Statistical interpretation of jet grouting field data regarding its strength and stiffness

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Abstract

Jet-grouting technique is one of the most widespread methods for soil reinforcement, used to make soil suitable to withstand forces transmitted by structures or the redistribution of stresses following excavations. The result of the treatment however is influenced by several factors, including type of treatment, type of soil, original stress state of the soil, machine operating parameters, and water-to-cement ratio. In particular, the strength of the treated material and its stiffness are very useful for designing the intervention for a specific case. Due to the uncertainty of the final strength and stiffness values, a test field is almost always required. But the design of the test field itself and the subsequent design of the intervention require some preliminary information on the expected values of the strength and the elastic modulus. An in-depth analysis of the scientific literature was conducted, allowing for the selection of a significant number of cases. For each case, the type of treatment, the type of soil, uniaxial compressive strength (UCS), and elastic modulus (E) values were recorded. It was possible to determine the trend of the average UCS values and the E/UCS ratio for each type of analyzed soil and for the two studied jet-grouting techniques. In addition to the average values, the variability intervals, centered on the mean, capable of enclosing 90% of the data in the sample were identified. The obtained graphs represent a useful tool for obtaining a preliminary estimate of the strength and stiffness of the treated soil using the jet-grouting technique.

Key words: jet grouting; cohesive soils; coarse soils; UCS; elastic modulus; statistical analysis; predictive estimation.

Introduction

The construction of underground works may require preventive consolidation interventions. Due to excavation in tunnels, for instance, the properties of the ground change (e.g., Zaheri and Ranjbarnia 2022; 2023). Therefore, ground improvement techniques are particularly useful in inconsistent or low-strength ground, especially in urban areas for the protection of buildings (De Rienzo et al. 2009). Grouting and temporary freezing (particularly suitable in fine-grained soils) are the best-known techniques (Lunardi et al. 1986). Permeation (chemical) grouting techniques can be employed down to silty-sandy soils, but uncertainties and costs increase as the in-situ permeability limit is approached, i.e., 10-6 m/s (Lunardi et al. 1986; Fraccica et al. 2022). Jet grouting is an alternative to chemical grouting, which can be expensive and may cause hazardous and structural issues. The basic procedure of jet grouting involves injecting grout into the subsurface at high pressure and velocity (e.g., Bergado and Lorenzo 2003; Shen et al. 2013; Croce et al. 2014).The mechanical properties of jet-grouted material can be significantly impacted by the composition of the original soil (cohesive or coarse), the utilized cement (CEM I, II, III…), the use of additives (e.g., bentonite, sodium silicate), and how well the soil is mixed and replaced by the cement (Croce et al. 2014).Field trials involve carrying out initial jet grouting treatments and conducting necessary testing to confirm that treatment outcomes adhere to design specifications. These trials assess mean column diameters and strength based on grouting parameters (flow, pressure, retrieval rate, rod rotation) and soil properties. Analyzing field trial outcomes may lead to reassessment of initially proposed solutions (Croce et al. 2014). Typically, uniaxial compressive strength (UCS) and sometimes stiffness are used to mechanically assess the quality of improved soils. According to Xanthakos et al. (1994), UCS values for jet-grouting material range from 1.5–10 MPa for fine-grained soils and 10–30 MPa for coarse-grained soils. The elastic modulus E, is normally 100 to 300 times the UCS values (JSG Association 1986). From a geotechnical perspective, estimating the UCS and E50 relationship based on jet grouting type and soil type can be valuable. This paper considers six studies that indicate UCS and E-values (sometimes specified as E50, sometimes not). A statistical analysis examines how these values vary based on soil type (coarse and cohesive) and jet grouting technique (single-fluid or double-fluid). Additionally, a confidence interval and prediction of the two mechanical parameters are developed as a function of soil type. The study yielded trends in mean UCS strength values and E/UCS ratios for different soil types and the two analyzed jet-grouting methods. Through statistical analysis, expected values (with 90% probability) of variability intervals for these parameters were identified, providing a preliminary estimate of treated soil strength and stiffness. This information is useful for defining test fields and designing soil reinforcement interventions.

Jet grouting technique

In Japan, the jet grouting technique was first developed approximately 40 years ago as a method of ground renovation to improve soils (Miki 1973; Yahiro and Yoshida 1973). Jet grouting technology erodes the soil using small-diameter nozzles to inject high-speed fluids into the subsoil. The eroded soil is then combined with injected grout to create a quasi-cylindrical soil-cement column. Based on the quantity of fluids injected into the subsurface, the various techniques are generally categorized into three primary jet grouting systems: single, double, and triple fluid systems (e.g., Brill et al. 2003; Shibazaki 2003; Burke 2004; Croce et al. 2014). In the single fluid system, one or more nozzles are used to inject water-cement grout into the ground. In this instance, the same fluid is responsible for both soil remolding and subsequent cementation. As air is not employed, single-fluid jet grouting produces less spoil compared to double-fluid systems (see Fig. 1).

In the double fluid system, water-cement grout is the only fluid used for both soil disaggregation and cementation. However, the grout jet is surrounded by a coaxial air jet, which increases the efficacy of the grout by reducing energy losses. This air jet is provided by a co-axial annular nozzle positioned around the grout nozzle. When using the triple fluid technique, cementation and soil remoulding are distinct processes. Specifically, soil disaggregation is caused by a high-velocity water jet delivered through a nozzle on the upper portion of the monitor. This water jet is surrounded by a coaxial air jet, powered by an annular nozzle similar to the one used in the double system. Then, a separate nozzle situated on the monitor's lower section delivers the water-cement grout. In this case, the grout is applied at a reduced velocity as its sole function is to cement the soil that the water jet had previously remoulded. Typical operational values for the three techniques are reported in Tab. 1, based on the authors' real job site expertise. Accelerators, hardening accelerating additives, and superplasticizers can also be used to improve and modify the strength of the grouted materials and the column diameters (e.g., Gurpersaud et al. 2013; Shen et al. 2013; Spagnoli et al. 2022).

Fig. 1. Single-fluid jet grouting with little spoil production (top) and double-fluid jet grouting with higher spoil production (below) (personal pictures).

Tab. 1. Main parameters of the three jet grouting types based on the authors' field experience.

Parameter	Single-fluid	Double-fluids	Triple-fluids
Water-cement ratio (-)	1.0-1.5	1.0-1.5	1.0-1.5
Grout-pressure (bar)	400-600	400-600	50-100
Nozzle diameter (mm)	1.8-2.8	2.0-2.5	4.5
Withdrawal rate (cm/min)	15-100	10-30	6-15
Rotation speed (rpm)	5-15	4-9	4-9
Grout flow (l/min)	70-600	70-600	70-600
Air flow (l/min)	-	7000-8000	4000-12000
Air pressure (bar)	-	6-20	7-12
Air nozzle (mm)	-	23	21-23
Water pressure (bar)	-	-	400-600
Water flow (l/min)	-	-	40-100
Water nozzle (mm)	-	-	2.3

Data on jet grouting considering UCS and E-modulus

Field data from Collotta et al. (2004), Fang et al. (1994; 2006), Lunardi et al. (1986), Shen et al. (2013), and van der Stoel and van Ree (2000), where field tests were performed and UCS and elastic modulus values were gathered, were analyzed. A total of 109 data points were collected. The literature data used for the statistical analysis consider single and double-fluid jet grouting in silt, silty sand, sandy gravel, sand, clay, peat, pure sand, and silty clay, as described in detail in the original papers. For the sake of simplicity, these soil types have been categorized as coarse (silty sand, sandy gravel, sand) and cohesive (silt, clay, peat, and silty clay). This subdivision results in a reasonable split with 52 data points for "coarse" and 57 data points for "cohesive" soils. Fig. 2 shows the diagrams of E-modulus vs UCS for coarse (Fig. 2A) and cohesive (Fig. 2B) soils. Coarse data show some deviation from the relation E50 = 300·UCS, with some elastic modulus values exceeding this ratio. For the cohesive soils, all data plot within the range provided by the JSG Association (1986).

