

Statistical Interpretation of Jet Grouting Field Data Regarding Its Strength and Stiffness

Original

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(Article begins on next page)

24 average values, the variability intervals, centered on the mean, capable of enclosing 90% of
25 the data in the sample were identified. The obtained graphs represent a useful tool for
26 obtaining a preliminary estimate of the strength and stiffness of the treated soil using the jet-
27 grouting technique.

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

30

31 **Introduction**

32 The construction of underground works may require preventive consolidation interventions.
33 Due to excavation in tunnels, for instance, the properties of the ground change (e.g., Zaheri
34 and Ranjbarnia 2022; 2023). Therefore, ground improvement techniques are particularly
35 useful in inconsistent or low-strength ground, especially in urban areas for the protection of
36 buildings (De Rienzo et al. 2009). Grouting and temporary freezing (particularly suitable in
37 fine-grained soils) are the best-known techniques (Lunardi et al. 1986). Permeation
38 (chemical) grouting techniques can be employed down to silty-sandy soils, but uncertainties
39 and costs increase as the in-situ permeability limit is approached, i.e., 10^{-6} m/s (Lunardi et
40 al. 1986; Fraccica et al. 2022). Jet grouting is an alternative to chemical grouting, which can
41 be expensive and may cause hazardous and structural issues. The basic procedure of jet
42 grouting involves injecting grout into the subsurface at high pressure and velocity (e.g.,
43 Bergado and Lorenzo 2003; Shen et al. 2013; Croce et al. 2014). The mechanical properties
44 of jet-grouted material can be significantly impacted by the composition of the original soil
45 (cohesive or coarse), the utilized cement (CEM I, II, III...), the use of additives (e.g.,
46 bentonite, sodium silicate), and how well the soil is mixed and replaced by the cement (Croce
47 et al. 2014). Field trials involve carrying out initial jet grouting treatments and conducting
48 necessary testing to confirm that treatment outcomes adhere to design specifications. These
49 trials assess mean column diameters and strength based on grouting parameters (flow,
50 pressure, retrieval rate, rod rotation) and soil properties. Analyzing field trial outcomes may
51 lead to reassessment of initially proposed solutions (Croce et al. 2014). Typically, uniaxial
52 compressive strength (UCS) and sometimes stiffness are used to mechanically assess the
53 quality of improved soils. According to Xanthakos et al. (1994), UCS values for jet-grouting
54 material range from 1.5–10 MPa for fine-grained soils and 10–30 MPa for coarse-grained
55 soils. The elastic modulus E , is normally 100 to 300 times the UCS values (JSG Association
56 1986). From a geotechnical perspective, estimating the UCS and E_{50} relationship based on

57 jet grouting type and soil type can be valuable. This paper considers six studies that indicate
58 UCS and E-values (sometimes specified as E50, sometimes not). A statistical analysis
59 examines how these values vary based on soil type (coarse and cohesive) and jet grouting
60 technique (single-fluid or double-fluid). Additionally, a confidence interval and prediction of
61 the two mechanical parameters are developed as a function of soil type. The study yielded
62 trends in mean UCS strength values and E/UCS ratios for different soil types and the two
63 analyzed jet-grouting methods. Through statistical analysis, expected values (with 90%
64 probability) of variability intervals for these parameters were identified, providing a
65 preliminary estimate of treated soil strength and stiffness. This information is useful for
66 defining test fields and designing soil reinforcement interventions.

67 **Jet grouting technique**

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

79 In the double fluid system, water-cement grout is the only fluid used for both soil
80 disaggregation and cementation. However, the grout jet is surrounded by a coaxial air jet,
81 which increases the efficacy of the grout by reducing energy losses. This air jet is provided

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



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

97

98 Tab. 1. Main parameters of the three jet grouting types based on the authors' field
 99 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

100

101 **Data on jet grouting considering UCS and E-modulus**

102 Field data from Collotta et al. (2004), Fang et al. (1994; 2006), Lunardi et al. (1986), Shen
 103 et al. (2013), and van der Stoel and van Ree (2000), where field tests were performed and
 104 UCS and elastic modulus values were gathered, were analyzed. A total of 109 data points

105 were collected. The literature data used for the statistical analysis consider single and
106 double-fluid jet grouting in silt, silty sand, sandy gravel, sand, clay, peat, pure sand, and silty
107 clay, as described in detail in the original papers. For the sake of simplicity, these soil types
108 have been categorized as coarse (silty sand, sandy gravel, sand) and cohesive (silt, clay,
109 peat, and silty clay). This subdivision results in a reasonable split with 52 data points for
110 "coarse" and 57 data points for "cohesive" soils. Fig. 2 shows the diagrams of E-modulus vs
111 UCS for coarse (Fig. 2A) and cohesive (Fig. 2B) soils. Coarse data show some deviation
112 from the relation $E_{50} = 300 \cdot UCS$, with some elastic modulus values exceeding this ratio.
113 For the cohesive soils, all data plot within the range provided by the JSG Association (1986).

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

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

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

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

- 126 • For clays, the elastic modulus of jet-grouting varies from $175 \cdot UCS$ to $450 \cdot UCS$, with an
127 average value of approximately $275.2 \cdot UCS$; UCS varies from 1.5 to 18 MPa, with an
128 average value of 7.3 MPa.

