile (CCP) in the late 1960s (Yahiro and Yoshida 1973; Miki 1973). In its crudest form, the jet grouting technique was exclusively executed using chemicals; however, due to several concerns relating to the environment, the chemical binders used in CCP method were almost immediately deputized for cement grouts. Since then, the jet grouting technique has gradually become popular around the world and coupled with new technological breakthroughs (still ongoing), new variations have emerged (Xanthakos et al. 1994; Croce et al. 2014a; Shen et al. 2014b).

The field applications of jet grouting extend to a relatively wide range of soils. It is generally acknowledged that acceptable soil properties are achievable by grouted columns (Guatteri et al. 1988; Shen et al. 2009b, 2013a), with the resistance and the final geometry influenced by the jet grouting variation and the type of soil. However, different jet grouting variations exhibit different effects and characteristics, depending on the strata within which they are implemented. For instance, investigating the impact of single-fluid jet grouting on flow deposits, Croce and Flora (1998) established that the jet action declines with the implementation depth and the occurrence of thin layers of naturally cemented soil substantially affects the geometry of the grouted element. Following this, additional effects associated with the construction sequencing and the variables influencing the treatment result were also pointed out by Croce and Flora (2000) and Shen et al. (2017a). As well, the uncertainties related to the strength variability of grouted bodies (raised by the jet grouting routine) have been attracting many scholars' interest in the recent years (Coulter and Martin 2006; Modoni and Bzòwka 2012; Wanik et al. 2017; Toraldo et al. 2017). Hence, there is room for reappraising and comprehending the parameters that underpin the performance of the jet grouting systems. A better understanding of the aforementioned jet grouting variations is in fact crucial for jet grouting design, especially, regarding the diameter of jet-grouted columns (Croce and Flora 2000; Modoni et al. 2006; Wang et al. 2012; Flora et al. 2013; Shen et al. 2013b; Ochmański et al. 2015a; Ribeiro and Cardoso 2017) and their mechanical properties. Besides, an idea on the final geometry and properties of grouted elements is not only vital for defining their effects in the soil, but also, to some extent, for reducing the construction costs.

Moreover, while it is true that the jet grouting method is advantageously versatile (Lunardi 1997; Burke 2004; Dhouib et al. 2004), its economical usage may be jeopardized as a result of the lack of awareness regarding jet grouting systems and or the deficiencies in the implementation. Indeed for some projects, it is essential to precisely define the most suitable jet grouting technology to be executed for given situations or geological conditions. Furthermore, the determination of the quantities to be implemented represents another major hindrance to the viability of jet grouting. The latter was found to have a substantial impact on the quality of the jet grouting treatment (Celma and Carrión 2003; Tornaghi and Pettinaroli 2004; Ni and Cheng 2014). This issue is particularly relevant for the twin-jet grouting method due to the complexity of its mechanism (Shen et al. 2009a, 2013c). It is therefore believed that the consideration (determination of optimal quantities, and the comprehensive description of the suitable conditions for each system) of the abovementioned attributes of jet grouting profitability will substantially contribute enhancing the efficacy in jet grouting practice.

This paper presents the state-of-the-art practice of the jet grouting technology by reviewing some comprehensive studies and projects selected from around the world that have focused on the application of jet grouting methods to solve various geotechnical issues. The purpose behind this approach is, on one hand, to demonstrate the efficacy of jet grouting technology in geotechnical engineering and, on the other hand, highlight both the suitable conditions for implementing each technological solution and the critical parameters for the design and modeling of jet grouting. This review work is organized around seven sections including the following: (1) the general overview of the jet grouting method and the issues related to its implementation, (2) the different features associated with the jet grouting technology, (3) the historical development of the technique and experiences from around the world, (4) some typical case histories of jet grouting practice, (5) an experimental study addressing the issue of optimum material quantities and aimed at improving the efficacy of the twin-jet grouting, (6) a brief summary of jet grouting practice and development, as well as a discussion on future developments, and (7) concluding remarks are provided at the end of the paper.

Jet grouting technology

Basic concepts of jet grouting

The jet grouting process involves the erosion of the in situ soil, by a jet of fluid projected at very high velocity from a small diameter nozzle mounted at a monitor (Fig. 1). The eroded soil is then mixed with a fluid (generally cement slurry) to form a mixture, which after hardening is called grout element. However, to efficiently implement this technique, it is imperative to carefully arrange the jet grouting equipment and methodically execute the process.
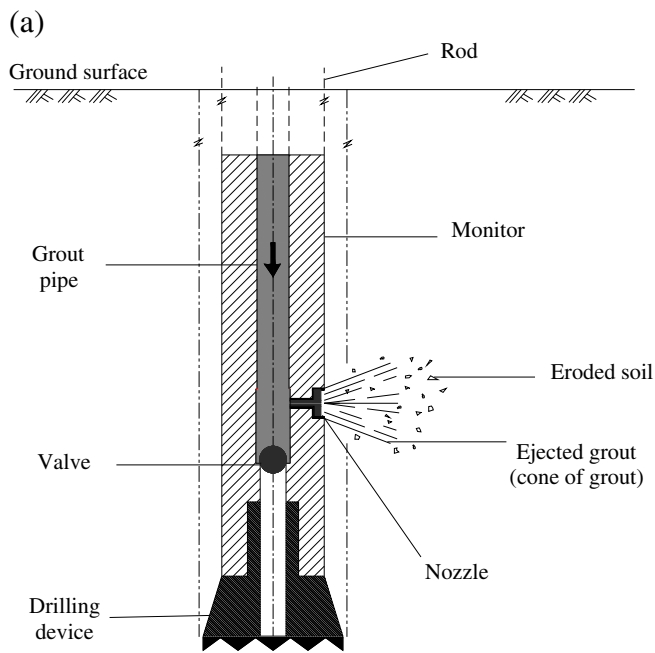
Fig. 1 **a** Schematic illustration of the jetting mechanism in the monitor (mono-fluid system). **b** Photograph of a monitor used for jet grouting

In practice, the grouted elements are executed vertically or in any inclination, including sub-horizontal columns which are commonly used as a solution for tunneling problems. Either for vertical or for sub-horizontal implementations, the equipment required to achieve the construction of grouted elements commonly include drilling and jetting devices (Xanthakos et al. 1994; Croce et al. 2014a). The drilling system consists of one or three inner pipes (depending on the jet grouting variation) arranged inside a rod, which is connected to a drilling device at its lower end. The role of the drilling device is to promote the creation of the borehole, even under challenging conditions (geotechnical profile). Besides, the jetting system mainly refers to a monitor on which one or more small diameter nozzles (depending on the jet grouting variation) are ordinarily installed. The objective of the nozzle is mainly to convert the fluid which is inside the pipe into a conical stream of fluid at high speed.

Subsequently, a precise methodological approach has to be adopted to achieve an efficient jet grouting treatment (Fig. 2). Firstly, a borehole is created up to the targeted depth by the drill stem (a). Yet, to avoid disturbances in the surrounding throughout the jet grouting treatment, the borehole must be sufficiently large to ensure the spoil backflow (Croce et al. 2004; Shen et al. 2012c; Wang et al. 2013b, 2014; Atangana et al. 2018). In the second step, the cement slurry is injected and mixed with the eroded soil, along with the slow and rotational ascent of the drill stem (b). The procedure ends with the complete removal of the drill stem from the borehole (c). Nonetheless, for some applications, the jet grout columns are frequently overlapped (d).

Traditional jet grouting variations

Based on the number of injected fluids and the injection method, the jet grouting technique can be classified into three major categories: the mono-fluid system, the bi-fluid system, and the tri-fluid system.

The mono-fluid system relies on the individual action of high-pressure jet of grout to erode and mix soil, which makes this technique relatively simple. In this case, an essential part of the jet energy is dissipated, owing to friction and viscosity effects within the soil mass subjected to the action of the fluid. The second system however corresponds to the coordinated injection of compressed air shrouding a cone of grout at high velocity. The shrouded air significantly enhances the eroding effect of the jet (since it considerably reduces the previously mentioned exchanges of mass and energy) and therefore increases the cutting efficiency of the jet with respect to the distance from the injection point (Burke 2004). In the tri-fluid system, the soil is eroded by means of water jet shrouded by compressed air at high speed, and the quantity of grout required for the mixing is subsequently injected from a separate nozzle located beneath the former (air-water nozzle).

Cemented soil elements of different geometries and dimensions are normally achievable with these systems: (i) with a full rotation of the monitor, a quasi-cylindrical shape element is produced; (ii) when the drill rotates partially, segments of a cylinder or elements in the form of "pizza slides" can be obtained; (iii) also, without any rotation of the monitor, the construction of linear elements of various thicknesses can be achieved (e.g., cutoff walls). In some situations, the
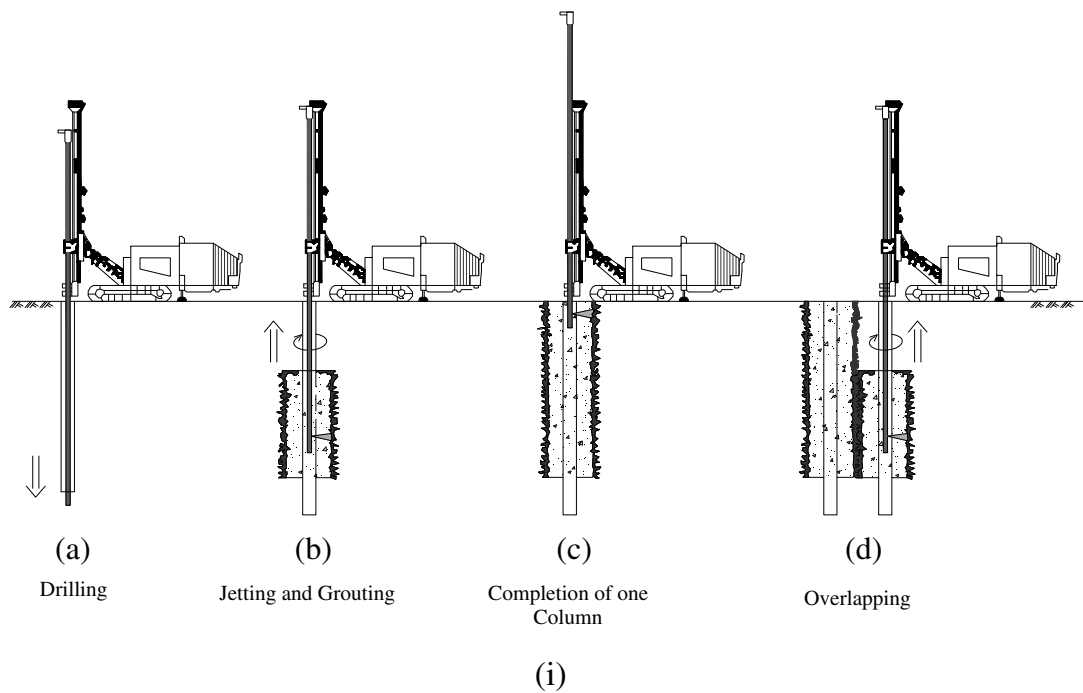
Fig. 2 **i** Illustration of the jet grouting procedure. **ii** Photograph of field implementation of jet grouting (source: http://www.chemicalgrout.co.jp/en/). **iii** Photograph of overlapped jet columns in sandy soil obtained from field trials (source: http://www.kftco.com/)

characteristics of grouted elements obtained with these variations are generally acceptable. Yet, a number of parameters have to be considered when reviewing the performance of jet grouting systems.

Fundamental features of jet grouting design

The jet grouting technique has the advantage of being very versatile, as it can be operated in all types of soils (Yin et al. 2010, 2011b, 2013b, 2014b, 2016a, b, 2017, 2018a, b). To a large extent, the performance of jet grouting systems depends on their capacity to provide grouted elements with adequate geometries, good mixing uniformity, and satisfactory strength characteristics. Ensuring the performance of jet grouting treatments thus imply, beforehand, the achievement of a suitable jet grouting design.

Diameter of jet grout columns

The diameter of the column can be defined as the maximum distance achievable by the erosive action of the injected fluid in the soil. As such, it is principally governed by the injection parameters (jetting energy) and the soil erodibility. The former is not only function of the injected fluid properties, but also

depends on parameters such as the fluid pressure, the injection flow rate, and the withdrawal speed of the monitor, as well as the number, shape, and diameter of the nozzles (Shibazaki 2003; Arson and Juge 2012). On the other side, the soil susceptibility to fluid erosion also plays a decisive role in the production of grouted columns: cohesive soils are typically less erodible by high-velocity fluid streams than cohesionless soils (Shibazaki 2003; Brill et al. 2003; Burke 2004; Shen et al. 2009b). For instance, as illustrated in Fig. 3, different soils exhibit different erodibility characteristics, appreciable in this case through the expected column diameters. With the mono-fluid system, for example, the cutting efficiency of the jet tends to be more effective for sands than other types of soils. The variation of the diameter of grout columns tends to decrease as the soil particles gain cohesion. Henceforth, it is clear that the jet grouting column diameter can be controlled by regulating the injection power with respect to the native soil properties.

However, in practice, controlling the diameter of jet grouting columns appears to be a formidable task, given the complexity of the construction process, and so, field trials are as rule required for tuning the treatment parameters. The arbitrary nature of this approach has notably triggered the development of various approaches for predicting of column diameter. This aspect is discussed in detail in "Prediction of jet grouting column diameter."

Mixing uniformity

Generally speaking, the influence of soil typology is also valid for the uniformity of the mixture. But, given the complexity of the mixing mechanism carried out in the ground during the jet grouting process (e.g., infiltration of the injected fluid through the inter-particle spaces), the evaluation of mixing uniformity is merely based upon visual observations. Grouted elements
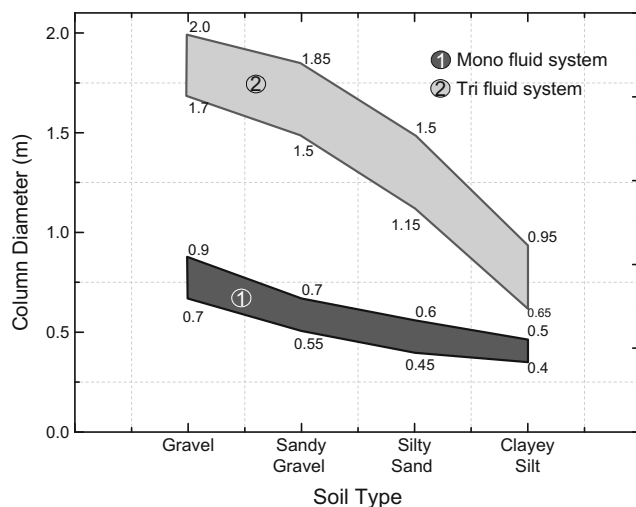
Fig. 3 Variation of column diameter with soil type for mono-fluid and tri-fluid systems (recreated after Morey and Bachy 1992)

are relatively more uniform in clayey soils than granular soils. As discussed later in this paper ("Field trial tests: application of RJP in Shanghai"), good mixing uniformity can ensure advantageous mechanical properties.