It must be pointed out that the values were selected only if:

- clear UCS and E-modulus of the jet-grouted material were stated in the reviewed papers;
- the type of soil was provided, and,
- the type of jet grouting was indicated.

It is also interesting to note that, in general, but more clearly for coarse soils, UCS and E-modulus values are higher for the single-fluid rather than the double-fluid system. UCS is influenced by the cement-to-water ratio and the type of treatment system (single, double, or triple fluid). Due to the presence of air, double-fluid jet grouting is expected to produce lower compressive strength compared to single-fluid. The experimental findings published by van der Stoel (2001) support this aspect.

As regards the single-fluid method, it is possible to observe how:

- For clays, the elastic modulus of jet-grouting varies from 175·UCS to 450·UCS, with an average value of approximately 275.2·UCS; UCS varies from 1.5 to 18 MPa, with an average value of 7.3 MPa.

- In sands, the elastic modulus of jet-grouting varies from 175·UCS to 550·UCS, with an average value of approximately 306.7·UCS; the UCS strength varies from 5 to 50 MPa, with an average value of 20.0 MPa.
- In sandy gravels the elastic modulus of jet-grouting varies from 500·UCS to 1500·UCS, with an average value of approximately 898.3·UCS; the UCS strength varies from 10 to 30 MPa, with an average value of 19.8 MPa.

As regards the double-fluid method, it is possible to note how:

- For clays, the elastic modulus of jet-grouting varies from 130·UCS to 220·UCS, with an average value of approximately 164.8·UCS; the UCS strength varies from 2 to 6 MPa, with an average value of 3.1 MPa.
- For silty clays, the elastic modulus of jet-grouting varies from 75·UCS to 120·UCS, with an average value of about 98.8·UCS; the UCS strength varies from 0.5 to 1.2 MPa, with an average value of 0.8 MPa.
- In silts, the elastic modulus of jet-grouting varies from 130·UCS to 260·UCS, with an average value of about 191.6·UCS; the UCS strength varies from 8 to 24 MPa, with an average value of 16.5 MPa.
- In silty sands, the elastic modulus of jet-grouting varies from 170·UCS to 300·UCS, with an average value of about 247.7·UCS; the UCS strength varies from 9 to 25 MPa, with an average value of 14.6 MPa.
- In sands, the elastic modulus of jet-grouting varies from 90·UCS to 200·UCS, with an average value of about 129.4·UCS.

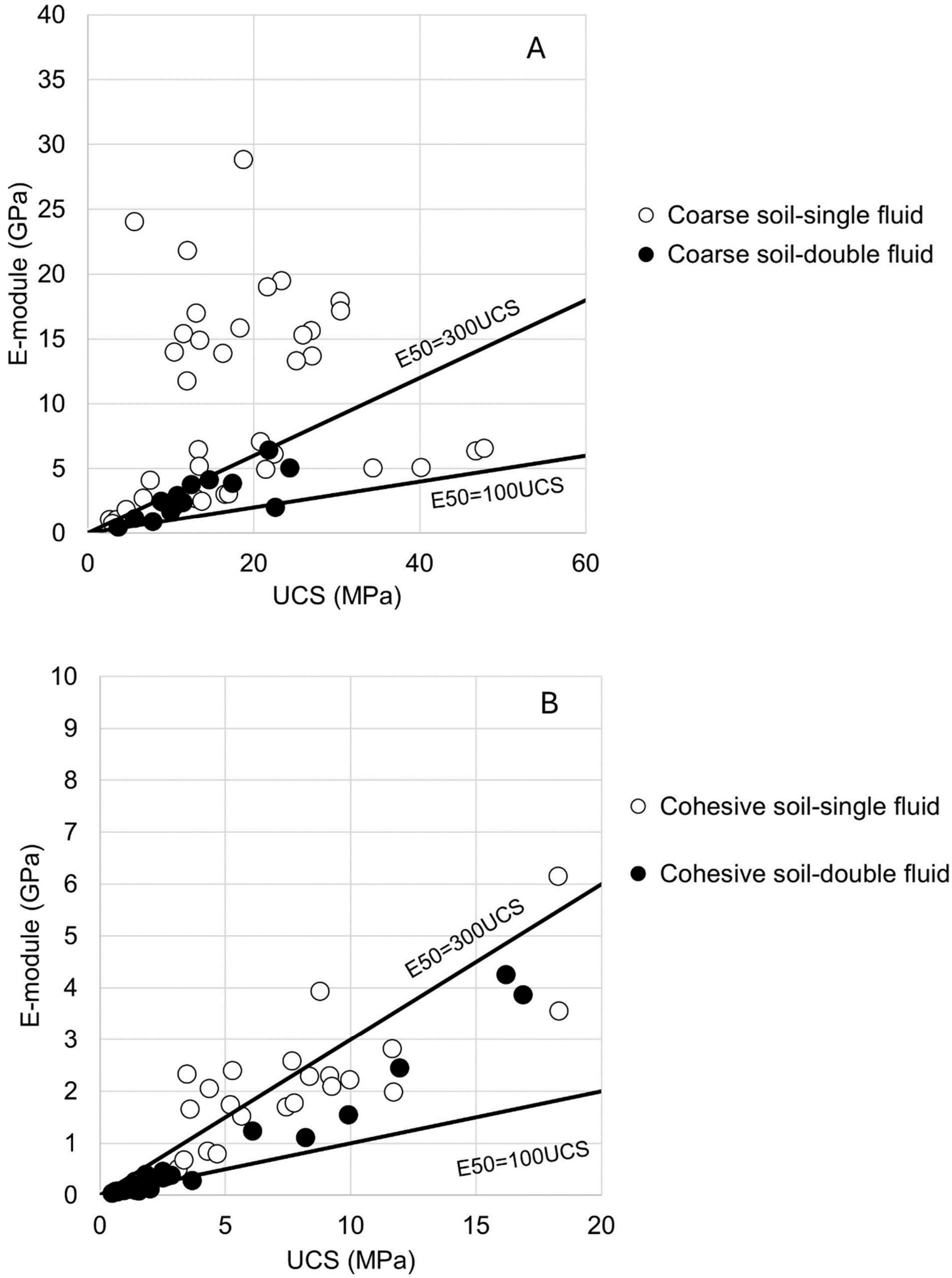

Fig. 2. Elastic modulus (E-modulus) versus Unconfined Compressive Strength (UCS) for coarse soils (A) and cohesive soils (B) based on data from Collotta et al. (2004), Fang et al.