129 • In sands, the elastic modulus of jet-grouting varies from 175·UCS to 550·UCS, with an
130 average value of approximately 306.7·UCS; the UCS strength varies from 5 to 50 MPa,
131 with an average value of 20.0 MPa.

132 • In sandy gravels the elastic modulus of jet-grouting varies from 500·UCS to 1500·UCS,
133 with an average value of approximately 898.3·UCS; the UCS strength varies from 10 to
134 30 MPa, with an average value of 19.8 MPa.

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

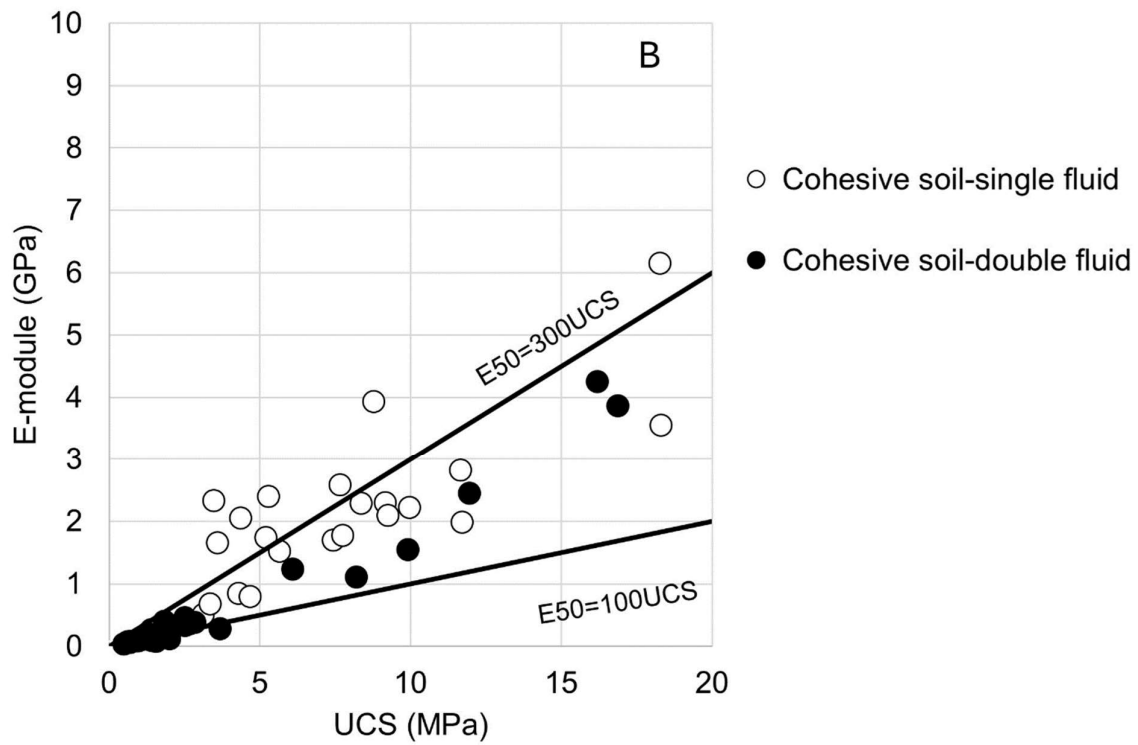
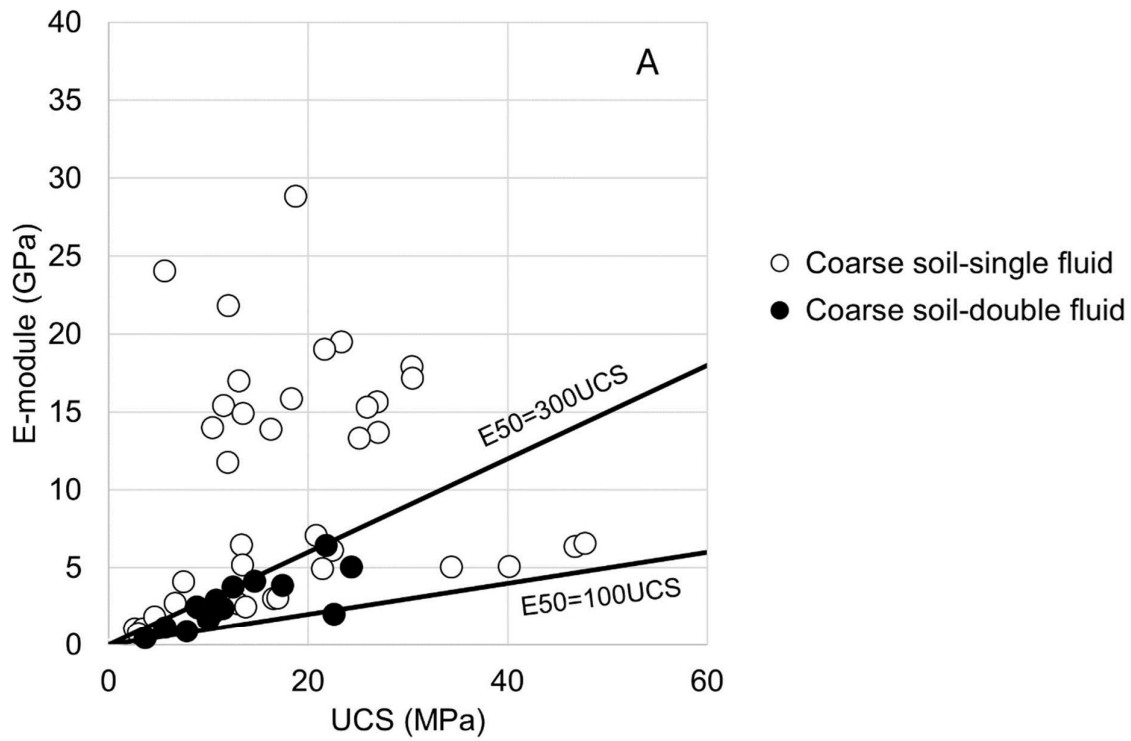
136 • For clays, the elastic modulus of jet-grouting varies from 130·UCS to 220·UCS, with an
137 average value of approximately 164.8·UCS; the UCS strength varies from 2 to 6 MPa,
138 with an average value of 3.1 MPa.