Strength and deformation properties of jet-grouted bodies

The strength and deformability characteristics of grouted elements play a decisive role in the design of jet-grouted structures, as they defined their performance at the service ability stage. In reality, the behavior of hardened jet grouting bodies can be assimilated to that of cement concrete, as for both, the stress-strain relationship is characterized by non-linear elastic responses followed by brittle failure. However, laboratory investigations on cement-treated sand revealed that the overall failure of the treated body does not directly stem from the initiation of partial failures, so that the partial failure can definitely be adopted in the ultimate limit state design of jet grouting in sandy soils (Namikaya and Koseki 2007; Jin et al. 2017, 2018a, b). Furthermore, given the aforementioned behavior characteristics of jet-grouted bodies, a linear elastoplastic model (e.g., Mohr-Coulomb failure criterion) is in practice sufficient to express the strength of these cemented elements, and yet, these deformation characteristics, as well as the strength parameters of jet-grouted materials, can be readily approximated using traditional testing methods. Following this logic, Gladkov et al. (2011) demonstrated the clear correlation existing between the cement consumption and the deformation modulus of jet-grouted bodies, which in turn can be correlated with the compressive strength of the cemented bodies using the relationship given in Eq. 1 (Modoni and Bzòwka 2012). The correlation coefficient β used in this equation is generally taken within the range of 300–400; σ_c and E_c are respectively the strength and the Young modulus obtained from the uniaxial compression test. Similarly, Wanik et al. (2017) proposed the following chart (Fig. 4) for a direct assessment of the unconfined compressive strength (UCS) of jet grout elements.

$$E_c = \beta \ \sigma_c \qquad (1)$$

Even though numerous studies and field applications (reported in "Case histories of the practice of jet grouting") have established that the jet grouting technique can guarantee grouted elements with satisfactory strengths and stiffness, still, the reliability of the jet grouting technique is strongly influenced by uncertainties related to the strength variability of the grouted bodies (Toraldo et al. 2017). These uncertainties are commonly associated with the jet grouting implementation conditions, including the composition of the jet grout, type of soils, and curing time. To illustrate this aspect, Modoni and Bzòwka (2012) and Toraldo et al. (2017) investigated
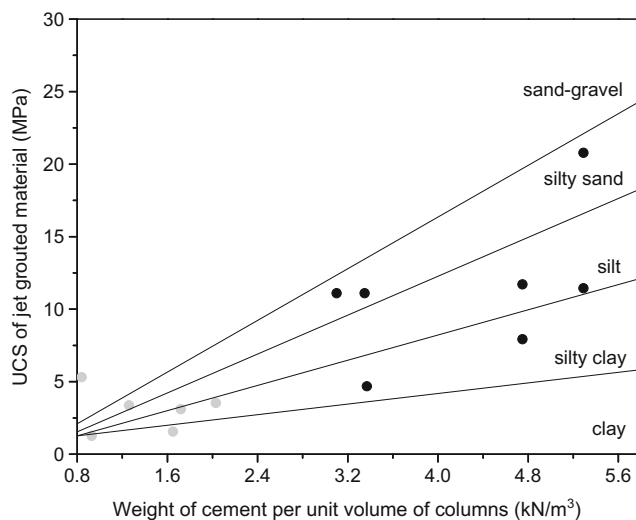
Fig. 4 Relationship between the strength of jet-grouted materials, the soil properties, and the quantity of injected cement (recreated after Wanik et al. 2017)

strength data collected from various literatures and found unusual disparities for soils having minor variations in their compositions, as well as apparent discrepancy of strength parameters for similar soils. It comes that consecutive columns constructed within the same soil may yield different strength and deformation properties. An evident conclusion is therefore that irrespective of the soil type, the jet grouting method produces completely different materials with random strength.

Given the relevance of strength variability as a hurdle to the reliability of jet grouting at the design stage, specific strategies must be envisaged. A possible alternative could be to link the timing and sequencing of the construction to the strength and deformability characteristics of the mixture (Coulter and Martin 2006). In particular, for the cases of mass treatment (e.g., the creation of jet grouting canopies; also see "Linear treatment: construction of the *Hurtiere* tunnel (Rhone-Alpes, France)"), an adequate curing time must be observed between the installations of two consecutive columns to ensure a specific mechanical performance, particularly, given that the hardness of the grouted bodies is quasi-linearly dependent on the curing time (Yao et al. 2008a, b; Yao et al. 2009; Yao and Zhou 2013; Wang et al. 2015, 2018; Liu et al. 2018).

In summary, the performance of high-pressure grouting systems involves a number of parameters that are intrinsically characterized by complex interactions. Furthermore, the complexity of the mechanism associated with the creation of jet-grouted columns is not only the origin of diameter and strength variabilities, but also that of uncertainties related to the prediction of the column diameter.

Prediction of jet grouting column diameter

As previously mentioned, the performance of jet grouting structures is strongly dependent upon the mechanical

properties and diameter of jet columns. Nonetheless, in some cases, the grouted structures tend to perform unreliably as a result of poor mechanical properties and or construction imperfections (untreated zones) among adjacent columns. Although the deviation of the drill during the execution process can account as a reason of these defects, the principal cause remains the geometry variability (Morey and Campo 1999; Wu et al. 2018). Indeed, it is well acknowledged that an efficient treatment is achieved when a beneficial compromise is found between the injection parameters and the properties of the soil, which task is rather difficult. Several studies have thus looked into this question and attempted providing a reliable base for the prediction of jet grouting column diameters. The available methods can be grouped into two categories, the first including the empirical, conceptual, theoretical, and semi-theoretical models (Table 1), and the second regrouping the models based on advanced statistics analysis also known as data mining (DM) approach. A recent paper by Ribeiro and Cardoso (2017) proposes a review of the models constituting this first category. The latter however does not include the approaches based in supervised DM algorithms and only focused on the injection mechanism to explain the correlation between final geometry and equipment used. Hence, this part in addition shed a light on the prominent variables in the prediction of geometrical and mechanical properties of jet grout columns, determined via using the DM approach.

In the first category, the empirical models are those established on the basis of various jet grouting implementation schemes, defined with respect to the injection settings, jet grouting systems, and type of soils. As such, the analytical formulas that characterize these models are derived from the observed behavior of grouted elements and the connectivity between these parameters. However, a problem related to these models is that they cannot be extrapolated or extended to new problem evolutions. This limitation stems principally from the reduced amount of field data used for building these models. In contrast, the conceptual models are adjustable correlations that integrate both the conditions of mass and energy exchanges and the volumes involved in the production of a column. Still, a major shortfall related to these models is that the described phenomena lack a strong theoretical meaning. The theoretical and semi-theoretical models are therefore more suitable approaches, as they are based on verified laws and notions that can describe the fluid-soil interaction mechanism (Ho 2007; Modoni et al. 2006).

On the other hand, owing to their flexibility and high learning capabilities, the support vector machines (SVMs), artificial neural networks (ANNs), and multiple regression analysis (MR) are the commonly used DM algorithms. These methods are clearly efficient in dealing with the high dimensionality of problems encountered in geotechnical engineering (Tinoco et

Table 1 Some available models for the prediction of jet grouting column diameter (modified after Ribeiro and Cardoso 2017)

Categories	Models	Applications	Comments
Empirical	Covil and Skinner (1994)	Single- and double-fluid	More indicated for pre-designing purposes
Conceptual	Mosiici (1994)	–	Adapted for the assessment of geometry and quality
	Croce and Flora (2000)		
	Arson and Juge (2012)	Single-fluid	
Theoretical	Modoni et al. (2006)	Single-fluid	• Relatively straightforward
	Wang et al. (2012)		• Advantageous in modeling and predicting column diameters
	Shen et al. (2013b)	Single-, double-, and triple-fluid	
Semi-theoretical	Flora et al. (2013)	Single-, double-, and triple-fluid	
Artificial intelligence	Tinoco et al. (2016); Ochmański et al. (2015a)	Single-, double-, and triple-fluid	Efficient in describing relationships among the jet grouting variables as well as their effects
	Tinoco et al. 2014	UCS	

al. 2011, 2014, 2016; Ochmański et al. 2015a; Xu et al. 2018). Basically, these nonlinear statistical data modeling tools attempt to explain complex relationships among a system's variables (inputs and outputs) via training it with an appropriate data set. Ultimately, these relationships are used to predict the future occurrences of a given phenomenon. Yet, for achieving this purpose, several steps are usually necessary. In the first step (model selection), the parameter settings of the algorithm are suitably selected. Subsequently, specific metrics are used to assess the model accuracy as well as its predictive capacity; this step is referred to as model assessment and performance. The final step of this procedure is the model interpretability, which consists of extracting relevant knowledges from the trained model. Indeed, one of the main limitations of the DM algorithms is their inability to facilely provide interpretable outputs, which drawback can be compensated via operating a sensitivity analysis (SA) after the training phase (Cortez and Embrechts 2013).

Models based on artificial neural network

The models based on ANN were proposed by Ochmański et al. (2015a) and Tinoco et al. (2016) to overcome some limitations of the theoretical methods (Shen et al. 2013b; Flora et al. 2013; Modoni et al. 2006), such as their practicability or the arbitrariness of assumptions considered in certain situations (prediction of large columns). A detailed presentation of ANN approach and some practical case studies can be found in Haykin (1998).

Model selection In the proposed models (Ochmański et al. 2015a; Tinoco et al. 2016), a feed-forward ANN with a connected multilayer perceptron involving one hidden layer is considered given the inherent independence between the variables involved (inputs). Tinoco et al. (2016) even suggest a hidden layer with H processing units, multiple bias connections, and logistic activation functions $1/(1 + e^{(-x)})$.

Furthermore, the selection of the input variables is achieved with regard to previous literatures and the mechanism involves in the creation of jet columns, i.e., considering the injection parameters and the soil properties, as discussed earlier in "Diameter of jet grout columns." As a matter of illustration, Fig. 5 shows the ANN structure adopted by Ochmański et al. (2015a), where the four variables (labeled (1) to (4)) composing the input layer can be readily discerned.

At this stage, to optimize the learning ability of the network and thus the performance of the model, a sufficient number of observation data are processed during the training phase (Ochmański et al. 2015a; Tinoco et al. 2016).

Model assessment and performance For assessing the prediction quality of the trained network, two approaches can be considered: (i) the first method (Ochmański et al. 2015a) involves evaluating the predictive ability of the model using the mean square error (MSE) (defined in Eq. 2) and quantified its reliability via using the mean absolute percentage error (MAPE), which have the advantage (over the MSE) of giving an approximation of the average percentage error achieved by the network (see Eq. 3).

$$MSE = \frac{1}{n} \sum_{i=1}^{n} \left(D_{i\_predicted} - D_{i\_measured} \right)^2 \quad (m^2) \quad (2)$$

$$MAPE = \frac{100}{n} \sum_{n} \frac{\left| D_{i\_predicted} - D_{i\_measured} \right|}{D_{i\_measured}} \quad (\%) \quad (3)$$

(ii) The second approach suggested by Tinoco et al. (2016) consists of adopting the three metrics frequently used for regression analysis, namely, the mean absolute deviation (MAD), root mean square error (RMSE), and the square correlation coefficient (R^2) given respectively by the following Eqs. 4, 5, and 6. In this case, the high predictive capacity of the model is achieved for low values of MAD and RMSE, as well as for values of R^2 close to the value unity. For instance, the model proposed by Tinoco et al. (2016) yielded a high
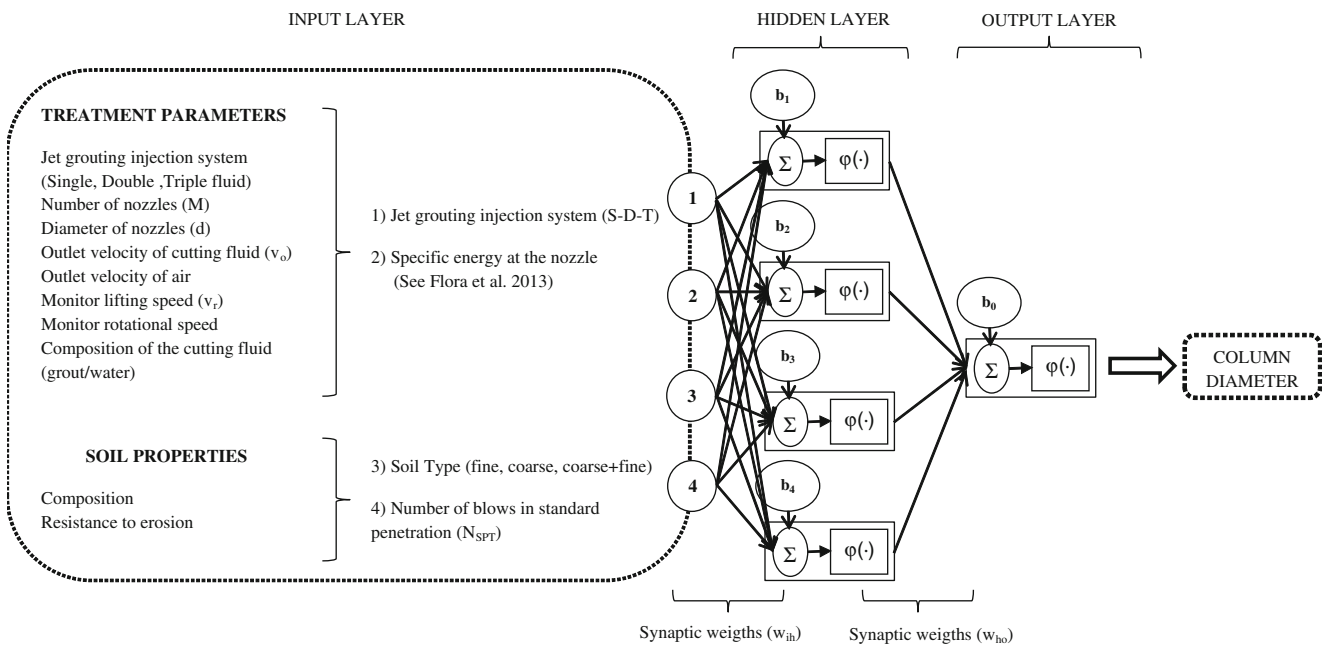
Fig. 5 Structure of the ANN-based model (recreated after Ochmański et al. 2015a)

predictive capacity with $R^2 = 1$. Interestingly, the desired accuracy once achieved, it is necessary to extract the fundamental knowledges among the model variables.

$$MAD = \frac{\sum\limits_{i=1}^{N} |y_k - \hat{y}_k|}{N} \qquad (4)$$

$$RMSE = \sqrt{\frac{\sum\limits_{i=1}^{N} (y_k - \hat{y}_k)^2}{N}} \qquad (5)$$

$$R^2 = \left(\frac{\sum\limits_{i=1}^{N} \left(y_k - \overline{y}_k\right) \cdot \left(\hat{y}_k - \overline{\hat{y}}_k\right)}{\sqrt{\sum\limits_{i=1}^{N} \left(y_k - \overline{y}_k\right)^2 \cdot \sum\limits_{i=1}^{N} \left(\hat{y}_k - \overline{\hat{y}}_k\right)^2}} \right)^2 \qquad (6)$$

Model interpretability This step is very crucial as it allows measuring the model responses along with the variation of inputs to discretely quantify their importance and effects on the target variable. Tinoco et al. (2016) proposed using one-dimensional SA (1-D) and two-dimensional SA (2-D). The first is used for ranging the importance of the different input variables, whereas the 2-D is performed on the "important" variables to evaluate their effects.

Following this approach, it was found that the withdrawal rate of the rod, the flow rate of the cement slurry, and the jet grouting system respectively are the most prominent factor affecting the diameter of jet-grouted column (Tinoco et al. 2016). In addition, it was found that the decrease in the clay

fraction of the soil has a significant effect on the diameter of jet column. These results are in good agreement with Ochmański et al. (2015a) that observed the reducing effect of high finer material content on the diameter of jet grouting columns, as well as the beneficial role of high energies against soil resistance.