(1994; 2006), Lunardi et al. (1986), Shen et al. (2013), and van der Stoel and van Ree (2000).

Statistical analysis of the data

The UCS and E-modulus data were analyzed considering:

- The distribution of the data;
- The variance of the data;
- The medians (or means) of the data, and;
- The confidence interval of the data.

Distribution of the data

All data sets were tested for normality, by using the Anderson–Darling normality test (Stephens 1974). The particular distribution is used by the Anderson-Darling test to determine critical values. The definition for the test statistic A of the Anderson-Darling test is (Stephens 1974):

$$A^2 = -N - S \quad (1)$$

where

N is the number of elements in the sample

$S = \sum_{i=1}^{N} \frac{(2i-1)}{N} [lnF(Y_i) + \ln(1 - F(Y_{N+1-i}))]$

F is the cumulative distribution function

i is the ith sample, calculated when the data is sorted in ascending order.

This approach has the benefit of making the test more sensitive, but it also has the drawback of requiring the calculation of critical values for every distribution. Figs. 3 and 4 show, as an example, the probability plots for UCS and E-moduli for single-fluid and double-fluid systems, respectively, in coarse soils. The probability plot is a graphical method for determining whether a data set follows a specific distribution, such as the normal distribution (Chambers et al. 1983). When plotting the data against a theoretical distribution, the points should form a roughly straight line. Deviations from this linear pattern signify deviations from the designated distribution. Results show that while the data for double-fluid systems in coarse soils are normally distributed for both parameters, the single-fluid values deviate from the straight line, with p-values close to (Fig. 3A) or less than 0.01 (Fig. 3B), indicating that the data are likely not normally distributed. For the other values of UCS and E-moduli in cohesive soils for both single-fluid and double-fluid systems, data are not normally distributed (not shown).

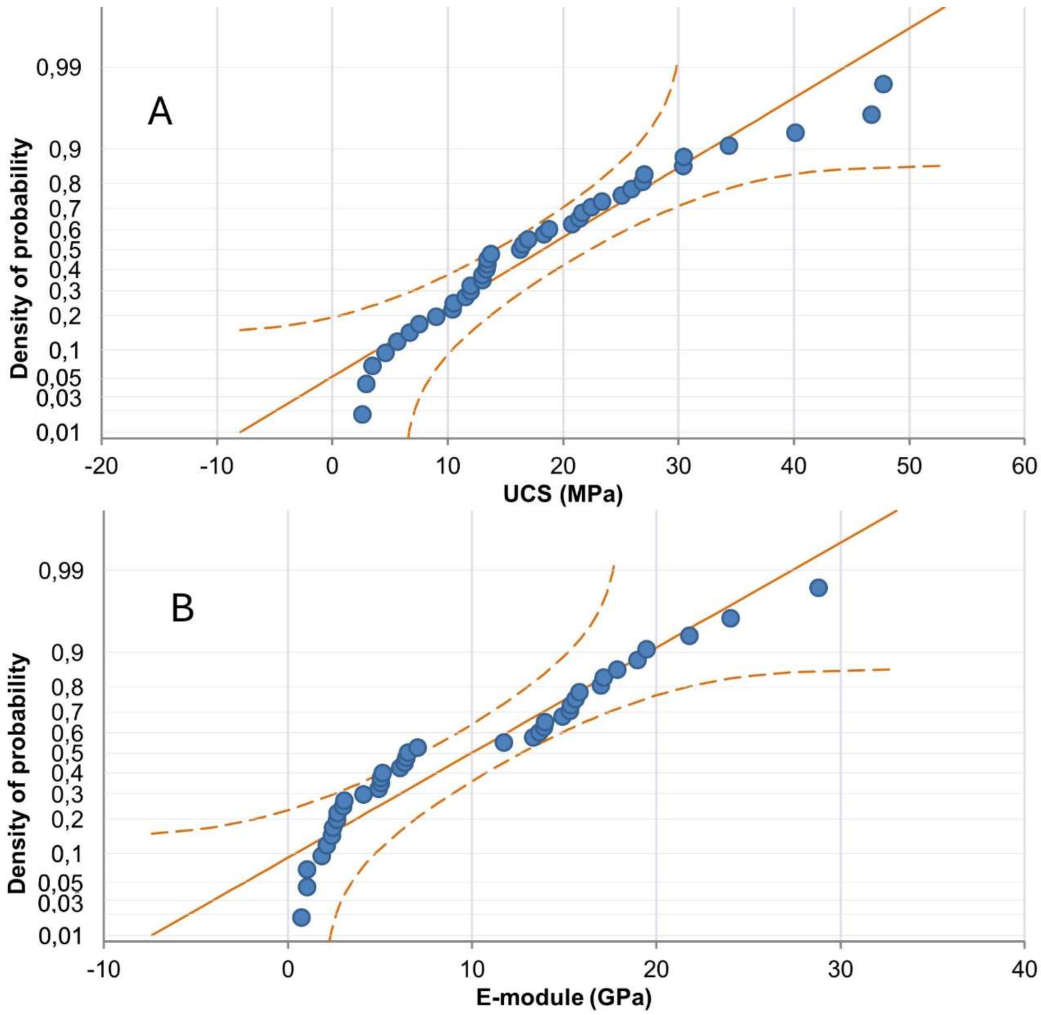

Fig. 3. Probability plots for single-fluid for UCS (A) and E-module (B) in coarse soils.