139 • For silty clays, the elastic modulus of jet-grouting varies from 75·UCS to 120·UCS, with
140 an average value of about 98.8·UCS; the UCS strength varies from 0.5 to 1.2 MPa, with
141 an average value of 0.8 MPa.

142 • In silts, the elastic modulus of jet-grouting varies from 130·UCS to 260·UCS, with an
143 average value of about 191.6·UCS; the UCS strength varies from 8 to 24 MPa, with an
144 average value of 16.5 MPa.

145 • In silty sands, the elastic modulus of jet-grouting varies from 170·UCS to 300·UCS, with
146 an average value of about 247.7·UCS; the UCS strength varies from 9 to 25 MPa, with
147 an average value of 14.6 MPa.

148 • In sands, the elastic modulus of jet-grouting varies from 90·UCS to 200·UCS, with an
149 average value of about 129.4·UCS.



150

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

153 (1994; 2006), Lunardi et al. (1986), Shen et al. (2013), and van der Stoel and van Ree
154 (2000).

155

156

157 **Statistical analysis of the data**

158 The UCS and E-modulus data were analyzed considering:

- 159 • The distribution of the data;
- 160 • The variance of the data;
- 161 • The medians (or means) of the data, and;
- 162 • The confidence interval of the data.

163 *Distribution of the data*

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

$$168 \quad A^2 = -N - S \quad (1)$$

169 where

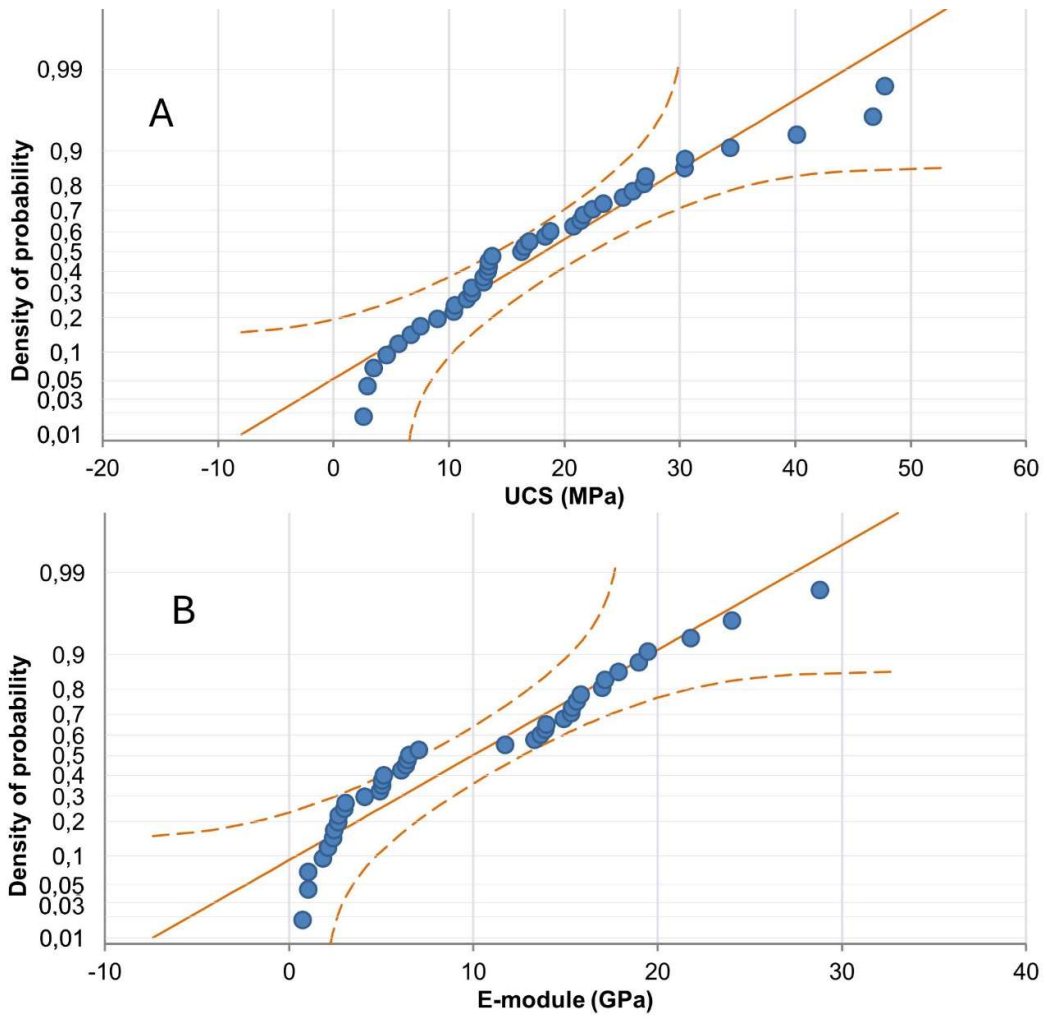
170 N is the number of elements in the sample

$$171 \quad S = \sum_{i=1}^N \frac{(2i-1)}{N} [\ln F(Y_i) + \ln (1 - F(Y_{N+1-i}))]$$