Models based on support vector machines

The suitability to the support vector machine (SVM) algorithm to the field of geotechnical engineering relies principally on its capability to reliably carry out prediction in multiple regression tasks and classification (Cortes and Vapnik 1995). This section discusses the SVM-based approach proposed by Tinoco et al. (2014, 2016) respectively for predicting the uni-axial compressive strength (UCS) and the diameter of jet grouting columns. However, since the procedures of "model assessment and performance" and "model interpretability" discussed in the previous section are also applicable to the SVM-based models, this section simply presents the SVM approach for "model selection." Moreover, as the data used and the approach adopted by Tinoco et al. (2016) for the prediction of column diameter using ANN and SVM are rather identical, this section puts more emphasis on the SVM-based UCS prediction (Tinoco et al. 2014).

To improve the learning efficiency of the algorithm, Tinoco et al. (2014, 2016) propose using the Gaussian kernel function defined by Eq. 7 and adopting the following "hyperparameters" adjusted considering the heuristics suggested by Cherkassky and Ma (2004): penalty parameter

$C = 3$ (as a standardized output was considered), width of a ϵ-intensive zone $\epsilon = \hat{\sigma}/\sqrt{N}$ (where $\hat{\sigma} = 1.5/N \cdot \sum_{i=1}^{N}(y_i - \hat{y}_i)^2$), and the kernel parameter γ was appropriately optimized.

$$k\left(x, x^{'}\right) = \exp\left(-\gamma \cdot \|x - x^{'}\|^2\right), \quad \gamma > 0 \qquad (7)$$

Regarding the prediction of jet grout column for example (Tinoco et al. 2016), the proposed model achieved a satisfactory accuracy level with $R^2 = 1$. On the contrary, rather low accuracy results ($R^2 = 0.51$) were obtained for the prediction of UCS of jet columns (Tinoco et al. 2014). Nevertheless, Tinoco et al. (2014) contented that the applicability of the proposed model is an important step towards the assessment of UCS in jet grouting and even implemented a sensitivity analysis to interpret the output data. It was found that the mixture porosity and volumetric content of cement, the jet grouting system, the mixture curing time, and the percentage of clay are the prominent variables in the prediction of UCS of jet-grouted elements. Ultimately, it was demonstrated that the curing time has the greatest influence on UCS of jet columns when the latter is constructed with the single-jet system. This again emphasizes the importance of jet grouting modeling.

Jet grouting modeling

A proper modeling of the phenomena associated with jet grouting treatments is crucial as it can ensure a reliable prediction of their effects on and or around the constructed structures. Two approaches are commonly used for achieving these purposes: analytical and numerical methods.

Analytical modeling

This mathematical modeling technique aimed at explaining and making predictions about the mechanisms involved in jet grouting. Its implementation has mainly focused on the prediction of the jet grout column diameter on one hand and the effect of high-pressure jet on the surrounding soil on the other hand. In point of fact, these two phenomena can account as the most critical in jet grouting practice from a technical viewpoint. For deriving the equations of jet grout column diameter (theoretical and semi-theoretical models discussed in the previous section), the modeling has been established on the concept of turbulent submerged free jet illustrated in Fig. 6. This theory attempts to describe the phenomenon of a fluid jet penetrating a quiescent body (in this case a soil mass). It is assumed that the radius of the jet is proportional to the downstream distance from the injection point, and also that the velocity decreases linearly with the distance from the discharge location. This decline can be ascribed to the reduction of jet energy and the resistance offered by the sol: the jet velocity is altered by tangential stresses that developed along
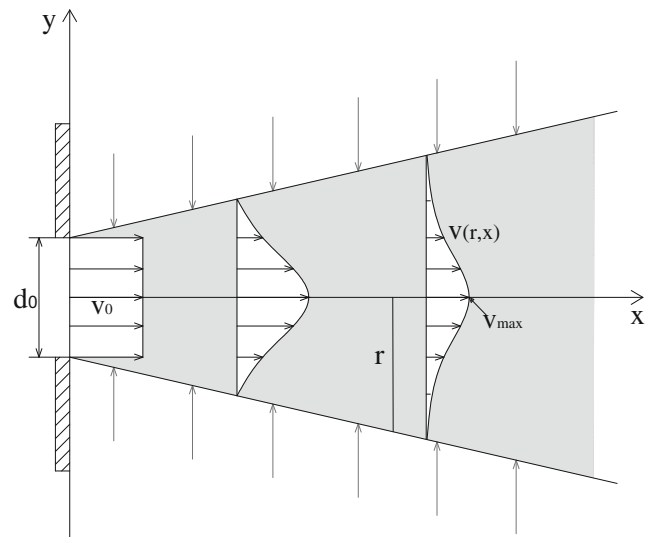

Fig. 6 Illustration of the turbulent submerged free jet concept (recreated after Abramovich 1963)

the fluid edges. Since the jet velocity conforms to the conditions of momentum conservation and the law of similarity, it is entirely legitimate to have Eq. 8 (Ho 2007). In this equation, v_0 represents the exit velocity, and $v(x,r)$ is the velocity at a given downstream distance x from the injection point (Eq. 9). The significance of this theory for assessing the diameter of jet grout column is simply that it allows approximating the maximum velocity and distance of a jet in a soil mass, as well as the excavated volumes. More details about this theory can be found in a paper by Ho (2007).

$$\frac{v_{\max}}{v_0} = \frac{x_0}{x} \qquad (8)$$

$$v(x, r) = v_{\max} \exp\left[-\frac{1}{2}\frac{r^2}{r_i^2}\right] \qquad (9)$$

where r represents the cross-jet radial distance from the centerline, r_i is the radial distance at any point of the exponential curve, and $v_{\max}$ is the maximum velocity at the centerline.

Moreover, for predicting the effect of high-pressure jet on the surrounding soil, the analytical modeling approaches adopted by various literatures (Chai et al. 2005, 2009; Wang et al. 2013b; Wu et al. 2016a, b; Liu et al. 2017; Shen et al. 2017a) nearly unanimously involved another important concept: the cavity expansion theory. Fundamentally, the theory of soil cavity expansion tries to elucidate the behavior of a cavity in a geomaterial submitted to an expansion in the surrounding mass (see Fig. 7). The Vesic (1972) approach is the most widely used method, as it allows the consideration of volume variations in the plastic range for elastic-plastic soil constitutive models. In this approach, the soil mass is assumed homogeneous under isotropic effective stress. The soil behavior in the elastic zone is defined by its Poisson's ratio υ and
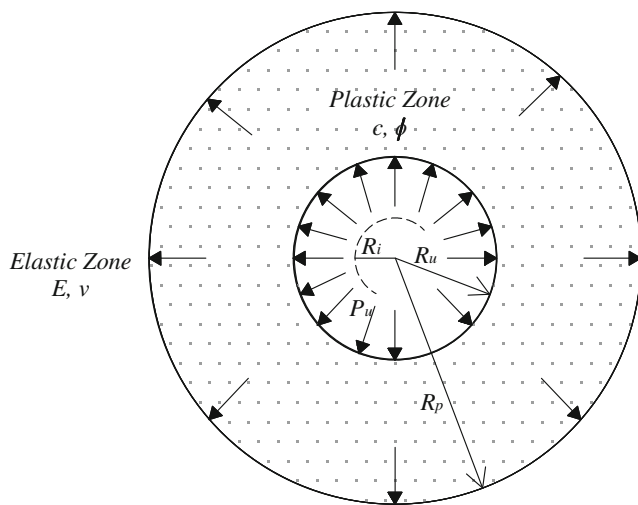
Fig. 7 Illustration of the Vesic model for cavity expansion (recreated after Vesic 1972)

Young's modulus E, whereas in the plastic range, it is characterized by the Mohr-Coulomb parameters. It is also supposed that as the cavity expands under uniform pressure, the surrounding medium goes into the plastic range. The limits of this plastic range are defined by the radius R_u (corresponding to a pressure P_u) and R_p (beyond which corresponds the plastic zone). If the radius R_u is known, R_p can be calculated using the following relationship Eq. 10. The cavity pressure P_u in Eq. 11 is obtained from the bearing capacity theory (Chai et al. 2005).

$$\frac{R_p}{R_u} = \sqrt{I_{rr}\sec\varphi} \tag{10}$$

$$P_u = cN_c + qN_q \tag{11}$$

In the above formulas, I_{rr} is the reduced rigidity index; ϕ is the internal friction angle, c is the cohesion, and q is the initial mean normal stress. N_c and N_q are called bearing capacity factors.

Numerical modeling

This approach is increasingly adopted for explaining the mechanisms associated with jet grouting. Its applications include the analysis of submerged flow (Modoni et al. 2014; Evangelista et al. 2015), investigation of jet grouting column response to axial load (Modoni et al. 2010), or the performance evaluation of grouted structures (Ochmański et al. 2015b). The principal characteristic of these analyses is the application of commonly utilized computational techniques such as finite volume method (FVM) or finite element method (FEM). The former plays an important role in solving fluid flow problems, while the FEM is more appropriate for solid mechanics applications. Apart from these methods, particle

approaches like discrete element method (DEM) or smoothed particle hydrodynamics (SPH) tend to be promising due to several attractive characteristics (Jiang et al. 2003, 2004, 2011; Liu and Liu 2010).

Historical development and experiences from around the world

On the basis of experimental works that started in 1965, the first version of mono-fluid jet grouting system also known as the Chemical Churning Pile (CCP) method was developed and patented in Japan in the early 1970s (Shibazaki 2003). According to Xanthakos et al. (1994), the same period has seen the development of the Jumbo Special Pile (JSP) in 1972, which can be considered as the precursor of the current bi-fluid systems. Interestingly, although the advancements in jet grouting technology took off in the early 1970s, its implementation in other countries was not effective until the late 1970s. For instance, countries such as the USA, China, Italy, or France to name a few adopted this technique along with its development to cope with challenging geotechnical problems. The following Fig. 8 gives an illustration of the historical development of jet grouting from the CCP to more recent technologies.

Mono-fluid system

The earliest use of the mono-fluid jet grouting method in Chinese soil (which corresponds to the first implementation of jet grouting technology in China) dates back to the late 1970s (Shen et al. 2012a); this method was operated in Shanghai for the construction of a retaining structure intended to support excavation works. During the same period in the USA, the mono-fluid jet method was frequently used for the stabilization of an existing railroad tunnel to minimize impact from new tunnel construction beneath in Washington, or for a riverwalk reconstruction project in Texas (Brill et al. 2003). Croce and Flora (2000) have also reported some applications of the mono-fluid jet variation in Italy. These applications include viaduct, riverwalk, and tunnel construction projects.

With regard to the application of the mono-fluid jet grouting system, other few cases, which are not specified in this paper, have also shown the importance of this variation for stabilizing soft ground. Actually, due to its simplicity, this technique has proven to be efficient for sealing vertical joints. In addition, the mono-fluid jet grouting system was found to be very effective in coarse-grained soil. This aspect was also demonstrated by Flora et al. (2013) who have established the evident influence of soil gradation on the energetic efficiency for single-fluid jet grouting. Due to the impossibility of using compressed air in closed underground spaces, the mono-fluid
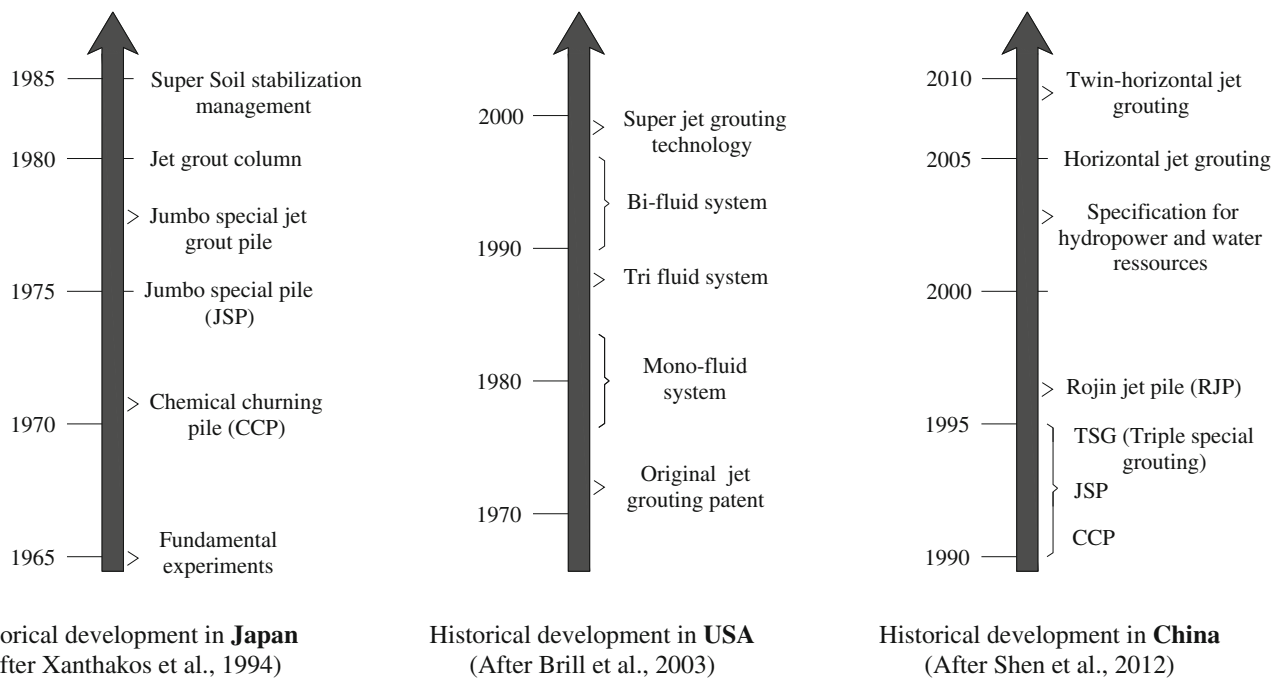
Historical development in **Japan**
(After Xanthakos et al., 1994)

Historical development in **USA**
(After Brill et al., 2003)

Historical development in **China**
(After Shen et al., 2012)

Fig. 8 Historical development of jet grouting in different countries

jet grouting is also used to provide temporary support for tunnels (Russo and Modoni 2005).

In spite of this, with its increasing popularity in the late 1980s, the mono-fluid jet grouting routine has raised some related to the variability of column diameters and their effect in the soils, as reported by Croce and Flora (2000). The reported difficulties in controlling quality in cohesive soils, and more importantly the relatively small diameter of jet grout column produced by the mono-fluid jet method, have initiated the development of a more performant variation, the tri-fluid system that produces larger geometries.

Tri-fluid system

Since the development of the tri-fluid jet grouting system in the late 1980s, four typical variations have been inventoried so far: the X-jetting method, the Rodin Jet Pile (RJP) method, the ultra-jetting system (UJS), and recently the twin-jet method. These methods have been implemented mostly in China, which, since 1990, is considered as the principal world customer of the jet grouting technology, owing to the importance of extensive construction projects that have been implemented since then (Wang et al. 2013a).

The Rodin Jet Pile method (see Fig. 9a) was first introduced to the public by Tsujita in 1996 (Wang et al. 2013a). Its principal characteristic is the double erosion process carried out in the monitor. The first erosion is achieved by a high-pressurized jet of water shrouded by air, while in a lower nozzle, the second involves compressed air wrapping a cone of cement slurry at high pressure (Shen et al. 2009a, 2012b).

Indeed, both the RJP and the X-jetting methods have been dedicated to the production of large cemented soil geometries (see Fig. 10), when compared to the conventional techniques. However, in the X-jetting method, the soil is disaggregated under the action of cross-water jets at high pressure (40 MPa) and enveloped by compressed air (0.6–1.05 MPa). Then the previously eroded soil is mixed with grout injected at a low pressure from another nozzle (see Fig. 9b). From a general point of view, the principle of this technology is underlined by the control of the erosion with respect to the range of soils, which bring about more confidence in the final body geometry (Burke 2004).