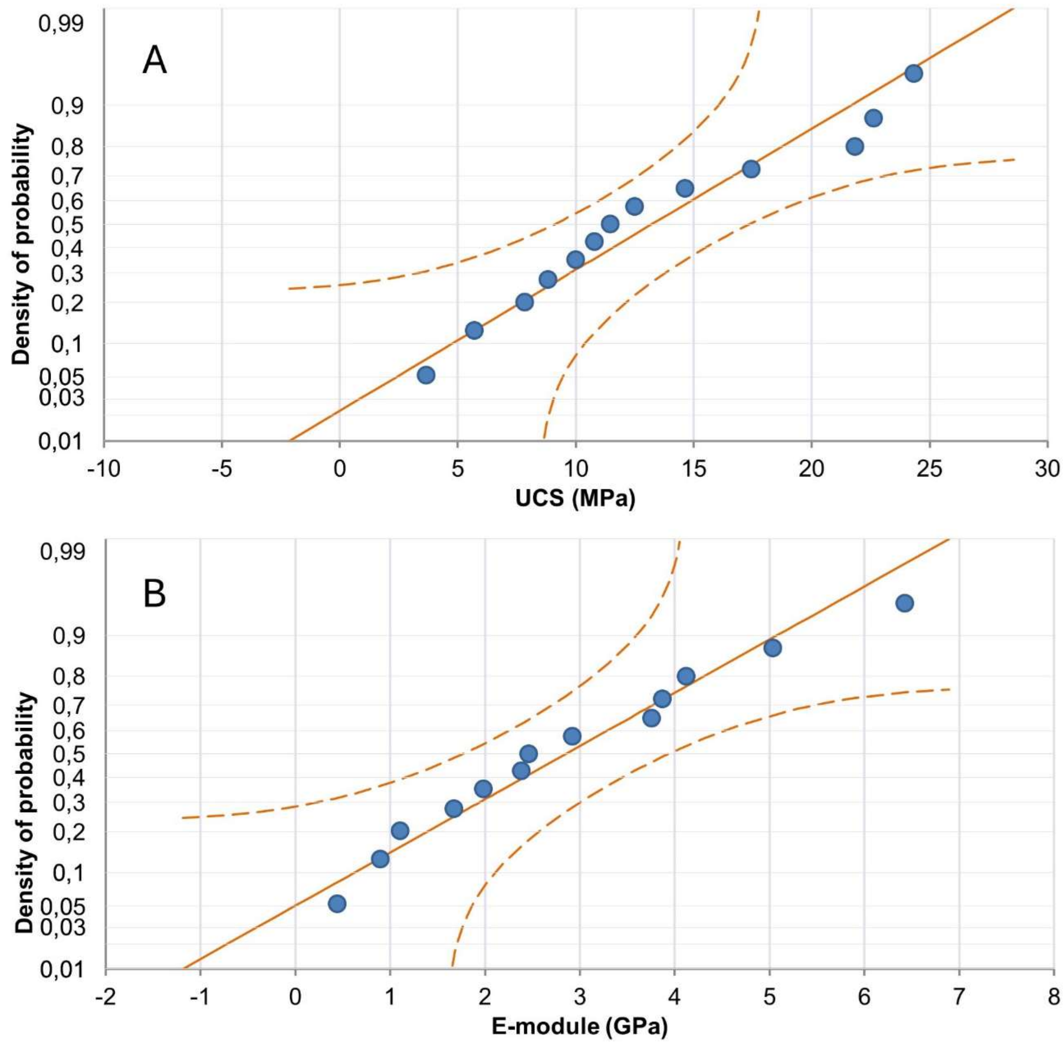

Fig. 4. Probability plots for double-fluids for UCS (A) and E-module (B) in coarse soils.

Figs. 5 and 6 show histograms and probability distributions of the data shown in Figs. 3 and 4. Fig. 5 shows that for UCS and E-modulus data, the fitting distributions are 2-parameter Weibull and 2-parameter exponential, respectively. Fig. 6 shows that UCS and E-modulus data are normally distributed. For the sake of transparency, UCS and E-modulus values for cohesive soils grouted with single-fluid are best fitted by 2-parameter LogNormal and 2-parameter Weibull distributions, respectively, while the double system data are best fitted by 2-parameter Log Logistic and 2-parameter LogNormal distributions, respectively.

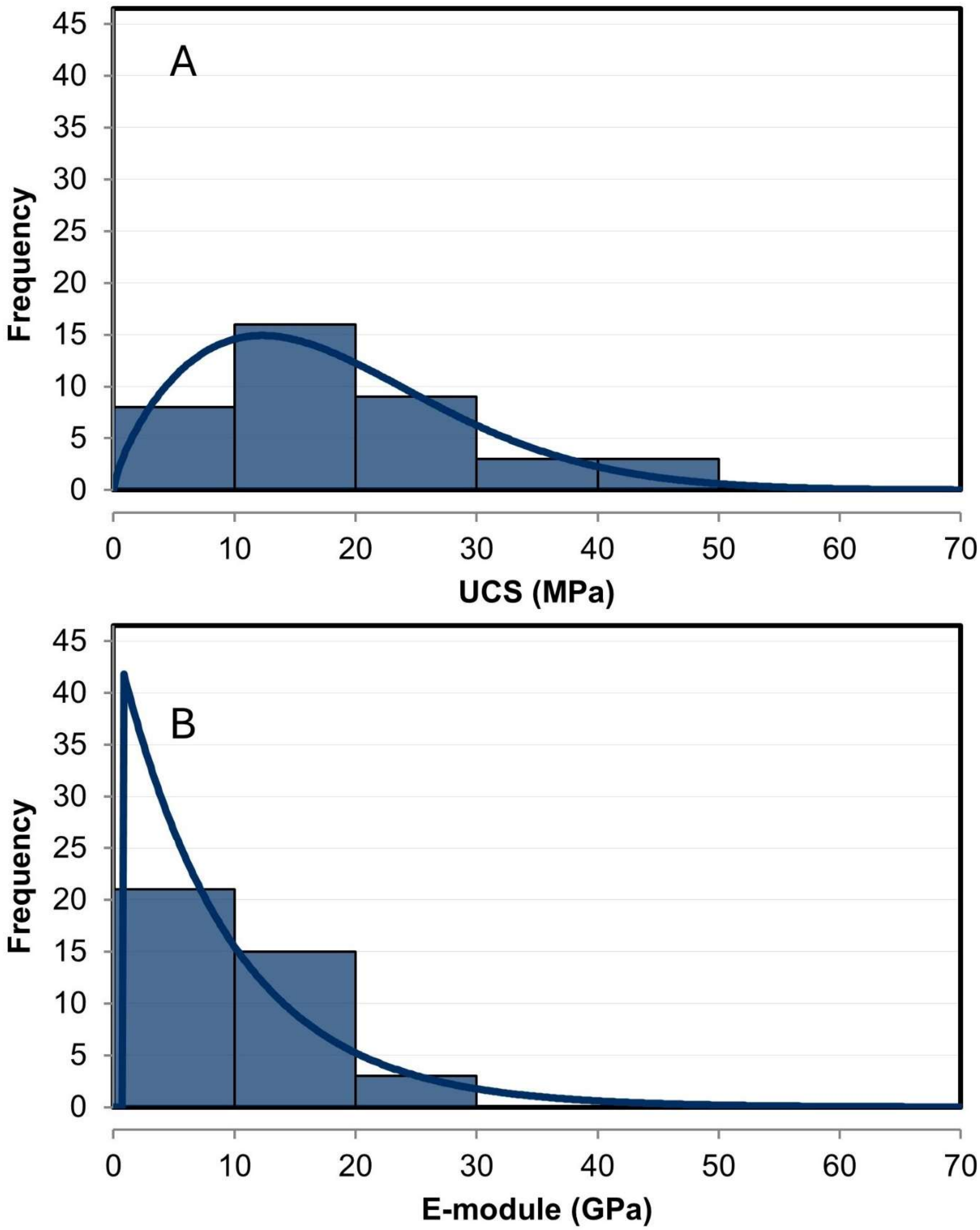

Fig. 5. Histogram and distribution of the data for single-fluid for UCS (A) and E-module (B) in coarse soils.