172 F is the cumulative distribution function

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

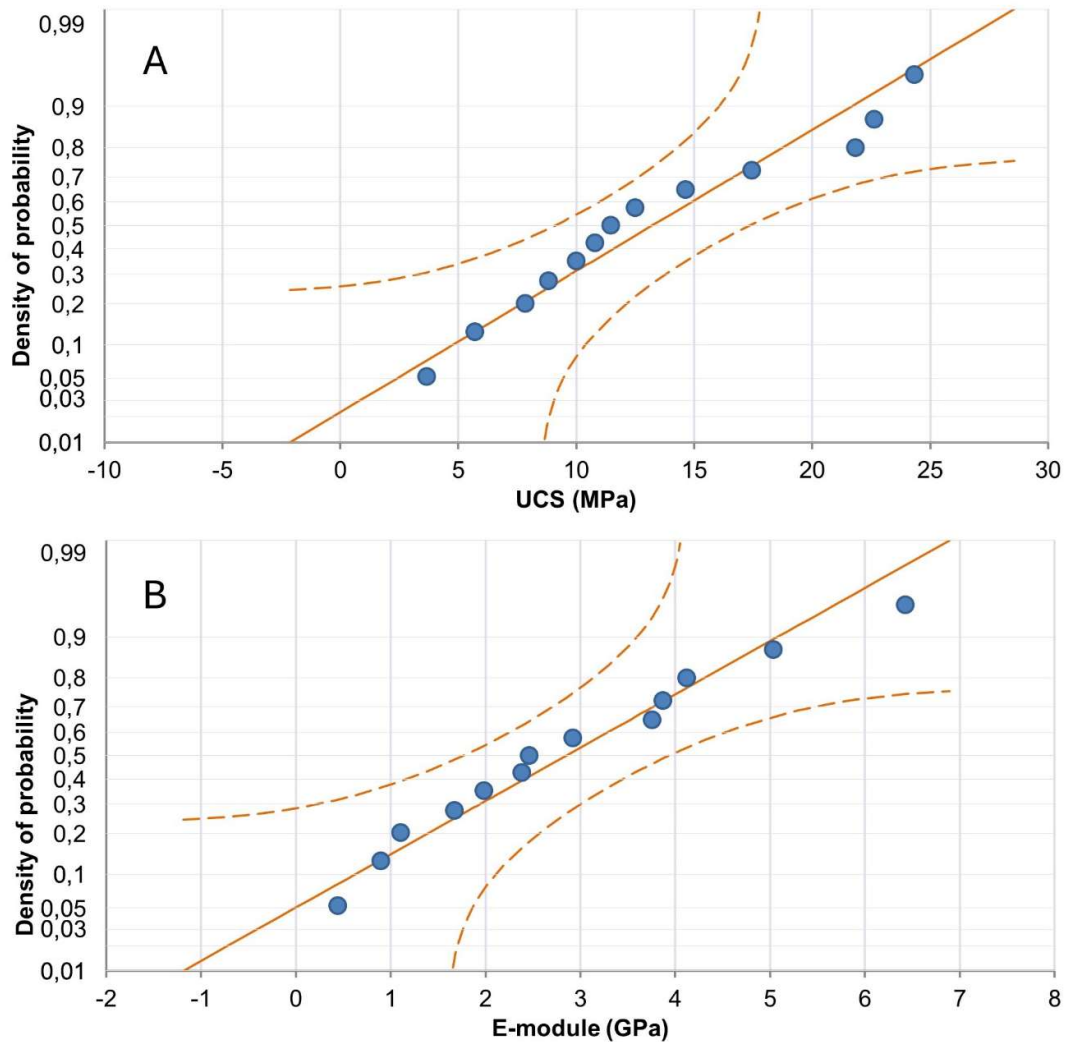
174 This approach has the benefit of making the test more sensitive, but it also has the drawback
175 of requiring the calculation of critical values for every distribution. Figs. 3 and 4 show, as an
176 example, the probability plots for UCS and E-moduli for single-fluid and double-fluid
177 systems,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



187

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

189



190

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

192 Figs. 5 and 6 show histograms and probability distributions of the data shown in Figs. 3 and

193 4. Fig. 5 shows that for UCS and E-modulus data, the fitting distributions are 2-parameter