The UJS is an ultra-high-pressure injection method with innovative improvements, developed by Yong-Hyun Kim (Shen et al. 2012a, 2013c). The method involves pre-jetting by water and air at high pressure, as well as the injection of cement grout mixing with soil to form columns. Indeed, the monitor used in the UJS is composed of three nozzles as illustrated in Fig. 11. The bottom nozzle is used for the pre-jetting of water and air at high pressure when the drill rod reaches the required depth. Also, the injection of cement grout is achieved from the lateral nozzles when the drill string is rotated upwardly. The principal characteristic of the UJS is the inclined injection operated in the pre-jetting phase, which allows minimizing disturbance to surrounding soil. The jet column diameters obtained with this method vary from 80 cm (cohesive soil) to 2500 mm (sandy soils). As a matter of fact, for the reinforcement work for *Mangwoo* Railway Bridge (South Korea) in 2003, jet columns of 200 cm diameter and design strength of 8 MPa were achieved in sandy soil.
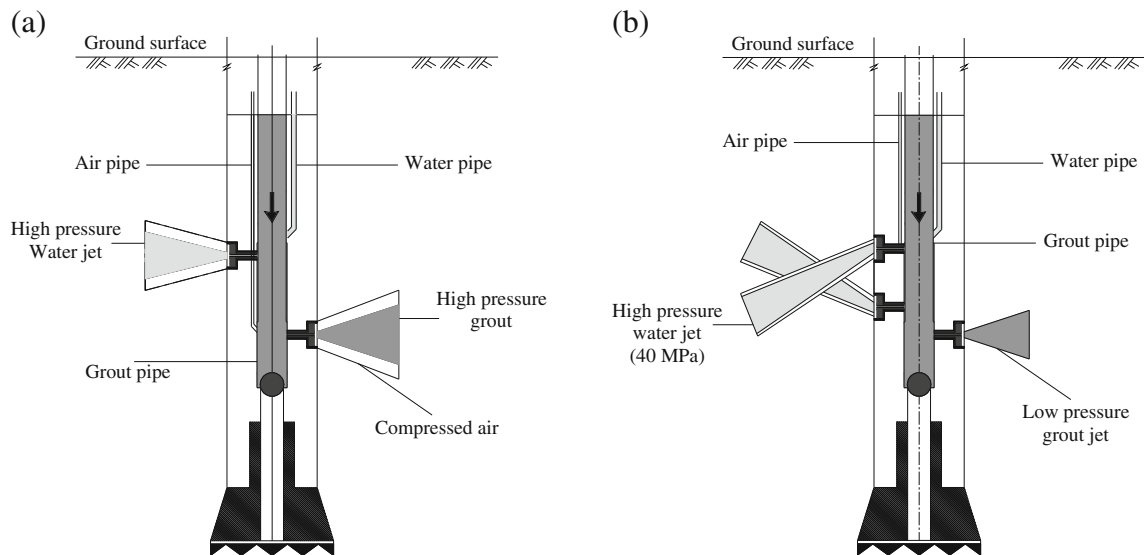
(a)

Ground surface

Air pipe — Water pipe

High pressure
Water jet

High pressure
grout

Grout pipe

Compressed air

(b)

Ground surface

Air pipe

Water pipe

High pressure
water jet
(40 MPa)

Grout pipe

Low pressure
grout jet

Fig. 9 Schematics illustrating the general principle of **a** RJP and **b** X-jetting methods

As far as the twin-jet method is concerned, its development was also initiated by Yong-Hyun Kim in 2004 (Shen et al. 2012a). This technique is characterized by a rapid set injection system on one hand and an instant solidification mechanism on the other. For the latter for example, a catalyst (sodium silicate or water glass) is employed to speed up the gelling and so better the uniformity of the mixture. The creation of the twin-jet technique, in fact, took place in a context where the existing jet grouting methods were no longer sufficient to overcome particular challenges such as loss of stabilizers or ground movements. Indeed, in some situations, the execution

of the traditional jet grouting techniques is accompanied by harmful consequences owing to ground movements such as protuberance, upheaval (Russo and Modoni 2005; Ochmański et al. 2015b), and subsidence (Eramo et al. 2012) in the surrounding ground. The development of this new technology has thus improved the implementation of underground works such as tunneling (Shen et al. 2014a; Wu et al. 2015e) and structural foundations in densely urbanized areas. Moreover, one of the earliest applications of this technology has been reported by Wang et al. (2013a); in this case, the twin-jet technique was used to improve the stability (by strengthening

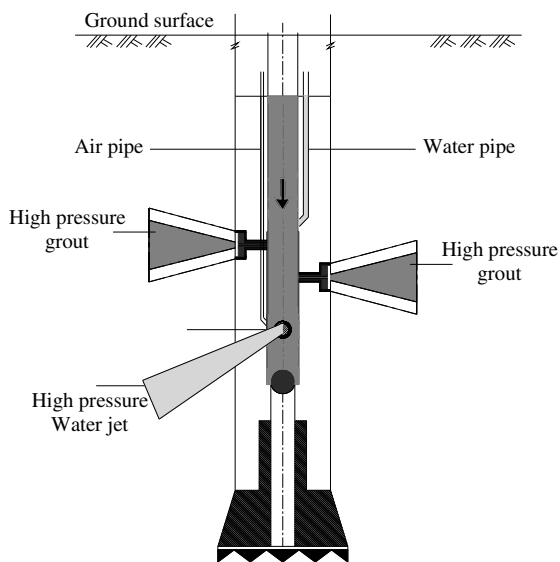**Fig. 10** Field trial column diameters achievable with **a** RJP, **b** super jet methods (source: http://www.chemicalgrout.co.jp/en/), and **c** UJS (source: http://www.kftco.com/)

(a)

(b)

(c)
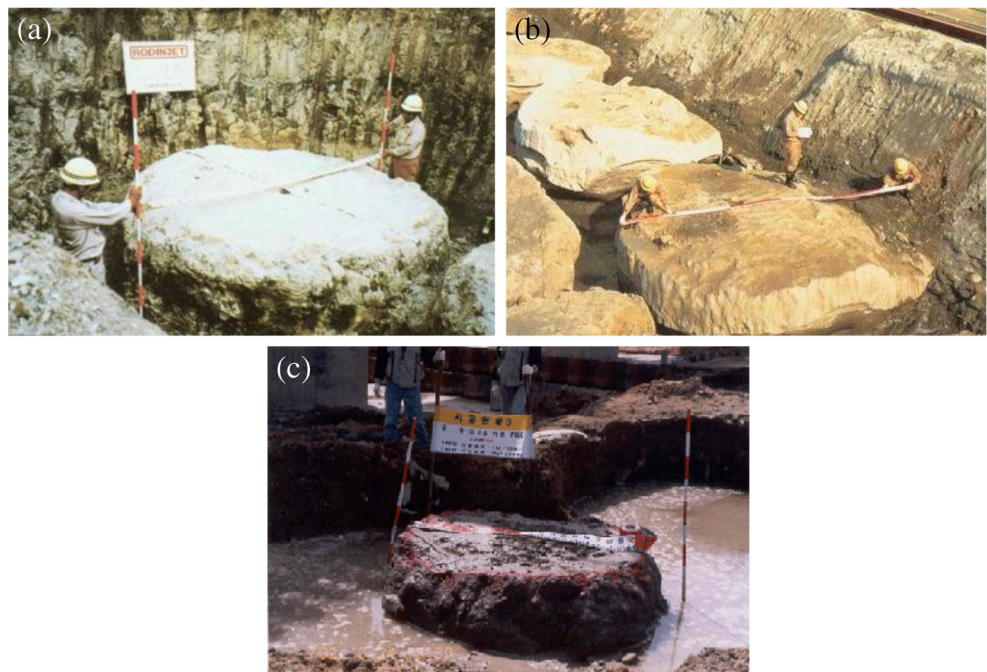
Fig. 11 Schematic representation of the UJS principle (picture source: http://www.kftco.com/)

the piers) of the historical *Nam Ji-Kyo Bridge* in Korea. Yet, the method was found effective within a challenging profile principally composed of cohesionless soil layers among four.

In spite of enhancing the erosive capability, the triple-fluid system suffers the main disadvantages of producing a larger amount of spoil that needs to be collected and conveyed to disposal plants. Re-use of the spoil would be particularly advantageous both from the economic and environmental viewpoints.

Bi-fluid system

The popularity of the bi-fluid jet grouting system reached its apex in the 1990s (Brill et al. 2003), due to the considerable cost saving gained from its use on one hand and the expanded range of applications it offered, including mass ground stabilization, dam renovations, and horizontal bottom seal, on the other hand.

However, in the late 1990s, a new variation of the bi-fluid system has emerged in Japan: the super jet grouting technology. The purpose of its development was to create larger columns of good quality and at a reduced cost. The difference with the conventional bi-fluid system was therefore the injection of a higher volume of grout on one hand and the reduction of the jet grout stream at the nozzles on the other hand (Burke et al. 2000; Brill et al. 2003). As illustrated in Fig. 12, this approach involves the use of compressed air (0.7–1.05 MPa) shrouding a cone of high-pressurized grout (30 MPa) and injected simultaneously from two different nozzles arranged oppositely.

One of the first applications of super jet grouting technology in China dates back to the year of 1995. This method was implemented for the construction of diaphragm walls, as part

of the "Xiao Langdi Dam project" in the vicinity of the Yellow River (Shen et al. 2012a). Moreover, exported from Japan in the early 2000s, the first application of this technology in the USA came as a part of a tunneling project in Atlantic City in New Jersey (Burke et al. 2000). The super jet technique was also used to carry out a cut-and-cover tunnel at the Minneapolis Airport, and Brill et al. (2003) even reported that the cost of this project was considerably lower than previously experienced. The cases of studies related to the use of super jet fluid method presented in this part are non-exhaustive and circumscribed to China and the USA.

From a general standpoint, although presenting some disadvantages (unsuitable for underpinning, difficulty in dealing with spoil, heave control in cohesive soil, etc.), the double fluid allows achieving good-quality geometries. Additionally, compared with the other jet grouting systems, the super jet technology allows important cost saving. Furthermore, several studies agree in that the super jet grouting technology achieves the largest column diameter (Burke 2004; Brill et al. 2003; Wang et al. 2013a) and exhibits the best mixing ability (Burke 2004). In point of fact, the eroding effect of the jet is significantly improved by the shrouded air that reduces the friction effects on one hand and further enhances the spoil backflow (thanks to an uplifting effect) on the other hand.

Case histories of the practice of jet grouting

This section depicts the practice of jet grouting as adopted around the world and throughout its evolution. In addition, it intends to highlight the suitable conditions for executing each system as well as the principal factors that underpin the
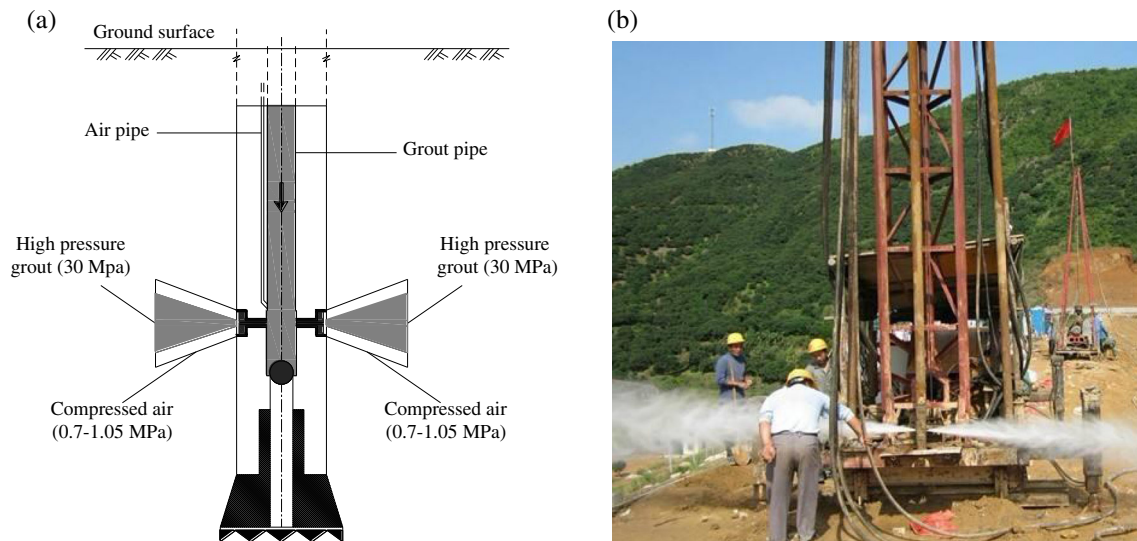
Fig. 12 **a** Schematic of the super jet fluid technology. **b** Photograph of super jet technology (picture source: http://www.sdssytgc.com/RiZhao-ytgcxq/239814.aspx)

modeling of jet grouting. Therefore, to strengthen the relevance of our approach, two important aspects were considered. Firstly, recent and relatively old case studies and projects are discussed herein. Then, different types of jet grouting treatments such as inclusions, liquefaction mitigation, linear and massive treatments are covered. The description of these procedures is not presented in this part, but some of them can be found in Croce et al. (2014b).

Linear treatment: construction of the *Hurtiere* tunnel (Rhone-Alpes, France)

This case history focuses on the application of the single-fluid jet grouting for the construction of the *Hurtiere* tunnel, located on the A43 motorway (Rhône-Alpes, France). Indeed, in the section *Aiton-Sainte-Marie-de-Cuisne*, the motorway A43 also called *Maurienne* motorway had to cross two adjacent tunnels located at the foot of a cavernous valley. On one hand, for the West section of the tunnel (see profile A), geological surveys and numerous soundings allowed identifying the complex configuration in plan and the irregular depth of a subglacial furrow filled with deposits conveyed by the floods of the *Seine*. It was therefore possible to adjust the tunnel alignment in such a way as to remain at a sufficient distance away from the furrow, as shown by the "profile A" Fig. 13. On the other hand, the geological surveys had not detected the presence of the subglacial furrow at the right of the second tunnel section (profile B). In other words, the surveys could not establish that the eastern tube would encounter the subglacial furrow about 50 m farther from the previous location. As a result, during the excavation of the East tube of the *Hurtières* tunnel, two sudden collapses of loose materials (sand, gravel, and silt) occurred within the tunnel. A rapid and effective remediation

approach was thus required to ensure the integrity of the "being constructed" tunnel. After a comparative study of various solutions, the engineers agreed on remedying this collapse with the force of a jet grouting treatment. It was decided to cross the center of furrow by the single-fluid jet grouting technique, specifically, by creating an umbrella arch of subhorizontal jet grout columns along with the advancement of the excavation (see Fig. 14).

The construction works required intensive treatment for crossing the furrow of 70–80 m deep and located entirely in the rock as shown in Fig. 13 (Bienfait et al. 1996). Also, a treatment involving vertical columns of cemented soil carried out by jet grouting was also used to consolidate the alluvial soils (consisting of sand, gravel, and silt) below the tunnel. During excavation, it was possible to verify that the actual diameters of the columns corresponding to the theoretical value of 60 cm and that contact zones between rock and alluvial materials were well treated. Furthermore, treatment effects, assessed in particular by unconfined compressive strength tests, have shown excellent results. Indeed, the UCS ranging from 10 to 77 MPa were obtained, with an average value of 30 MPa. Such resistances in strata essentially composed of sand-gravel tend to be close to that of the cement concrete, but testifies, however, of a poor mixing uniformity (Shen et al. 2009b).