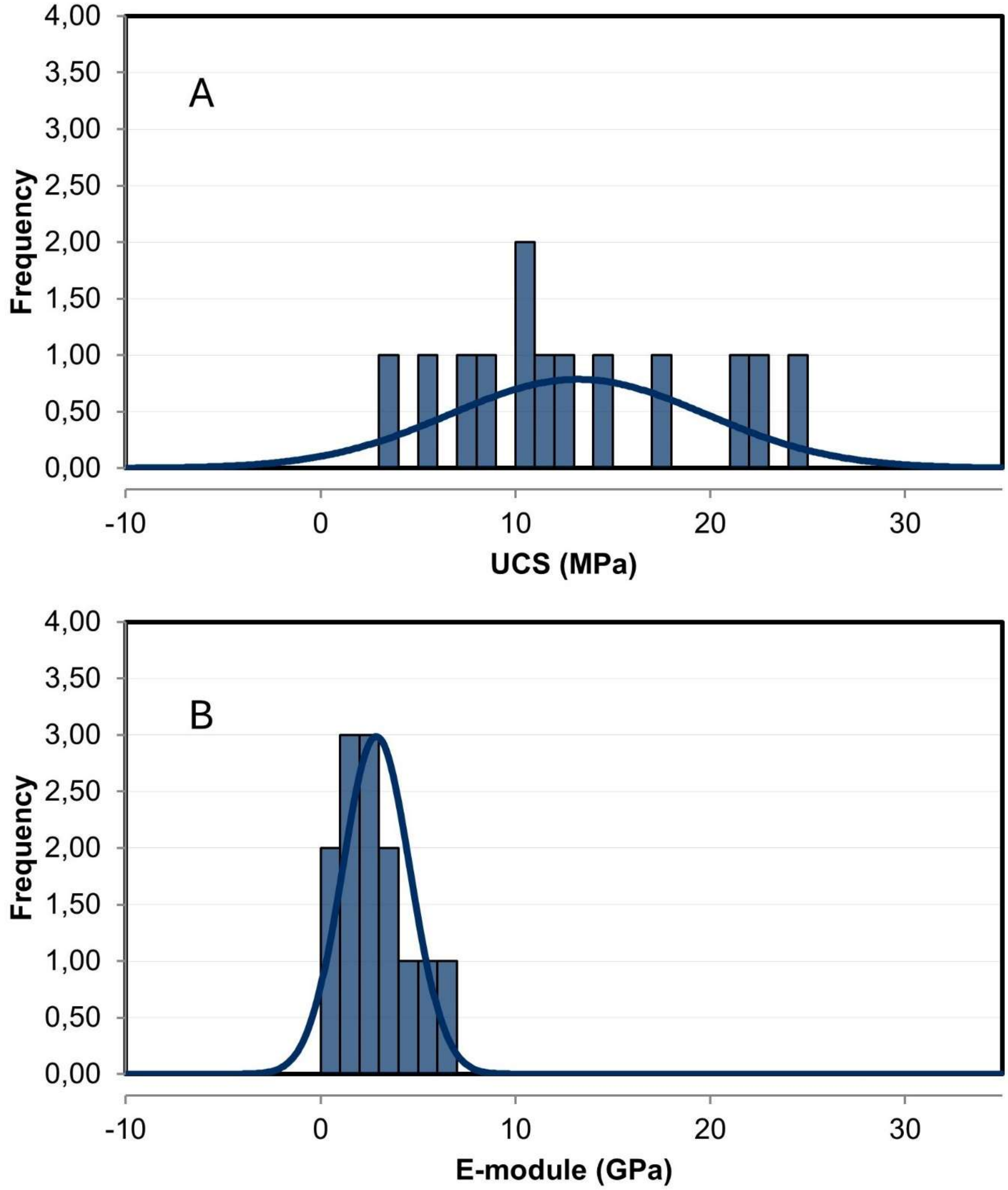

Fig. 6. Histogram and distribution of the data for double- fluids for UCS (A) and E-module (B) in coarse soils.

Variance and median (or mean) of data

The goal of analyzing the variance of the data was to understand the spread between the values in a dataset for UCS and E-modulus for the single and double-fluids data. This comparison was carried out and is also valid for the mean or median values.

1. UCS coarse mono-fluid vs UCS cohesive mono-fluid;
2. UCS coarse double-fluids vs UCS cohesive double-fluids;
3. E-module coarse mono-fluid vs E-module cohesive mono-fluid;
4. E-module coarse double-fluids vs E-module cohesive double-fluids;
5. UCS coarse mono-fluid vs E-module coarse mono-fluid;
6. UCS coarse double-fluids vs E-module coarse double-fluids;
7. UCS cohesive mono-fluid vs E-module cohesive mono-fluid;
8. UCS cohesive double-fluids vs E-module cohesive double-fluids.

Different techniques were used for comparing the variance and median (or mean). When data are not normally distributed, the test focuses on the median since the mean is no longer the best measure of central tendency. Table 2 summarizes the results. For non-normally distributed values, the variance was calculated using Levene's test (Levene 1960), while the Mann-Whitney test (Mann and Whitney 1947) was used for the median. For normally distributed values, the F-test (Berger et al. 2018) was used for the variance, and the two-sample t-test (Snedecor and Cochran 1989) was used for the mean.

For the majority of the data, the values do not have the same variance or median. This is due to the heterogeneity of the data points.

Tab. 2. Comparison for variance and mean (or median) for the UCS and E-module values.

No.	**Comparison**	**Variance**	**Median (or mean)**	**Test used**

1	UCS coarse mono-fluid vs UCS cohesive mono-fluid	Not equal (p-value < 0.05	Not equal (p-value < 0.05	Levene (variance) Mann-Whitney (median)
2	UCS coarse double-fluids vs UCS cohesive double-fluids	Equal (p-value > 0.05)	Not equal (p-value < 0.05	Levene (variance) Mann-Whitney (median)
3	E-module coarse mono-fluid vs E-module cohesive mono-fluid	Not equal (p-value < 0.05	Not equal (p-value < 0.05	Levene (variance) Mann-Whitney (median)
4	E-module coarse double-fluids vs E-module cohesive double-fluids	Equal (p-value > 0.05)	Not equal (p-value < 0.05	Levene (variance) Mann-Whitney (median)
5	UCS coarse mono-fluid vs E-module coarse mono-fluid	Equal (p-value > 0.05)	Not equal (p-value < 0.05	Levene (variance) Mann-Whitney (median)
6	UCS coarse double-fluids vs E-module coarse double-fluids	Not equal (p-value < 0.05	Not equal (p-value < 0.05	F test Two sample t (mean)

7	UCS cohesive mono-fluid vs E-module cohesive mono-fluid	Not equal (p-value < 0.05	Not equal (p-value < 0.05	Levene (variance)
				Mann-Whitney (median)
8	UCS cohesive double-fluids vs E-module cohesive double-fluids	Not equal (p-value < 0.05	Not equal (p-value < 0.05	Levene (variance)
				Mann-Whitney (median)

Fig. 7 shows comparative box plots for comparisons 1 and 2 as mentioned above. The data dispersion, which is divided into quartiles, is shown using box plots. This technique is applied to identify skewness, dispersion, symmetry, and outliers (if any) in the data (Reagan and Kiemele 2008). In a box plot, the interquartile range (IQR) is represented by a box, with the 25th and 75th percentiles at the bottom and top of the box, respectively. The whiskers extend to 1.5 times the IQR from the edge of the box, representing the final data value inside the inner fence. The height of the box shows the interquartile range. According to Reagan and Kiemele (2008), data points that extend to 3×IQR are considered outliers.