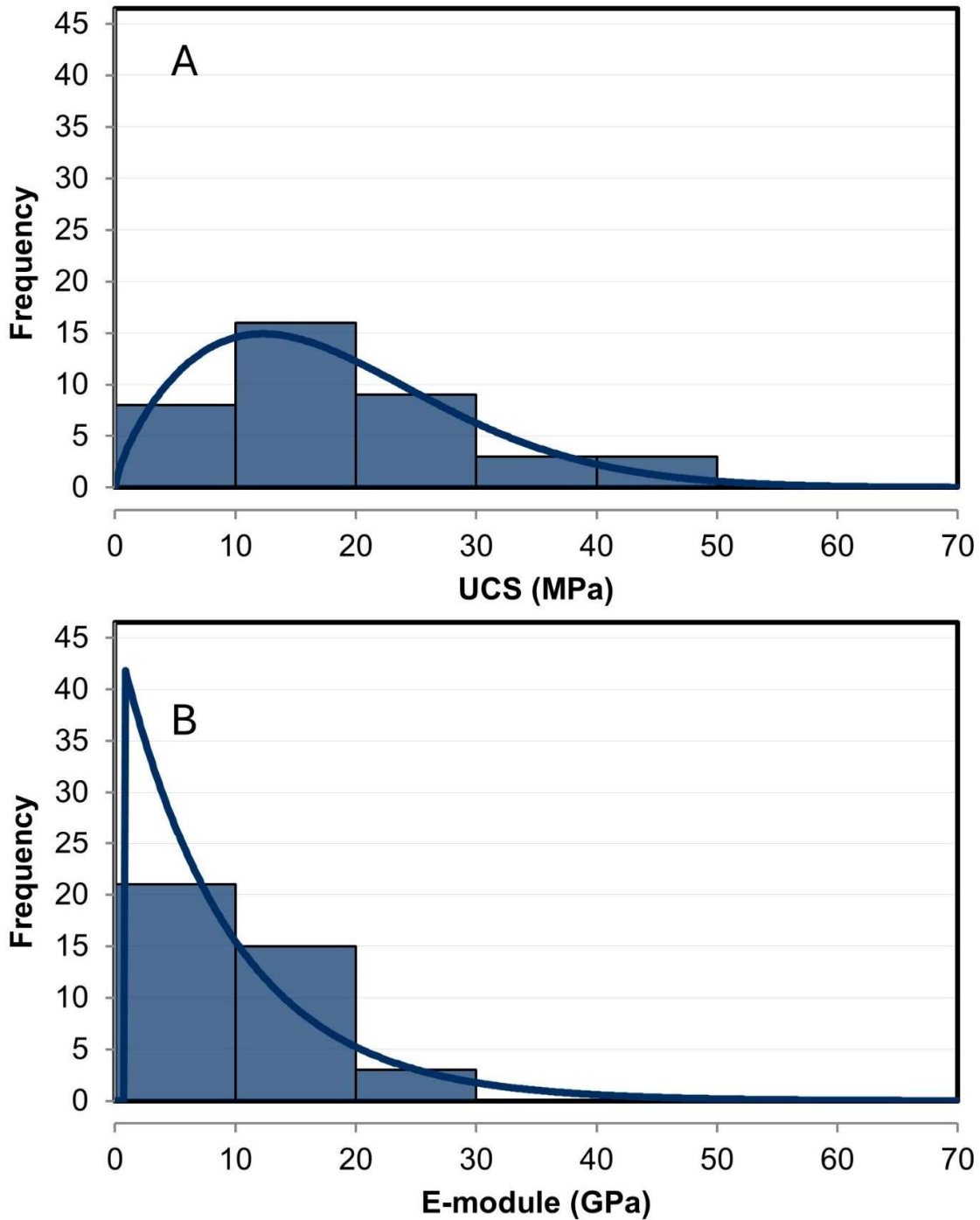
194 Weibull and 2-parameter exponential, respectively. Fig. 6 shows that UCS and E-modulus

195 data are normally distributed. For the sake of transparency, UCS and E-modulus values for

196 cohesive soils grouted with single-fluid are best fitted by 2-parameter LogNormal and 2-

197 parameter Weibull distributions, respectively, while the double system data are best fitted

198 by 2-parameter Log Logistic and 2-parameter LogNormal distributions, respectively.