Croce et al. (2004) have reported a case in Italy analogous to that of the *Hurtieres tunnel*. In their study, the issue of failure mechanisms during tunneling projects (Shen et al. 2016) has been addressed, with a particular emphasis on the determinant role of jet grouting in the realization of grouted canopies (Cheng et al. 2017a, b). What is more, the efficacy of jet grouting in controlling settlement in challenging geological conditions was also demonstrated.
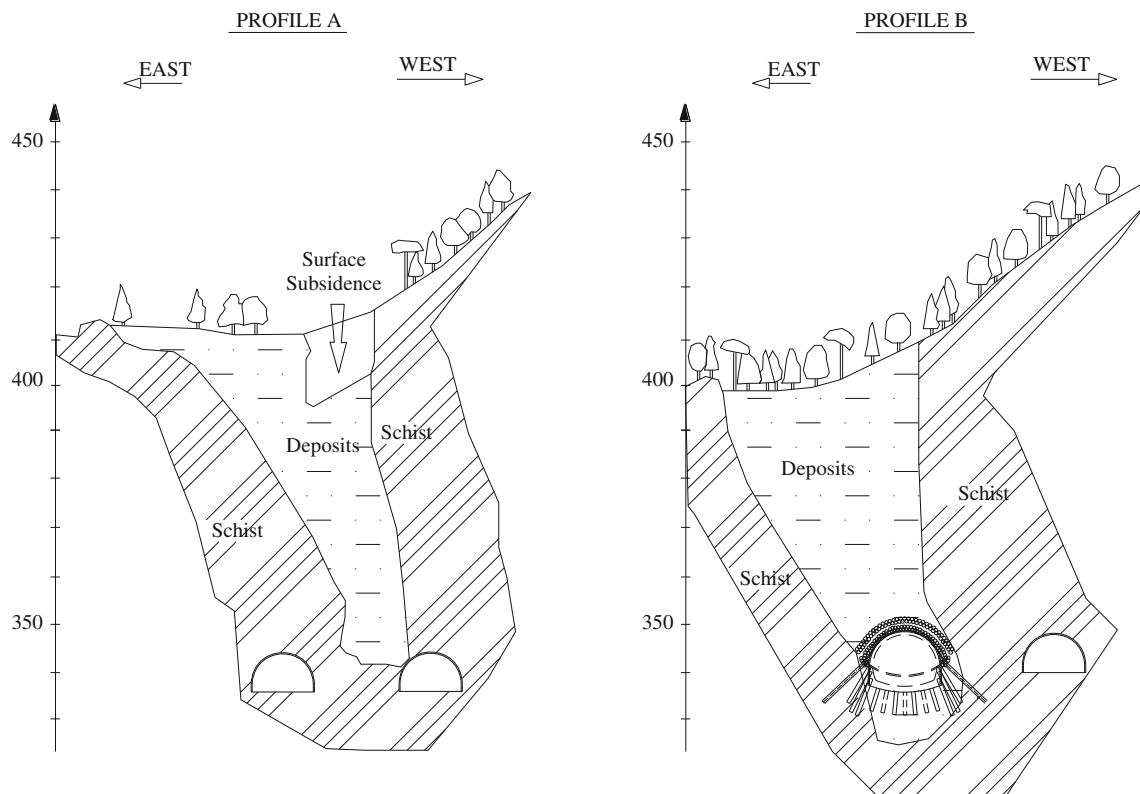
Fig. 13 Tunnel of Hurtieres: cross-sections at the right of the West tube (profile A) and the East tubes (profile B) (recreated after Bienfait et al. 1996)

Inclusions: rehabilitation of the RER C (subway connecting *Versailles* to the heart of *Paris*) in France

This case history discusses the rehabilitation of the "RER C" in Paris (in 1996), located on the left bank of the *Seine*. The project consisted of reinforcing the piers and foundation slab of a trench that were subjected to some disorders. These disorders were purely the result of excessive subsidence arising in particular from a delicate geological profile. Indeed, the

strata to be improved were essentially composed of deposits transported by the floods of the *Seine*, predominantly silty-clay of low consistency. In order to minimize the harmful effect of ground movement to the structure, the latter was strengthened by the mean of sub-vertical jet grouting columns (see Fig. 15). However, before this treatment, trial tests were implemented to calibrate the processing parameters with respect to the expected performance. Figure 16 shows a view of the site where the traditional field trials were performed. As

Fig. 14 Typical section of treatment by single-fluid jet grouting in the East tube (recreated after Bienfait et al. 1996)
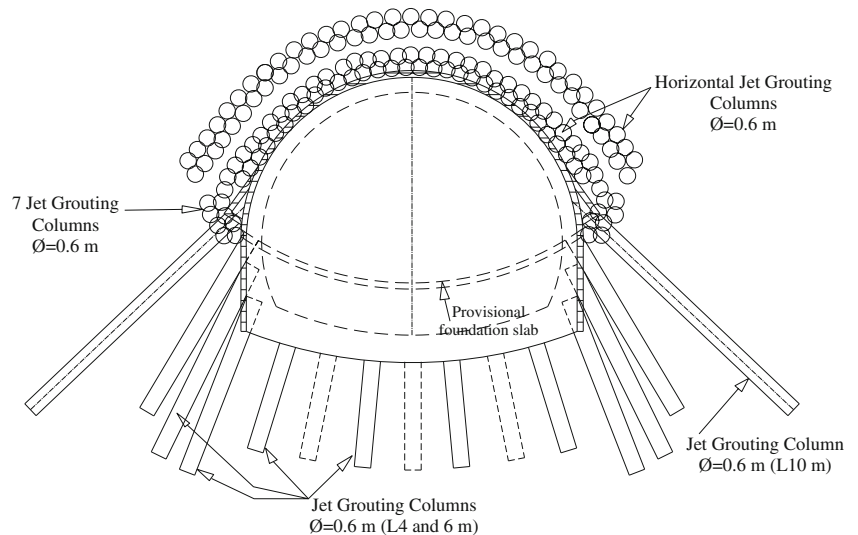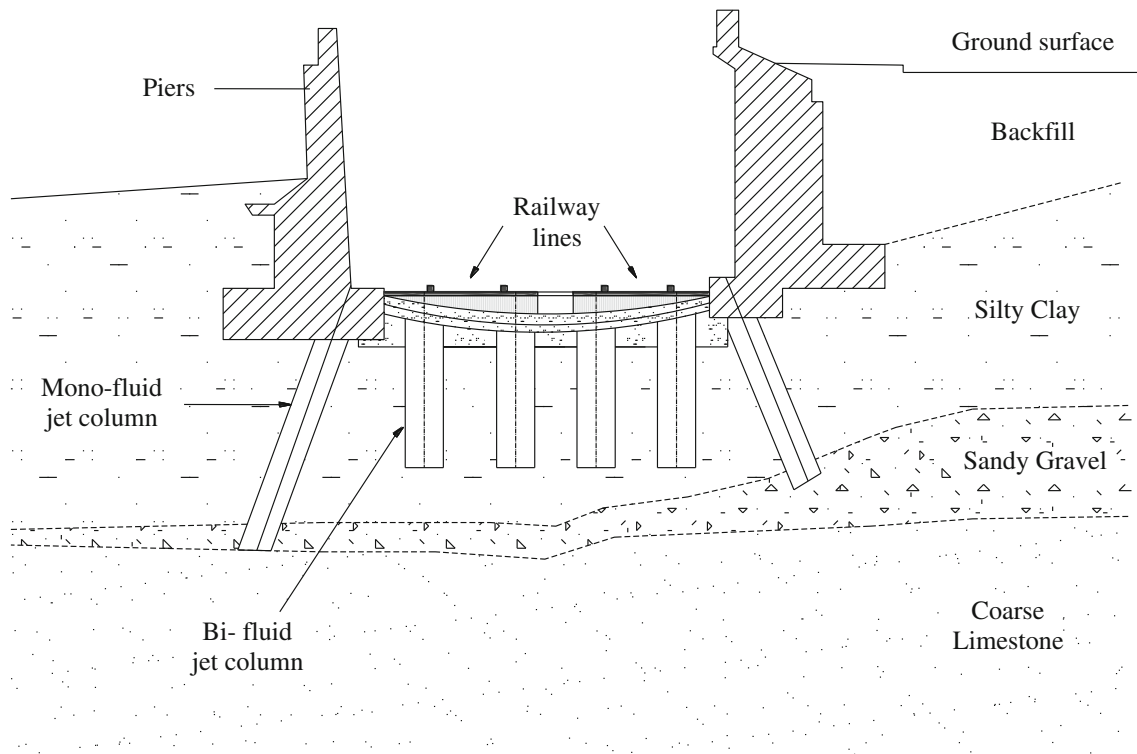
Fig. 15 Illustration of the RER C project (Tranchee *Saint Bernard*) in Paris, France (1996) (source: http://www.soletanche-bachy.com)

for Fig. 17, it illustrates the results obtained by varying the main jet grouting parameters: single or double jet, energy used (flow rates, pressures), cement content.

It was observed that the diameter of the jet grout columns was of the order of 80 cm for low energies (10 to 25 MJ/m^3). Moreover, for the single-jet technique, it was necessary to increase the jetting energy (to approximately 300 MJ/m^3) to achieve a diameter of 180 cm, whereas with the double-jet system, the same diameter was reached nearly from 50 MJ/m^3. These results notably show the advantage of the double jet when it comes to producing large geometries. It was also concluded that the compressive strength of the columns was

less influenced by the jet grouting variation. The compressive strength of jet grout columns increased along with the increased of cement content and depending on the type of soils. It varied approximately from 3 to 6 MPa for single fluid, and from 5 to 9.5 MPa for double fluid. A similar result is shown by Wanik et al. (2017) who observed largely different values of the uniaxial compressive strength of sand treated with single- and double-fluid jet grouting. Figure 18 shows two micrographs obtained with scanning electron microscope of samples treated with (a) single or (b) double fluid. Together with micrometric grains of quartz, present in both figures, the former scan presents plate-like aggregates of

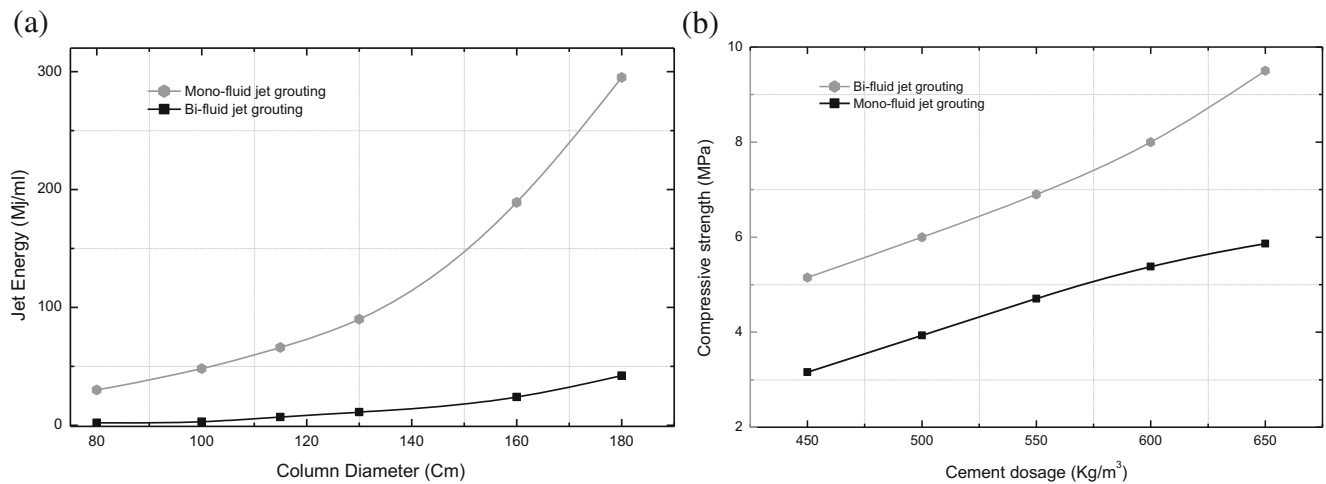Fig. 16 View of the on-site trial and the grouted columns obtained from the trial test (source: http://www.soletanche-bachy.com)

(a)

(b)

Fig. 17 Result of the jet grouting trial tests of the RER C project. **a** Variation of column diameter with jet energy. **b** UCS of jet columns against cement content (recreated after Dhouib et al. 2004)

portlandite crystals and very small particles of calcium silicate hydrate (CSH). Portlandite and CSH phases, that represent the typical hydration phases of cement, are absent in the micrograph of the sample treated with double fluid (b) prevalently characterized by micrometric quartz particles.

One of the advantages of the jet grouting method as an inclusion technique is therefore its capability to reinforce the soil under and or through constructed structures. Another case of treatment by inclusion has been reported by Wang et al. (2013a), about the strengthening of a historical bridge in South Korea.

Jet grouting for liquefaction mitigation in Turkey

The liquefaction of loose medium sands is a major concern in the construction of underground structures, especially, in seismic regions. It is widely accepted that, under seismic loading

or during a seismic event, the liquefaction of loose granular soils may result in ground displacements and or local subsidence in the vicinity of the constructed structures (underground stations, tunnels, pipes, etc.). To reduce their vulnerability against these liquefaction-induced geotechnical hazards, adequate preconstruction and or post-construction measures must be undertaken. Moreover, it is necessary to assess the effectiveness of ground consolidation techniques in reducing the liquefaction-induced ground displacements and permanent ground deformations on the construction site. The mitigation approaches usually adopted in these cases involves (i) the consolidation of liquefiable soils to prevent them from liquefaction and (ii) the strengthening of the relevant structures to avoid their collapse in case of soil liquefaction. Interestingly, the jet grouting technique belongs to the second category.

The present case history summarizes the application of the jet grouting as remediation method against liquefaction for the
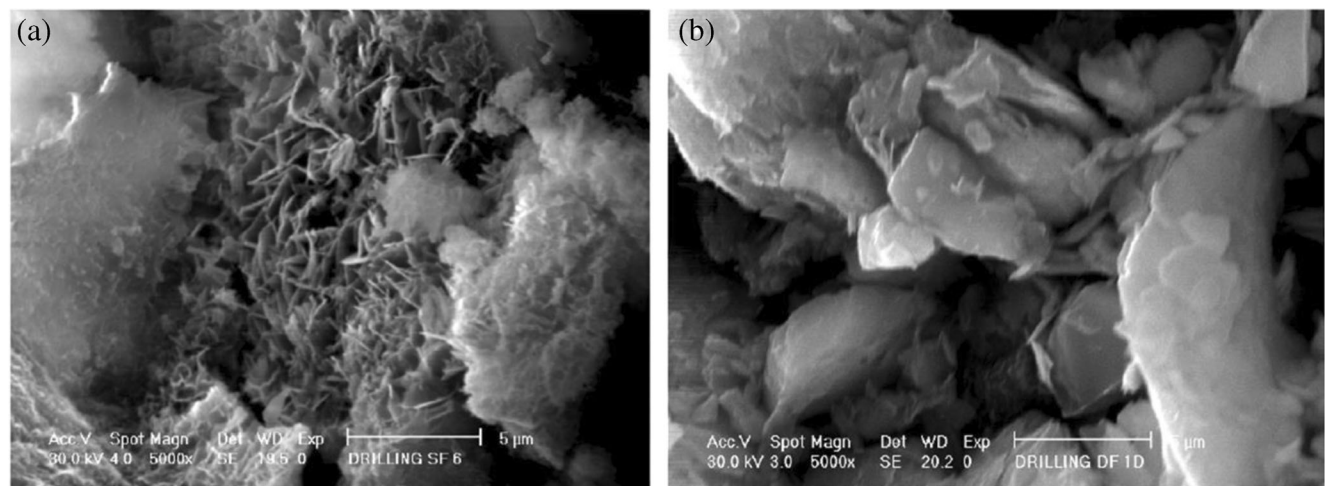
(a)

(b)

Fig. 18 SEM micrographs of samples treated with **a** mono- and **b** bi-fluid sytems (after Wanik et al. 2017)

Table 2   Geotechnical profile of the construction site (after Durgunoglu et al. 2003)

Strata	Thickness (cm)	Depth to the base of layer (cm)	Predominant types of soils
Uncontrolled fill	0–150	0–150	Medium dense sandy silt
Alluvium	300–800	300–1000	Loose sandy silt interbedded with loose silty sand and soft clay
Colluvium (residual soil)	200–500	700–1400	Firm to stiff clay
Bedrock	–	–	Very weak fractured micashist

construction of a cigarette factory in Turkey (Durgunoglu et al. 2003). The site was located in the coastal city of Izmir, which is known as a high-risk earthquake zone. The ground investigations revealed that the stratigraphy of the site was mainly composed of alluvial deposits ranging from micaceous silt to stiff clay (see Table 2). In view of the fact that alluvial soils have a rather high tendency for liquefaction during earthquake shaking, a soil improvement was required to minimize their stiffness degradation and increase their shear resistance. Various improvement options were evaluated in terms of their effectiveness, costs, applicability, and the soil conditions. Subsequently, the jet grouting treatment was adopted as the final implementation scheme given the relatively high compressibility of the sandy silt soil in the alluvium stratum. This approach was indeed aimed at improving the soil bearing capacity and reducing its liquefaction potential.