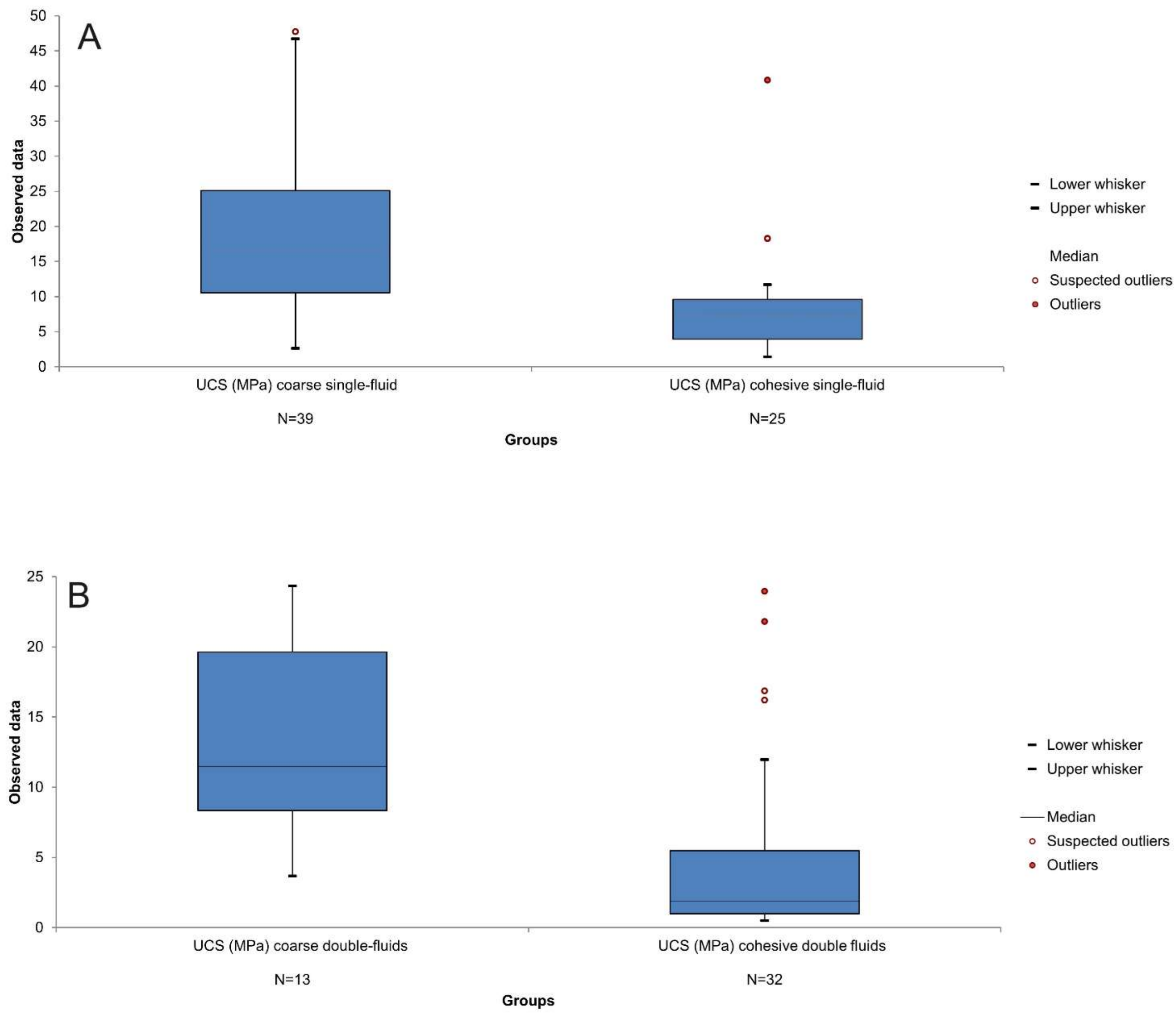

Fig. 7. Comparative box plot for case 1 (UCS coarse mono-fluid vs UCS cohesive mono-fluid) (A) and 2 (UCS coarse double-fluids vs UCS cohesive double-fluids) (B).

Confidence interval and predictions of mechanical parameters as a function of soil types and jet-grouting method

The uniaxial compressive strength and elastic modulus of jet-grouting columns vary significantly depending on the soil type and the operating parameters used. It is almost always necessary to proceed with an in-situ field test to detect the strength and stiffness of the treated soil. However, even in-situ tests require detailed planning and design, which can be based on results obtained in the past for similar soil types using the same jet-grouting techniques intended for adoption. The available data, selected from all those available in the scientific literature, represent a very valuable resource that has been analyzed in detail to obtain the trend of variability intervals as the soil type varies. For the data relating to single-fluid technology, three types of soils were considered in this section: cohesive (clays), coarse (sandy gravels), and intermediate between the two previous ones (sands and silts). The values of the UCS strength and the ratio between the elastic modulus and the UCS (E/UCS) were considered. After calculating the average value of the two parameters for each soil category, the variability intervals (centered on the average value) capable of enclosing 90% of the detected values were evaluated. Figure 8 shows the trend of the average UCS value and its variability interval for the three identified soil types. Figure 9 shows the same results obtained for the E/UCS ratio.

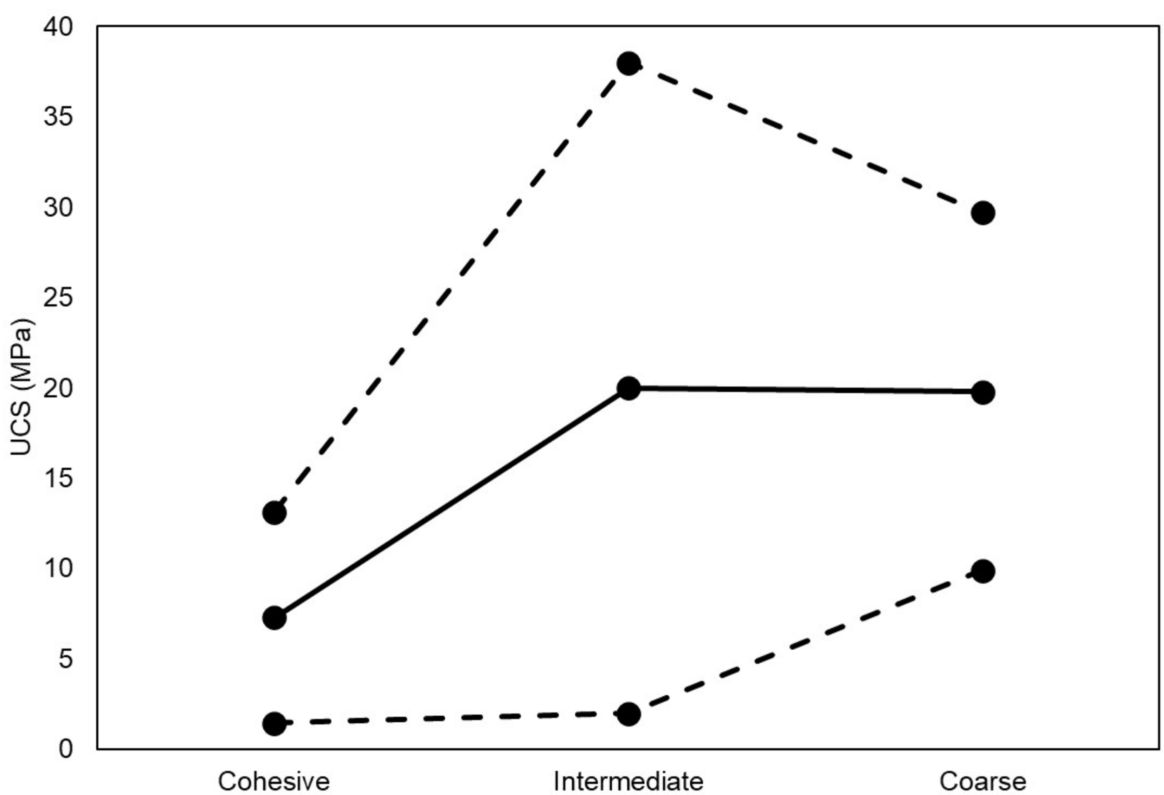

Fig. 8. Single-fluid technology. Trend of UCS strength in the three identified types of soil (cohesive, intermediate, coarse): mean value and variability range that is able to include 90% of the available data. Key: solid line: mean value; dotted lines: minimum and maximum value of the variability range.