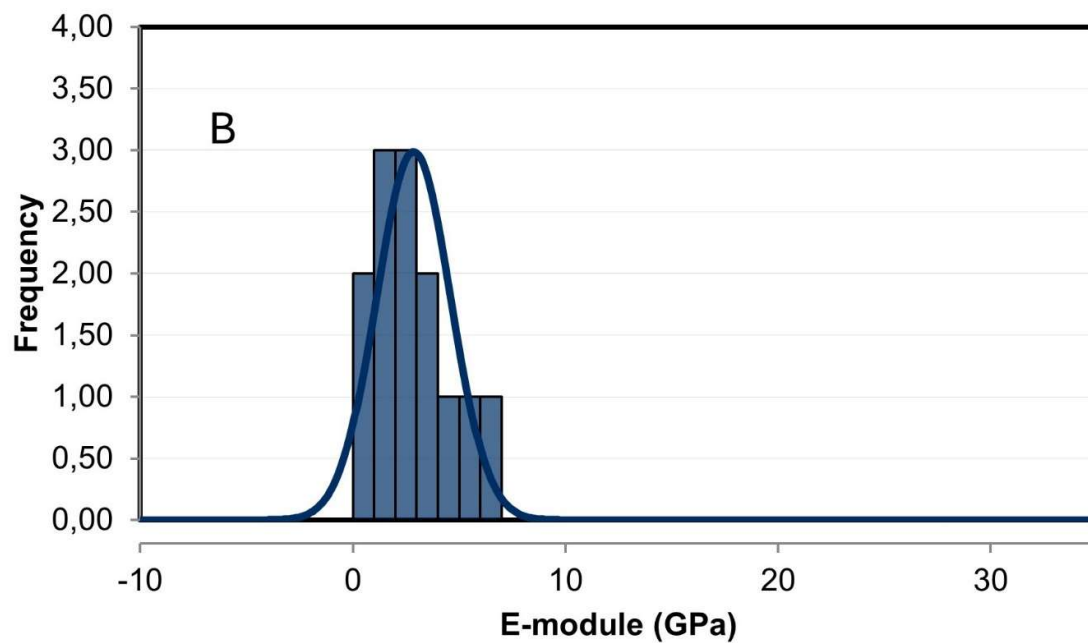
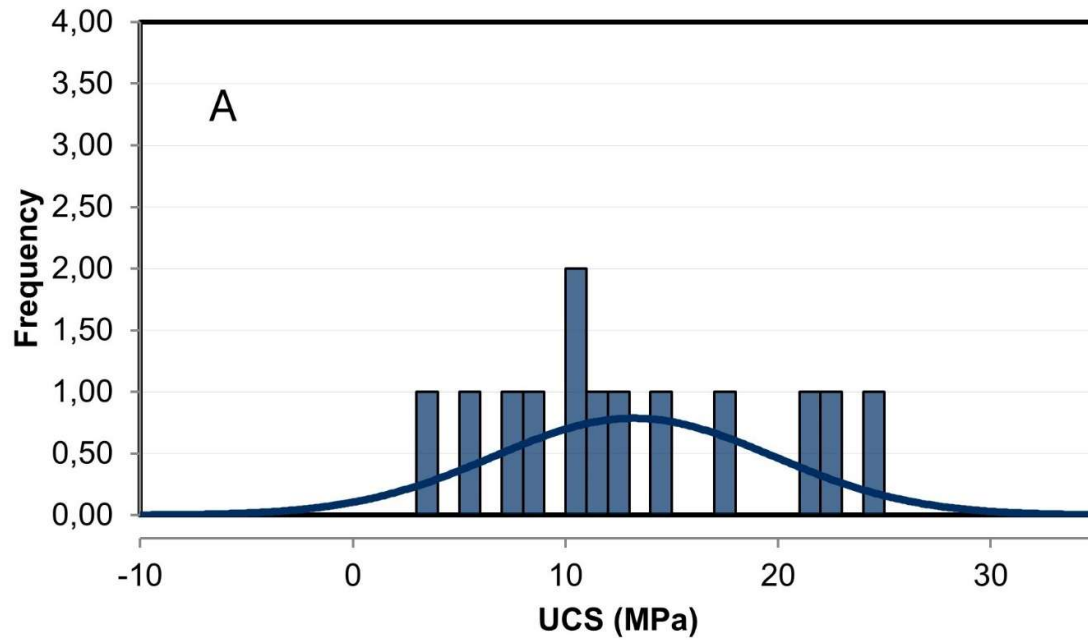


199

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

201 in coarse soils.

202



203

204 Fig. 6. Histogram and distribution of the data for double- fluids for UCS (A) and E-module

205 (B) in coarse soils.

206 *Variance and median (or mean) of data*

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

- 210 1. UCS coarse mono-fluid vs UCS cohesive mono-fluid;
- 211 2. UCS coarse double-fluids vs UCS cohesive double-fluids;
- 212 3. E-module coarse mono-fluid vs E-module cohesive mono-fluid;
- 213 4. E-module coarse double-fluids vs E-module cohesive double-fluids;
- 214 5. UCS coarse mono-fluid vs E-module coarse mono-fluid;
- 215 6. UCS coarse double-fluids vs E-module coarse double-fluids;
- 216 7. UCS cohesive mono-fluid vs E-module cohesive mono-fluid;
- 217 8. UCS cohesive double-fluids vs E-module cohesive double-fluids.