The proposed jet grouting implementation scheme assumed an area replacement ratio of $A_r = 0.23$, i.e., with jet columns of 80 cm diameter and spacing of 210 cm from the center of columns. In addition, the design and technical specifications required the production of grouted columns with strength values higher than 0.6 MPa. As such, a preliminary trial testing program was carried out for calibrating the different design parameters. These field trials involved the implementation of the mono- and double-fluid methods for the construction of 10 grout columns (among which three were produced using the mono-fluid system). At the completion of the testing program, the grout columns were excavated, core samples were tested for UCS, and the following results were observed.

Following the trial testing program, it was observed that the best combination for satisfying the design requirements was the double-fluid jet method. Indeed, the jet grout column diameters obtained with this variation varied from 95 to 120 cm, while the ones obtained with the mono-fluid system were relatively smaller (55 to 60 cm) as shown in Fig. 19a. Besides, value of UCS greater than 1.0 MPa was achieved for jet column diameters larger than 90 cm; the UCS of the columns however varied from 0.3 to 3.4 MPa. It is also noteworthy that the increase of jet grout column diameter caused by ground condition (variability of diameter) led to the decrease in cement content, which at its turn contributed to the reduction of UCS values (see Fig. 19b). Furthermore, during the treatment process, a number of load tests confirmed the effectiveness of the method. Martin II and Olgun (2006) have also reported another case where jet grout columns were successfully used for liquefaction mitigation after the Kocaeli (Turkey) earthquake in 1999.

Mass treatment: tunnel excavation in Barcelona (Spain)

This part reports the case of massive jet grout treatment that was undertaken for a tunnel excavation during the construction of a high-speed railway link section in Barcelona (Arroyo et al. 2012). This project was carried out following the partitioned section procedure and adopting two construction approaches for the tunnel excavation: (i) the Earth pressure balance (EPB) shield tunneling when shafts for EPB were readily accessible and (ii) the traditional mined excavation procedure when the opposite situation was encountered. Only the latter construction scheme is discussed herein. The principal concern during the tunnel construction was to avoid the risk of any geotechnical hazards. Indeed, the tunnel was sited on the alluvial plain of Barcelona, which predominantly consists of quaternary deposits overlying a Tertiary substratum. Figure 20 depicts the geological profile alongside the concerned tunnel section.

Importantly, with the construction ongoing, specific investigations established not only a potential risk of ground flows towards the excavation at the central and most profound portion of the tunnel, but also the existence of granular deposits (QP_{Ar} and Q_R) coinciding with the water table just above the tunnel head. However, as the surrounding natural ground offered subsequent resistance and stiffness to withstand the tunnel construction without much deformation, the principal function of the jet grouting treatment was thus that of a waterproof barrier. Hence, for the treatment of zones accessible to the EPB shaft, double- and tri-fluid jet grout (vertical and subvertical) columns with a design diameter of 250 cm were envisaged, with the guarantee of an efficient spoil evacuation. As can be seen in Fig. 21, the layout of the treatment included sections simply surrounded by jet columns and sections with the entire tunnel face fully covered by overlapped jet grout columns. The primary function of these full-face sections was
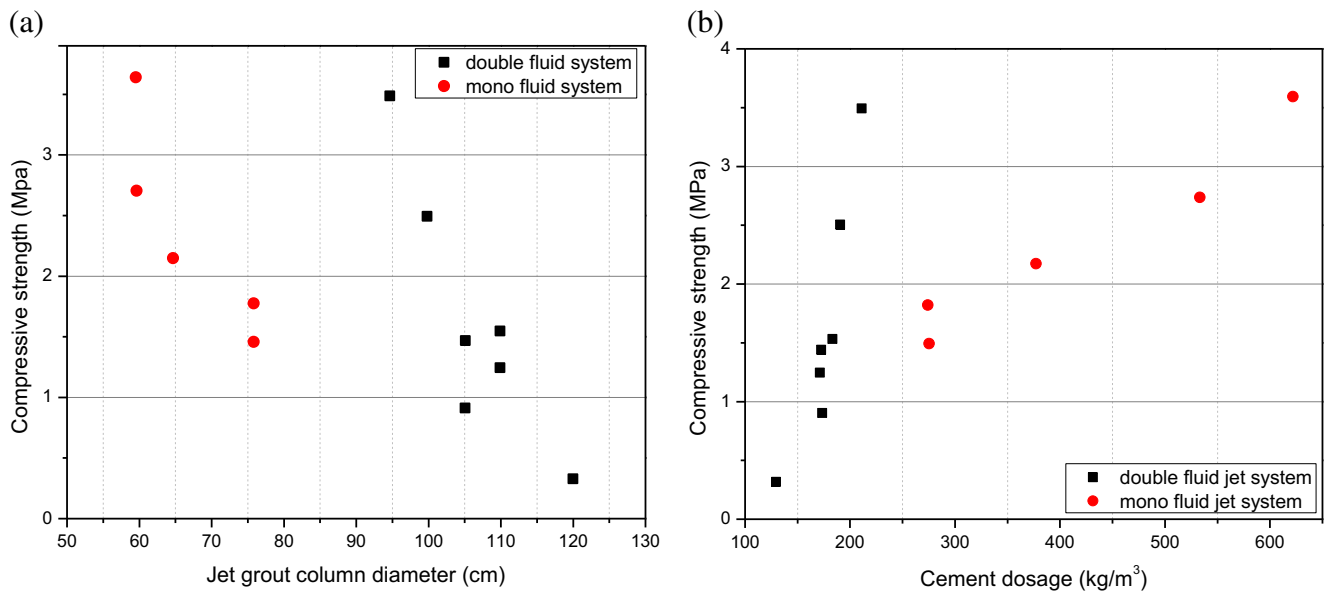
(a)

(b)

Fig. 19 **a**, **b** Results of the preliminary trial testing program (recreated after Durgunoglu et al. 2003)

to minimize the extension of hypothetic failures, by creating longitudinally isolated zones.

Furthermore, to ascertain the effectiveness of this treatment, preliminary field trials were performed prior to the execution of the jet grout technique. It should be noted that as the treatment addressed the problem of impermeability, the continuity of the overlapped jet columns required particular attention. However, the field testing program was achieved through the production of mono-fluid jet grout columns within intermediate deep access ramps to the tunnel (typically clay-like consistency). Their properties assessed by field observations and laboratory testing were in agreement with the results discussed in "Inclusions: rehabilitation of the RER C (subway connecting *Versailles* to the heart of *Paris*) in France,"

regarding the relationship between jetting energy and cement content of jet column diameters. Also, it was made clear that, although larger amounts of water in the mixture contributed to improving the erosive action of the jet (i.e., larger diameters), it adversely affects the mechanical properties of the grouted elements.

Field trial tests: application of RJP in Shanghai

The field trial tests of Rodin Jet Pile (tri-fluid system) on the Shanghai soft soils came as part of the reparation of the collapsed tunnel on the Metro Line No. 4 Fig. 22. Indeed in June 2003, an anthropic-induced hazard occurred in the portion of Shanghai metro line located between the *South Pudong Road*

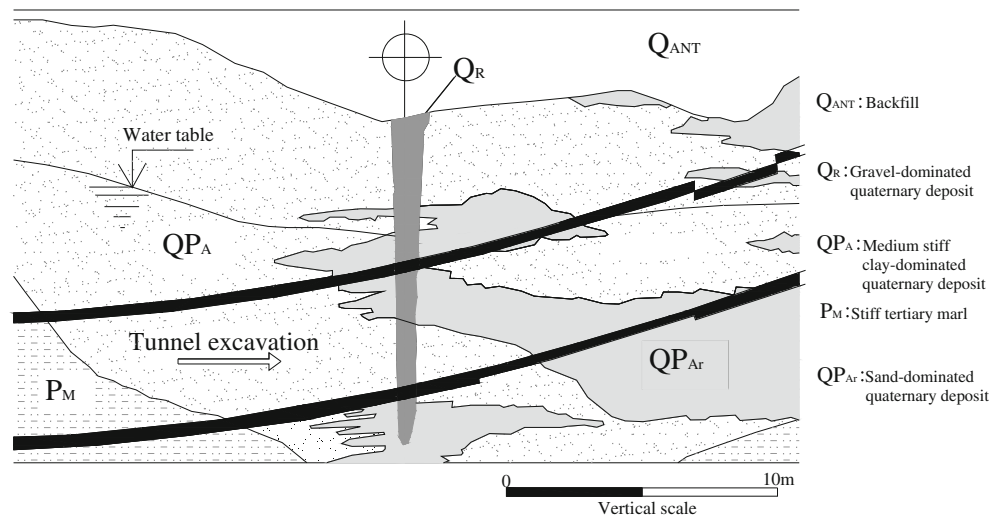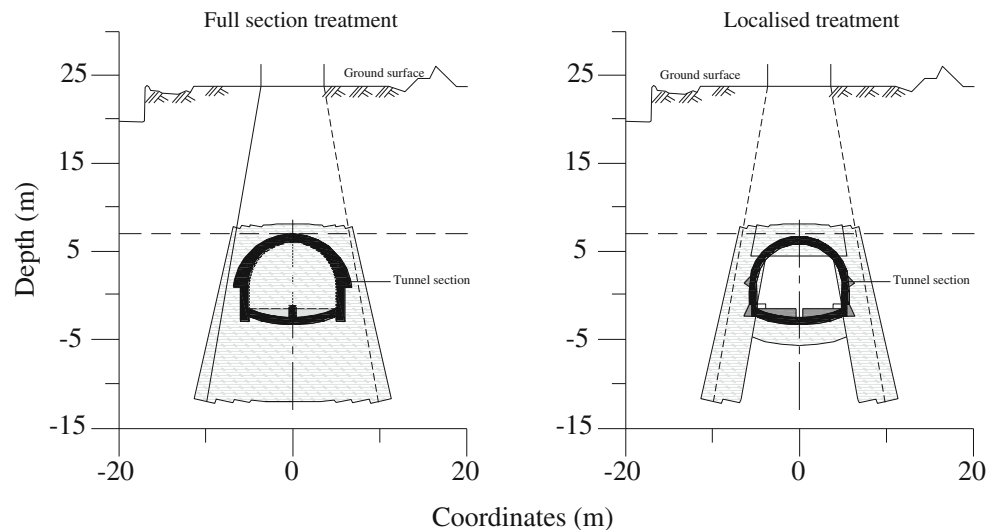**Fig. 20** Subsoil geological profile (recreated after Arroyo et al. 2012)

Fig. 21 Illustration of the jet grouting treatments envisaged for the zones accessible to EPB shaft (recreated after Arroyo et al. 2012).

and the *Nanpu Road* station (Xu et al. 2009). The investigations revealed that the severe damages to the tunnel were principally arising from infiltrations inside the tunnel, which caused ground loss and ground subsidence. More importantly, the company in charge of remediating was required to perform jet grouting in situ tests, to assess the efficacy of the RJP technology.

The construction site is adjacent to the Huangpu River, with a particular stratigraphy distributed as follows: backfill (7.6 m), clayey silt (8 m), soft clay (9.8 m), stiff clay (4.2 m), sandy silt (9.9 m), and silty sand underlying the latter layer. Moreover, three columns (C1, C2, and C3) of 40 m long were constructed within this problematic geological profile, using the Rodin Jet Pile technique. More details regarding the site conditions, as well as the construction parameters of this project, can be found in Shen et al. (2009a, 2012b). Also, as depicted in the following Table 3, the diameters of the RJP cylindrical grouted elements were measured at different depths of the implementation zone.

It was reported that the diameters of grouted columns were influenced by the soil characteristics. In fact, the diameters vary with the degree of cohesion of the soil. For instance, the diameters obtained in clayey silt layer were greater than those obtained in stiff silt clay. This agrees well with the idea according to which the diameter of the columns is affected by the soil's susceptibility to fluid jet. This conclusion was consistent with the erodibility scale for different types of soils established by Burke (2004). Then again, the mixing uniformity assessed by in situ observations pointed out the importance of considering the soil properties during the jet grouting procedure. Indeed, as far as the above-described trial tests are concerned, a satisfactory mixing was most effective in the clayey soil layer than in sandy soil layer. Besides, it was demonstrated that the compressive strength of RJP columns was significantly affected by mixing uniformity: more uniform was the mixing, higher was the UCS of the grouted columns (Shen et al. 2009a).

Fig. 22 Damages caused by the collapse of the tunnel of the Shanghai Metro Line 4 (after Xu et al. 2009)

Table 3 Measured column diameters after tests (after Shen et al. 2009a)

Soil layer	Depth (m)	Column diameters (m)	Uniformity of column
Backfill	< 7.5	2.0~3.0	Uniform
Clayey silt	7.5~16	1.6~2.6	Uniform
Very soft clay	16~25	1.8~3.3	Uniform
Stiff silt clay	25~30	0.8~1.2	Uniform
Sandy silt	30~38	1.9~2.3	Non-uniform
Silty sand	> 38	~ 2.0	Non-uniform

Implementation of the innovative elliptical jet grout columns for installation bottom plugs in the USA

Initially developed in Italy, the elliptical jet grouting technology relies on the alternation of slow and rapid rotational rates to produce elliptical columns. The present case history has been reported by Leoni and Pianezze (2017). It presents the application of elliptical bi-fluid system for the construction of bottom plugs as part of a drainage project carried out in New Orleans in 2014. Specifically, the portion of the project discussed herein stretches (within a densely urbanized area) from *Jefferson Avenue* to *Prytania Street*. In this case, the consolidation of the ground was an imperative requirement owing to the delicate geological profile of the construction site located in the vicinity of the Mississippi River, and, in majority composed of very soft sensitive clays, and silty sands. The choice of the bottom plug treatment was thus aimed at eliminating under-seepage. The design of the treatment targeted the full coverage of the volume sandwiched between two parallel rows of sheet piles. Thus, a net improvement volume of nearly 46,000 m^3 (on nearly 57,000 m^3 total) was achieved by producing 2400 columns. These columns were however constructed following the two different layouts shown in Fig. 23a.

The traditional preconstruction trials carried out in this case allowed for the quality control and calibration of the best implementation scheme. The results showed that the average compressive strengths of the elliptical columns varied from 2.49 to 2.21 kPa, according to the location (*Jefferson Av.– Prytania St.*). This observation was also true for the average values of hydraulic conductivity of that varied from 5.45E − 07 to 2.67E − 07 cm/s. From a general stand point, and compared with the traditional high-pressure jetting techniques, the elliptical jet grouting technology is more flexible when it comes to produce specific geometry and avoid excessive overlapping (Fig. 23b). Accordingly, it is the recommended technique for enhancing productivity, reducing material waste and even construction cost (Leoni and Pianezze 2017).