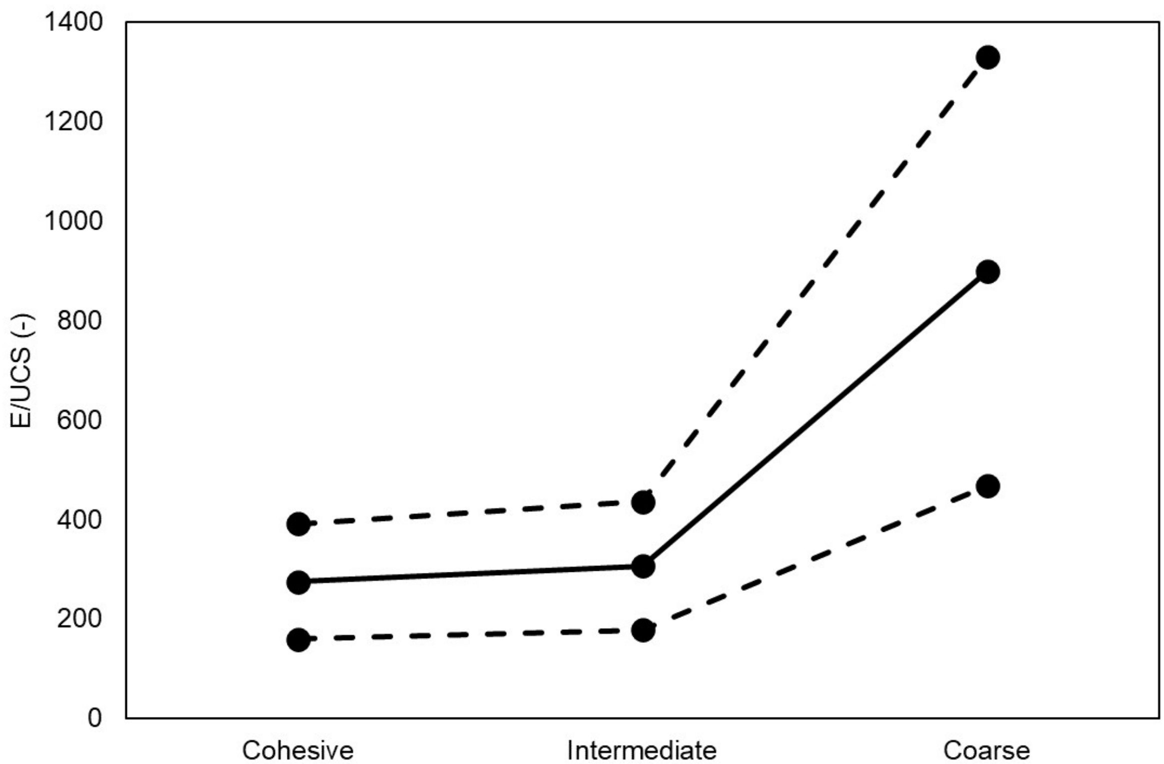

Fig. 9. Single-fluid technology. Trend of the E/UCS ratio in the three identified types of soil (cohesive, intermediate, coarse): average value and variability range that is able to include 90% of the available data. Key: solid line: average value; dotted lines: minimum and maximum value of the variability range.

For the double-fluid technology, the same trends were obtained (Figures 10 and 11) for the following soil types: clay, silty clay, silt, silty sand, sand.

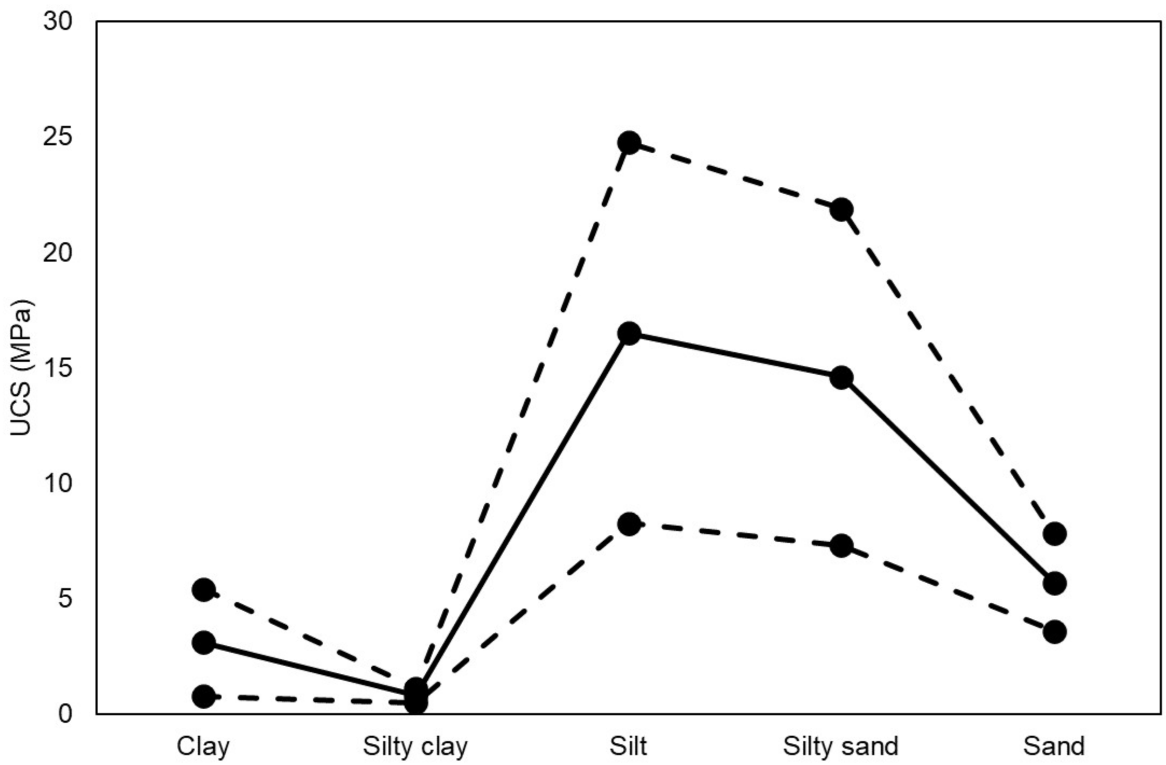

Fig. 10. Double-fluid technology. Trend of UCS strength in the five identified types of soil (clay, silty clay, silt, silty sand, sand): mean value and variability range that is able to include 90% of the available data. Key: solid line: mean value; dotted lines: minimum and maximum value of the variability range.