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

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

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

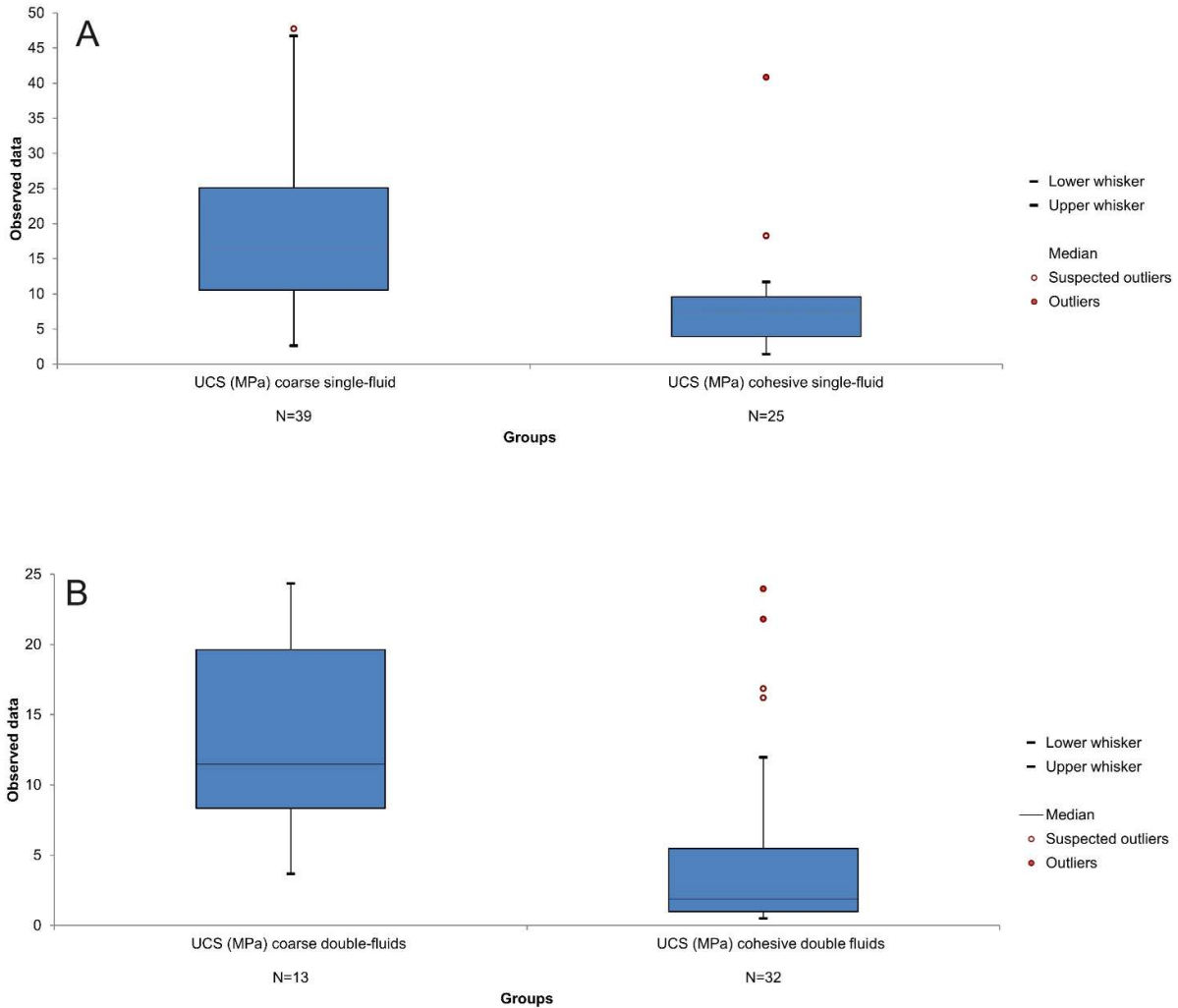
No.	Comparison	Variance	Median (or mean)	Test used

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)

228

229 Fig. 7 shows comparative box plots for comparisons 1 and 2 as mentioned above. The data
230 dispersion, which is divided into quartiles, is shown using box plots. This technique is applied
231 to identify skewness, dispersion, symmetry, and outliers (if any) in the data (Reagan and
232 Kiemele 2008). In a box plot, the interquartile range (IQR) is represented by a box, with the
233 25th and 75th percentiles at the bottom and top of the box, respectively. The whiskers extend
234 to 1.5 times the IQR from the edge of the box, representing the final data value inside the
235 inner fence. The height of the box shows the interquartile range. According to Reagan and
236 Kiemele (2008), data points that extend to $3 \times \text{IQR}$ are considered outliers.



237

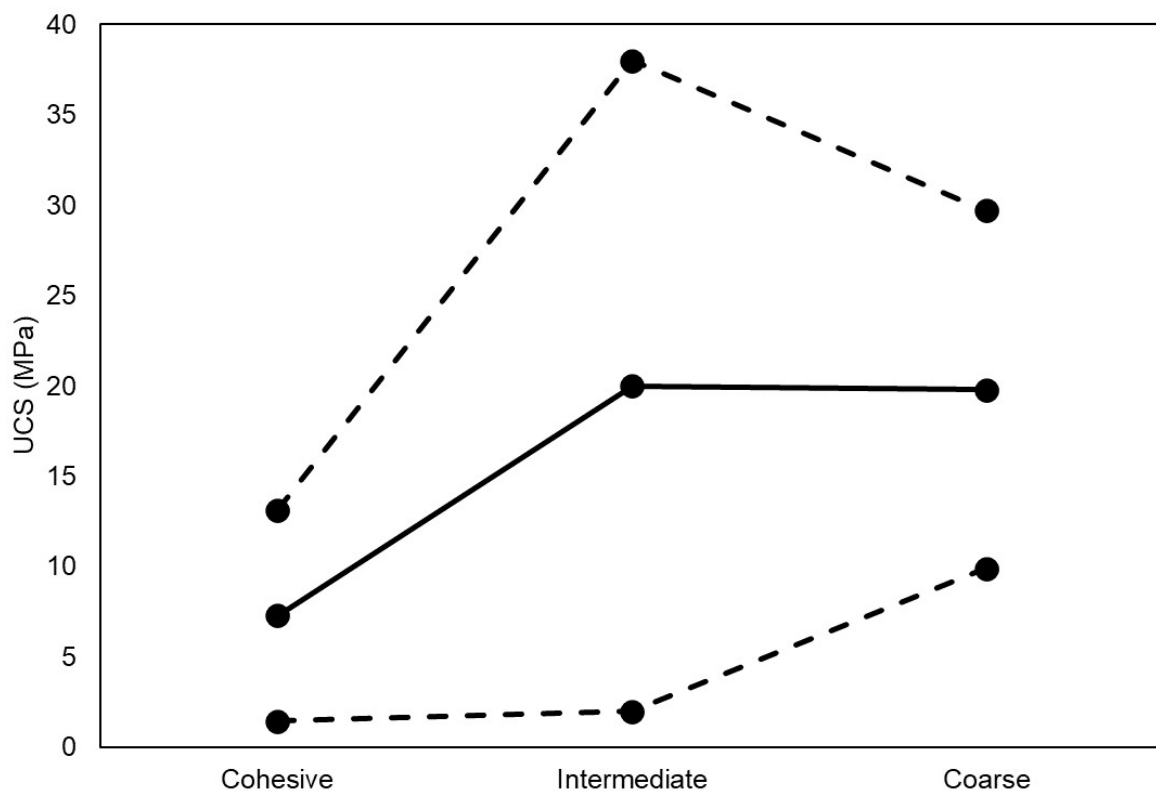
238 Fig. 7. Comparative box plot for case 1 (UCS coarse mono-fluid vs UCS cohesive mono-
239 fluid) (A) and 2 (UCS coarse double-fluids vs UCS cohesive double-fluids) (B).