## Improvement efficacy of twin-jet method

The twin-jet method has overcome pressing challenges in jet grouting practice in recent year, among them the grouted column mixing uniformity, the loss of admixture, difficulties in horizontal implementation, and slow gelling (Shen et al. 2009b). In addition, this technique has demonstrated the valuable ability to be achievable horizontally or vertically, with in most cases, the insurance of satisfactory effects (Shen et al. 2012c, 2013a, c; Yuan et al. 2016). However, the effectiveness of this method is frequently undermined during field construction, in particular when it comes determining the optimum proportions to be implemented. It is therefore believed that the efficacy of twin-jet method can be substantially improved in terms of construction control and quality as well as economic rationality if the parameters that underpin this technique are well comprehended. Hence, an experimental study was carried out to determine the optimum construction parameters for the twin-jet method, notably, the cement content, cement type, cement-water glass ratio, and water glass concentration.

Experimental approach

This experiment was conducted on the basis of field implementation of horizontal double-fluid jet grouting system in Shanghai. The silt-clay suitably collected from the drilling was used for test specimens. Besides, the ordinary portland cement and water glass were meticulously mixed into certain proportions so as to define various samples. For instance, the concentration of water glass was defined following a rather simple but effective principle: in jet grouting practice, the concentration of water glass usually varies from 10 to 70% by volume, depending on the type of soil and the expected performances. Interestingly, this concentration is proportional to the viscosity of liquid glass, which at its turn is closely related to the induction time. Considering these aspects, and in order to reliably simulate different field conditions, the following concentrations were adopted: 1:1, 2:1, and 4:1. All the samples were then subjected to unconfined compressive strength and constantly investigated after 7, 14, and 28 days curing respectively. Also, the materials used for this experiment included ordinary portland cement no. 325 and no. 425, water glass (30.4 Baume degree, modulus 2.6), silty clay (see Table 4), and water.

The principal objectives of this approach were to investigate the effects of cement content, cement type, cement-water

(a)

Elliptical columns layout   Traditional columns layout
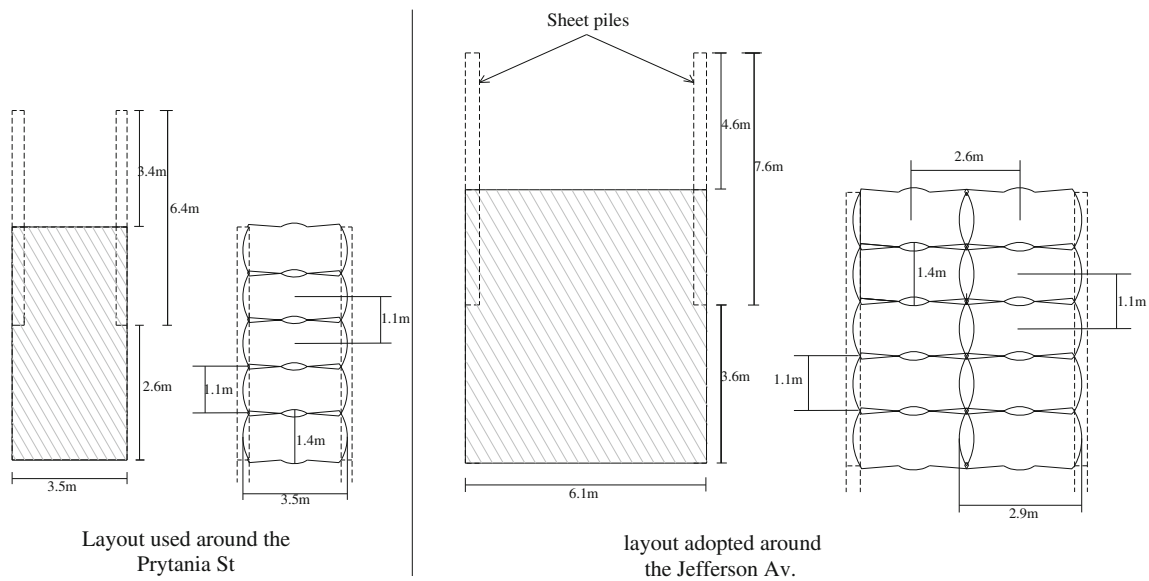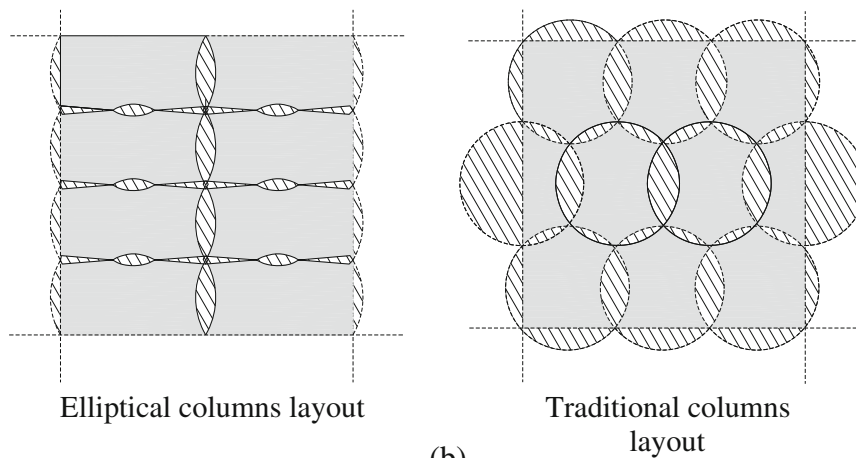
(b)

Fig. 23 **a**, **b** Comparison of jet grouting arrangements for the construction of bottom plugs (recreated after Leoni and Pianezze 2017)

glass ratio, and water glass concentration on compressive strength. In point of fact, the unconfined compressive strength (UCS) is considered as the basic mechanical index of jet-grouted elements and used to quantitatively characterize a material (Basu and Aydin 2006). In this study, the loading steps and loading rates of unconfined compressive strength and compressive deformation tests were in essence based on the test method for the strength of low-grade concrete speci-mens (Institute of Geotechnical engineering 2003).

Tests results

The different tests of this laboratory program were labeled as nos. 1, 2, 3, 4, and 5, respectively, for the effect of cement content, the influence of water-cement ratio, the influence of water-cement ratio, the effect of cement-water glass ratio, and the effect of cement type on compressive strength.

Moreover, the conditions of each test are summarized in Table 5. For example, for the test no. 1 (effect of cement

Table 4 Chemical and physical mechanical parameters of mucky clay

Unit weight γ (kN/m³)	Water content w (%)	Liquid limit w_L/%	Plastic limit w_P/%	Compression modulus E_{S1-2} (MPa⁻¹)	Internal friction angle Φ (°)	Cohesion c (kPa)	UCS q_u (kPa)
17.1	32.65	46.82	29.98	2.23	12	14	41.3

Table 5 Summary of the conditions adopted for the laboratory program

Test no.	Portland cement (no.)		Water glass ratio			Cement content (%)						Water cement ratio					Water glass concentration (°Be′)		
	325	425	1:1	2:1	4:1	5	10	15	20	25	30	0.6:1	0.8:1	1:1	1.2:1	1.4:1	14	17	20
1	✦				✦	✦	✦	✦	✦	✦	✦			✦					
2	✦				✦		✦							✦			✦	✦	✦
3	✦				✦		✦					✦	✦	✦	✦	✦		✦	
4	✦		✦	✦	✦		✦							✦				✦	
5	✦	✦			✦				✦	✦				✦					

content on compressive strength), the ordinary portland cement (no. 325) was used, and the following cement content was considered 5, 10, 15, 20, 25, and 30%. The ratio of water to cement was taken as 1:1, while the ratio of cement to water glass was 4:1. As for the curing period, three increments of 7 days were adopted through the duration of the test.

Effect of cement content on compressive strength

As illustrated in Fig. 24, the strength of the reinforced soil regularly increased with the increase of cement content. In the first stage of hardening (0–14 days), the sample strength increased rapidly, and yet after 28 days curing, the strength of the specimen was still increasing. Interestingly, it was observed that at low cement content (5%), the effect of the curing time on the strength of the reinforced soil was not significant. Moreover, the stress-strain relationship showed in Fig. 25 was mainly in accordance with Hooke's law for small values of stress. Conversely, at high cement content (more than 10%), and under the same magnitude of strain, the stress of the specimen was relatively higher. Plastic damage was frequently observed for small cement content (less than 10%).

Effect of water glass concentration on compressive strength

As depicted by Fig. 26, the compressive strength progressively decreases with the increase of the water glass concentration after 7 days curing. Conversely, after 14 and 28 days curing, the compressive strengths of water samples at 14 and 28 sodium silicate concentrations were respectively 85.9%, and 95.8% of the specimen. It was observed that for the curing times of 14 and 28 days, the strength of the specimen increases gradually with the increase of the water glass concentration, until to reach a peak, then decreases progressively. The optimum value of the water glass concentration seems to be 17°; in fact, any larger value tends to reduce the strength of the specimen. Figure 27 shows the stress-strain relationship for different water glass concentrations, and it can be observed that at the beginning of the force application, this relationship is basically consistent with Hooke's law.
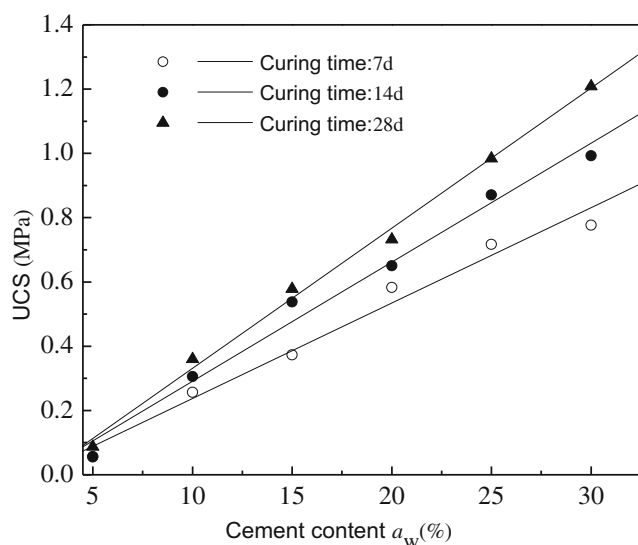

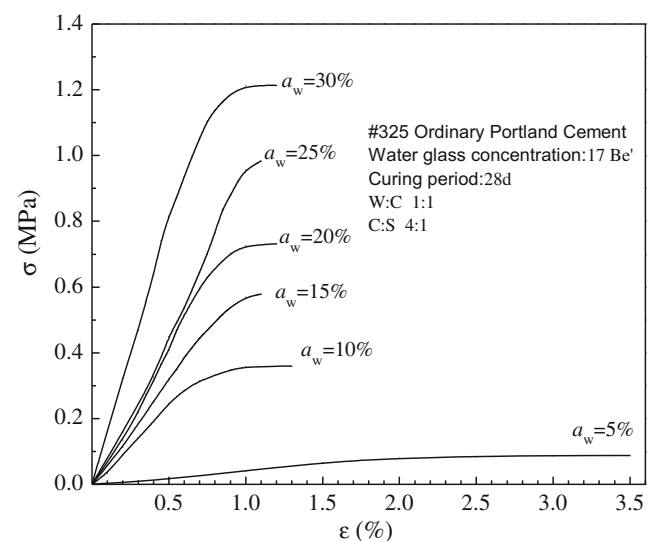**Fig. 24** Unconfined compressive strength versus cement content

Fig. 25 Stress-strain relationship of the mixed soil for different cement contents
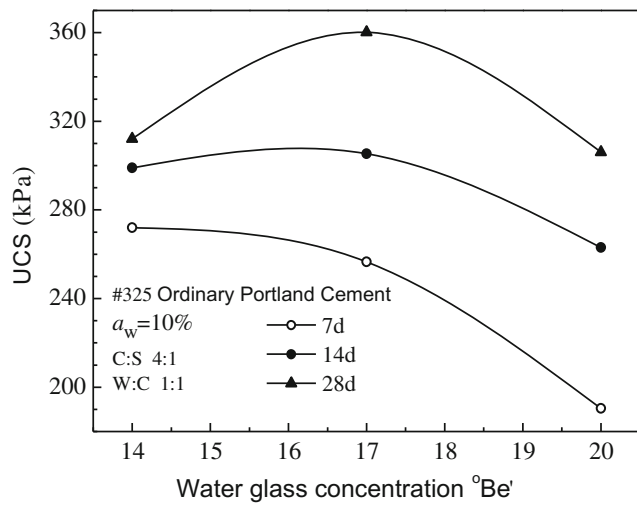
Fig. 26 Unconfined compressive strength versus concentration of water glass

Influence of water-cement ratio on unconfined compressive strength

Figure 28 shows the variation of unconfined compressive strength for different water-cement ratios. The compressive strength substantially decreases as the water-cement ratio increases. This can be ascribed to the increase of water-cement ratio along with the increase of water content of the specimen. Thus, the water-cement ratio can be considered as a major factor affecting the strength of reinforced soil. Besides, for the different water-cement ratios, the stress-strain relationship after 28 days curing was obtained (Fig. 29). It is shown that the stress-strain relationship satisfies Hooke's law at the beginning of the force application, and the plastic strain becomes obvious as the water-cement increases. Conversely, there is no noticeable plastic deformation when the water-cement is relatively small. What is more, the axial strain at the time of specimen failure increased with the increase of water-cement ratio. As a matter of fact, the values of axial strain after the
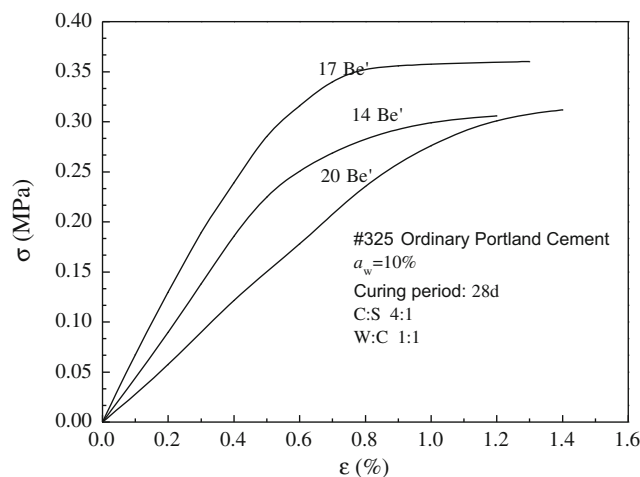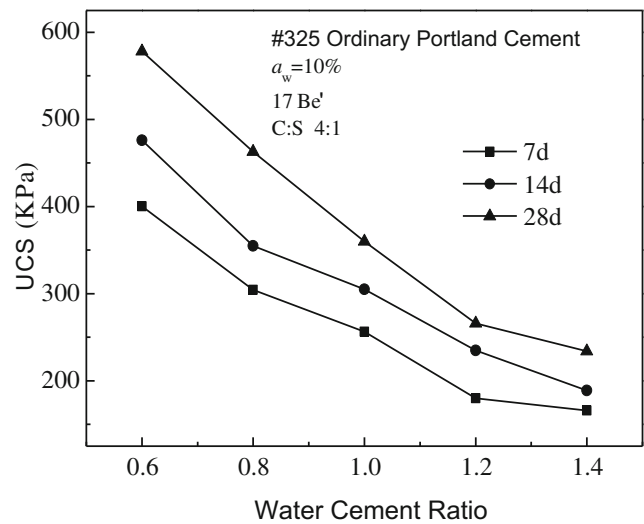

Fig. 27 Stress-strain relationship

Fig. 28 Unconfined compression strength versus ratio of water and cement

failure of the specimen were 0.6, 1.4, 1.3, 1.2, and 1.2%, respectively, for the following water-cement ratios 0.6:1; 0.8:1; 1:1; 1.2:1; and 1.4:1.