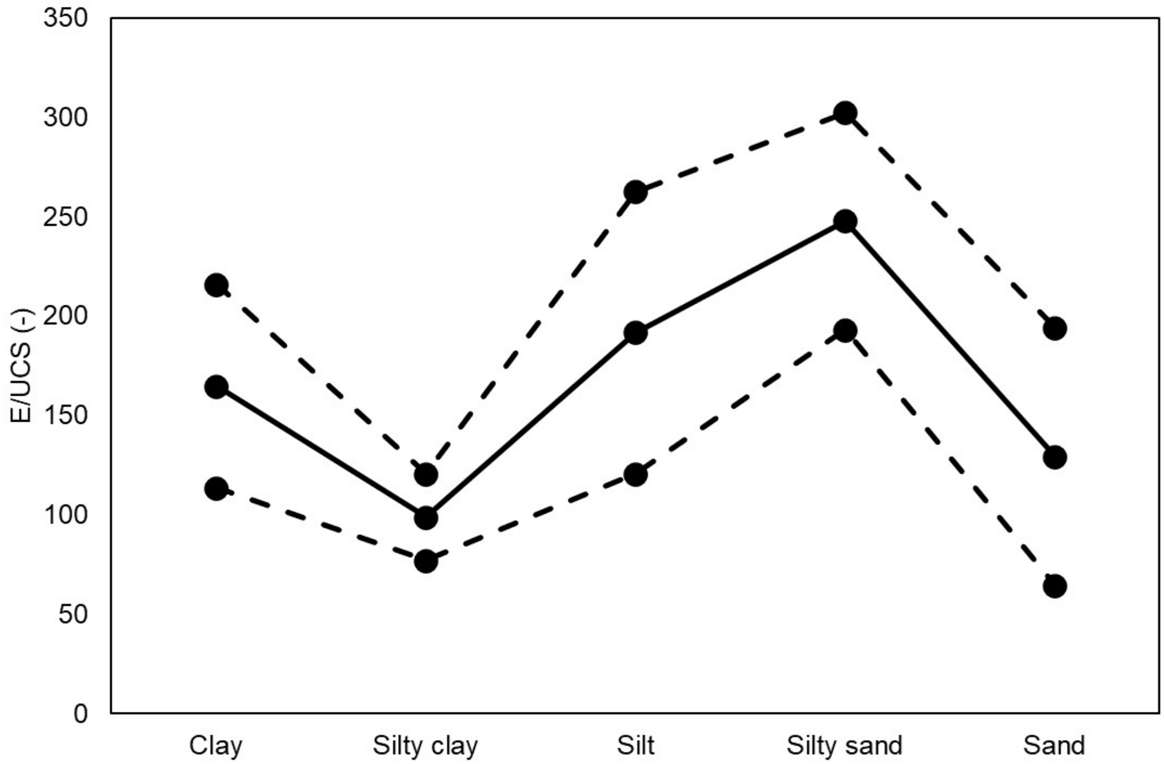

Fig. 11. Double-fluid technology. Trend of the E/UCS ratio in the five identified types of soil (clay, silty clay, silt, silty sand, sand): average value and variability range that is able to include 90% of the available data. Key: solid line: average value; dotted lines: minimum and maximum value of the variability range.

From the analysis of the obtained graphs (Figures 8-11) it emerges that:

- The single-fluid technology allows to reach non-negligible average strengths of the treated soil, even in cohesive soils
- In the single-fluid technology, the average strength values for coarse soils and for intermediate soils (between the coarse and the cohesive ones) are similar and of significant value (about 20 MPa)
- The amplitude of the variability interval of UCS for the single-fluid technology is minimal for cohesive soils, relatively low for coarse soils; it is significant for intermediate soils

- The E/UCS ratio in the single-fluid technology is on average equal to about 300 for cohesive and intermediate soils; it increases on average up to about 900 for coarse soils
- The amplitude of the variability interval of the E/UCS ratio in the single-fluid technology is relatively small for cohesive and intermediate soils; becomes significant for coarse soils
- The average strength of the treated soil can be low (in clays) or even very low (in silty clays) with the double-fluid technology; it is on average higher in silts and silty sands
- The amplitude of the strength variability interval for the double-fluid technology is relatively small in clays and sands, very small for silty clays, while it is significant for silts and silty sands
- The average value of the E/UCS ratio for the double-fluid technology has a similar trend to that of UCS: it is low for clays and sands, very low for silty clays; is greater for silts and silty sands
- The amplitude of the variability range of the E/UCS ratio for the double-fluid technology is relatively small in clays, very small in silty clays, while it is significant for silts and sands

The diagrams shown in Figures 8-11 allow for a quick evaluation of the main mechanical characteristics of the treated soil in various soil types, for the two main jet-grouting techniques used (single-fluid and double-fluid), in terms of variability intervals and expected average values. They provide a certain level of precision in defining field tests for evaluating the intervention effectiveness in a specific soil type.

Conclusions

Ground improvement using jet-grouting has been very successful in recent decades and represents a widespread methodology for improving the mechanical characteristics of soils. Due to various factors influencing the final result of the treatment, there is uncertainty about the final mechanical parameters of the treated soil, particularly regarding the uniaxial compressive strength (UCS) and the elastic modulus. To manage this uncertainty, it is almost always necessary to create a field test capable of verifying the final outcome of the treatment. However, designing a field test requires a series of preliminary indications, which can be obtained by analyzing collected data based on previous experience in similar soil types. Thanks to the analysis of numerous scientific publications reporting information on the outcome of jet-grouting treatment in different soil types, it was possible to select a series of data on the strength and stiffness of the treated soil, which was then statistically analyzed. The selected sample consisted of 109 cases. For each case, the type of jet-grouting, soil type, UCS, and E values were recorded. The detailed statistical analysis provided further useful information on the selected sample. Furthermore, for each type of intervention (single-fluid and double-fluid), it was possible to determine the trends of the average UCS values as the soil type varies. Along with the average value, a UCS variability interval was identified, centered on the average value, capable of enclosing 90% of the sample cases. The same analysis was then also developed for the E/UCS ratio, which allows determination of the elastic modulus E once the UCS is known. Ultimately, thanks to the four obtained graphs, it is possible to have a preliminary estimate of the strength and stiffness of the treated soil for each adopted type of jet-grouting and for each soil type to be treated. These graphs, therefore, allow for the design of field tests and the correct design of ground improvement interventions.

Conflict of interests

Authors declare they have no conflict of interest. The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Author contributions

All authors contributed to the study conception and design. Data collection and analysis were performed by Giovanni Spagnoli and Pierpaolo Oreste. The first draft of the manuscript was written by Giovanni Spagnoli and Pierpaolo Oreste commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data Availability

The datasets analyzed during the current study are publicly available from the sources cited, and they can also be obtained from the corresponding author upon reasonable request.

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