Effect of cement-water glass ratio on compressive strength

Figures 30 and 31 are respectively the effect of CS ratio on the unconfined compressive strength and the stress-strain relationship after 28 days curing. It can be seen that the compressive strength of specimens with CS ratio of 4:1 is significantly higher than that of CS of 2:1 and 1:1. To be more specific, CS ratio has a substantial effect on the strength of the specimen. From Fig. 31, it can be concluded that the stress-strain curve of the specimen with CS ratio of 4:1 develops quickly. Besides, there is no obvious plastic deformation, and failure
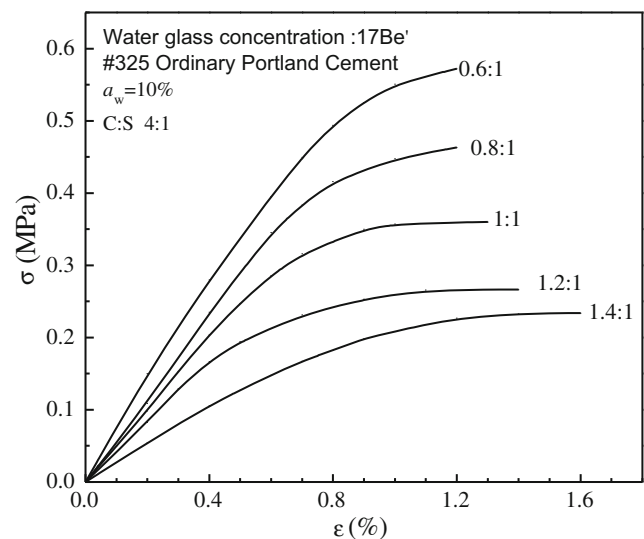

Fig. 29 Stress-strain curves of test samples in different ratios of water and cement
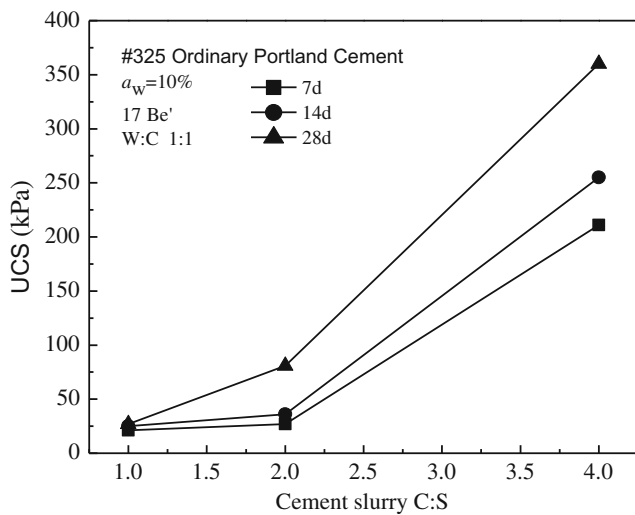
Fig. 30 UCS versus different ratios of C:S

strain value is small, only 1.3%. On the other hand, for the CS ratio of 2:1 and 1:1, specimen stress-strain curve is characterized by a slower growth and a relatively larger value of failure strain (2 and 4% respectively). What is more, with a CS ratio of 4:1, the strength is only 7.6 and 22.5% of the compressive strength of the specimen. Therefore, the excessive use of water glass considerably affects the quality of the constructed element, in addition to be an economic loss. This aspect is thus crucial in the determination of the reasonable proportion to be implemented.

Effect of cement type on compressive strength

It can be seen in Fig. 32 that the UCS of the high-grade cement specimen is higher than that of the low-grade cement reinforced soil under the same cement content. In the case of high cement content, the compressive strength of unconfined
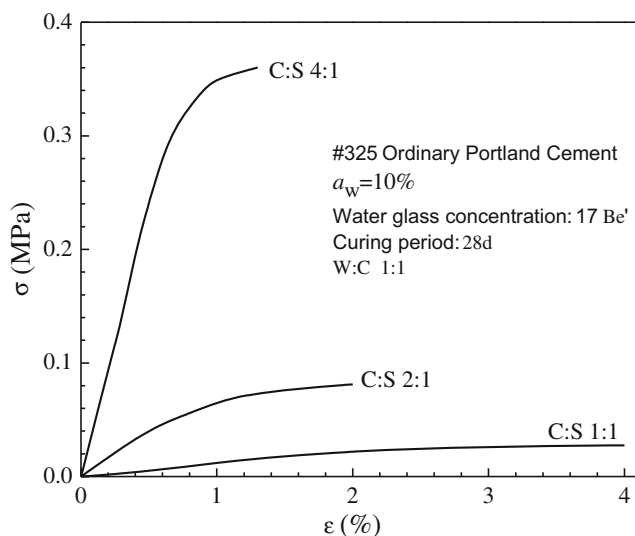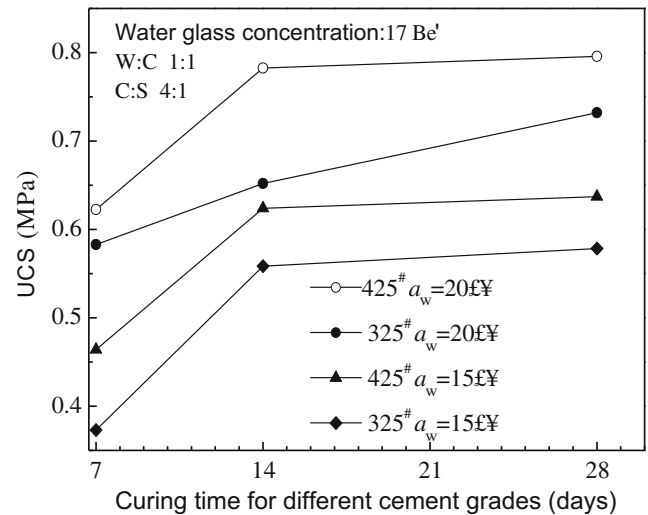

Fig. 32 UCS versus curing time of samples with different types of cement

compressions increased significantly after 28 days of curing. Therefore, the cement varieties can also be considered as one of the main factors influencing the strength of the reinforced soil. From the analysis of Fig. 33, we can see that with the increase of cement content and labeling, the stress increases with strain.

Discussion

Based on investigation described above, it appears that the water glass concentration, water-cement ratio, cement variety, and CS ratio are the chief factors that affect the unconfined compressive strength of the twin-jet-grouted element. However, the effect of some factors is more pronounced than that of the others. For instance, it was found that along with the increase of the cement content, the strength of the specimen rapidly increased with the curing time. Although this effect

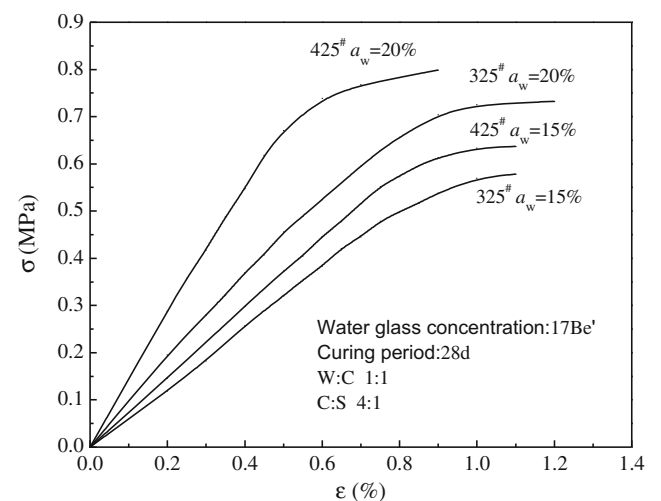Fig. 31 Stress-strain relationship for different ratios of C:S

Fig. 33 Stress-strain curves of test samples mixed with different grades of cement

was not obvious for small cement content (5%), a substantial escalation (five to six times higher) of the UCS was noticed for three times the previous value of cement content, respectively, after 14 and 15 days of curing. In addition for higher values of the cement content, the UCS barely doubled from one curing period to another one; this may indicate the possibility to obtain the targeted compressive strength by correlating the cement content with the curing time. Furthermore, it was observed that the smaller the water-cement ratio, the higher the compressive strength of the specimen. Therefore, the inadequate increase of the cement-water content is detrimental to the economics of the twin-jet method in terms of quality and control. In particular, the disproportionate prescription of water-cement ratio may result in a poor mixing quality of the grouted element. Nonetheless, as discussed by Eskisar (2015), increase of the cement content can result in the increase of the mixture workability. On the other hand, the influence of the ratio of the cement slurry (CS) and water glass on the compressive strength of the reinforced specimen was also demonstrated. It was noticed that the UCS increase sharply with the increase of cement slurry-water glass ratio. Then again, it is believed that in addition to be an economic loss, the excessive use of water glass may result in the increase of soil moisture content and so affect the mixture compressive strength throughout its gelling. Also, as highlighted above, in such conditions, the quality of the construction may be jeopardized. In the same perspective, the effects of water glass concentration and cement variety on the UCS were found to be less significant. Indeed, by varying different varieties of cement at different water contents, a very slight increase in the resistance to compression was observed. After a period of 14 days, it was noticed that with the aging of the specimen, the resistance to compression tended to be constant. Yet, in spite of the fact that the UCS of the high-grade cement specimen was found higher than that of the low-grade cement reinforced soil, based on Fig. 22, the adoption of ordinary portland cement no. 325 with a 20% content arguably seems to be the best scheme, from an economical and mechanical points of view. Using a similar approach, it was also possible to establish the optimum value of the concentration of water (see the corresponding section).

Synopsis and future perspectives

On one hand, as demonstrated by the previous sections, the jet grouting technology has considerably evolved from the Chemical Churning Pile (CCP) to more innovative and efficient technologies. As a matter of fact, the field challenges and the quest for grouted columns more and more efficient have triggered the development of new jet grouting systems. However, the choice of an appropriate treatment method (mono-fluid, bi-fluid, tri-fluid) usually considers several

criteria, such as the mechanical performance, geometrical characteristics, economic criterion, and ease of implementation. Interestingly, the most significant difference between the above-discussed jet grouting variations is the diameters of column obtained in each case and for the similar soil conditions. As a matter of illustration, it was observed that at equal energy, the radius of columns performed with the bi-fluid system was approximately two times the one obtained with the mono-fluid system. From an economic point of view, the mono-fluid method is advantageous when it comes to producing small diameter columns, whereas the multi-fluid systems (bi- and tri-fluid systems) can easily accomplish bigger geometries, generally up to 3 m. Moreover, to the extent that the bi-fluid and the tri-fluid systems significantly reduce the number of inclusions (number of operation), these two methods significantly improved the construction speed. This aspect is particularly relevant for cases of mass treatment, where the overlapping of grouted columns is prevalent. Furthermore, the tri-fluid system is the best underpinning system and the system that gives the highest quality under challenging soils (Burke 2004).

On the other hand, even if the jet grouting technology is continuously ameliorated (Atangana et al. 2018), further developments must be concerned about three fundamental issues: technology, environment, and modeling. Regarding the first point, improving the functionality, the flexibility, and the reliability of the jet grouting equipment may positively affect the implementation conditions. In particular, the heaviness, the shape, and the functioning of the monitor (and or the drill stem) can be considered for optimization, as they significantly influence the construction process. For instance, recently developed (innovative) solutions have focused on the production of multifan-shaped or elliptical jet grouting columns that are more viable and economic. They are particularly integral when it comes to constructing bottom plugs or retaining structures (Shinsaka et al. 2017; Leoni and Pianezze 2017).

Ensuring the spoil backflow and more importantly managing it is a formidable task in jet grouting practice. At this stage, a sustainable development approach is necessary and should integrate the recycling and reuse of the soil-cement mixture that returns at the surface. For this purpose, setting up a special treatment station is thus conceivable.

Finally, performed new advances in jet grouting also involve developing new modeling techniques. Although the available analytical and numerical models performed satisfactorily so far, new realms should be explored, particularly when the latter seem promising and tend to simulate the jet grouting phenomena better. The smoothed particle hydrodynamics (SPH) belongs to the set of methods possessing attractive features. It is a meshfree Lagrangian computational technique initially developed for astrophysical applications (Gingold and Monaghan 1977; Lucy 1977) and subsequently extended to fluid dynamics and solid mechanics. The SPH is in fact

believed to be suitable for simulating specific behaviors of soils arising from its particulate nature, which is not the case with traditional methods. Another example is its capacity to model the erosion mechanism of the soil by hydraulic jet (Bui et al. 2007). Additionally, regarding the prediction of jet grouting column diameter, the application of artificial intelligence was found promising (Ochmański et al. 2015a; Tinoco et al. 2016) and has paved the road for new approaches such as analytic hierarchy process (AHP) (Lyu et al. 2018a, b, c) and deep learning technique. It should be noted that the different perspectives of jet grouting development highlighted above are not exhaustive, given its versatility and continuous practice.

Conclusions

The present paper has systematically reviewed the development and practice of jet grouting technology through some fundamental concepts and relevant case studies. Additionally, the issue of the twin-jet grouting efficacy was discussed on the basis of laboratory experiment reported herein. The following conclusions can be made:

(i) Jet grouting was originally initiated in the UK and progressively developed following the needs of wider geometry, ease of implementation, economic rationality, and better mechanical properties. Although its use was initially circumscribed in Japan, the jet grouting technique was later gradually spread throughout China, the USA, and Europe. This method has demonstrated a reliable ability in coping (horizontally or vertically) with the most problematic challenges.

(ii) When implemented with the same jetting energy, the double-fluid system is practically two times more effective than the mono-fluid system. Moreover, thanks to their aptitude to reduce the number of operation, the double- and the triple-fluid systems allow to significantly improve the construction speed. These systems are therefore more indicated for the cases of mass treatment where the overlapping of grouted columns is prevalent.

(iii) The single-fluid system is the more polyvalent variation; in fact, its implementation is more indicated for coarse, silty, and clayey soils. With respect to the geological conditions, the general characteristics (mixing uniformity, geometry, mechanical properties) of the jet-grouted elements obtained with the different jet grouting variations were as a rule found satisfactorily. These characteristics are affected by some factors applicable to jet grouting modeling, namely, the jetting energy, the nature of the strata, and the properties of the mixtures.

(iv) The laboratory program proposed in this paper allowed determination of some parameters having a direct influence on the UCS. It follows that, at the same cement content, the UCS of high-grade cement specimen is higher than that of the low-grade cement reinforced soil. Comparably, the strength of the specimen increases: sharply along with the increase cement slurry-water glass ratio and rapidly along with that of the cement content. Conversely, the UCS substantially decreases as the water-cement ratio increases.

(v) The unconfined compressive test is the quintessential laboratory approach for the quantitative evaluation of the mechanical properties of jet grout elements, as well as the description of some crucial jet grouting concepts such as jet grouting efficacy and the economical usage of jet grouting.

(vi) In terms of construction control and quality, as well as economic rationality, the efficacy of the twin-jet grouting method primarily depends on the proper adequacy of the key parameters used in the mixtures. These parameters are principally the cement content, the water cement ratio, and cement slurry-water glass ratio. The inadequate increase of the cement-water content is detrimental to the economics of the twin-jet method. Yet the excessive prescription of cement slurry-water glass ratio may affect the mixture quality and to some extent result in economic losses.

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