240

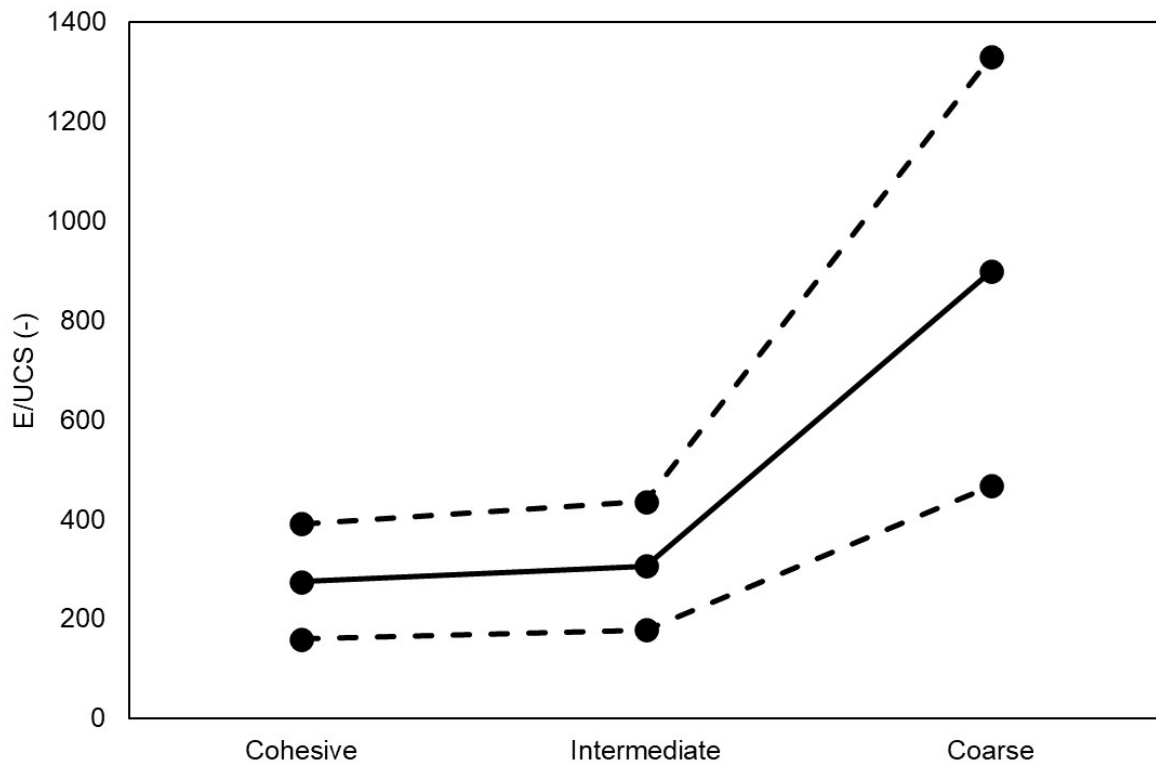
241 **Confidence interval and predictions of mechanical parameters as a function of soil**
242 **types and jet-grouting method**

243 The uniaxial compressive strength and elastic modulus of jet-grouting columns vary
244 significantly depending on the soil type and the operating parameters used. It is almost
245 always necessary to proceed with an in-situ field test to detect the strength and stiffness of

246 the treated soil. However, even in-situ tests require detailed planning and design, which can
247 be based on results obtained in the past for similar soil types using the same jet-grouting
248 techniques intended for adoption. The available data, selected from all those available in
249 the scientific literature, represent a very valuable resource that has been analyzed in detail
250 to obtain the trend of variability intervals as the soil type varies. For the data relating to
251 single-fluid technology, three types of soils were considered in this section: cohesive (clays),
252 coarse (sandy gravels), and intermediate between the two previous ones (sands and silts).
253 The values of the UCS strength and the ratio between the elastic modulus and the UCS
254 (E/UCS) were considered. After calculating the average value of the two parameters for
255 each soil category, the variability intervals (centered on the average value) capable of
256 enclosing 90% of the detected values were evaluated. Figure 8 shows the trend of the
257 average UCS value and its variability interval for the three identified soil types. Figure 9
258 shows the same results obtained for the E/UCS ratio.



260 Fig. 8. Single-fluid technology. Trend of UCS strength in the three identified types of soil
261 (cohesive, intermediate, coarse): mean value and variability range that is able to include
262 90% of the available data. Key: solid line: mean value; dotted lines: minimum and maximum
263 value of the variability range.



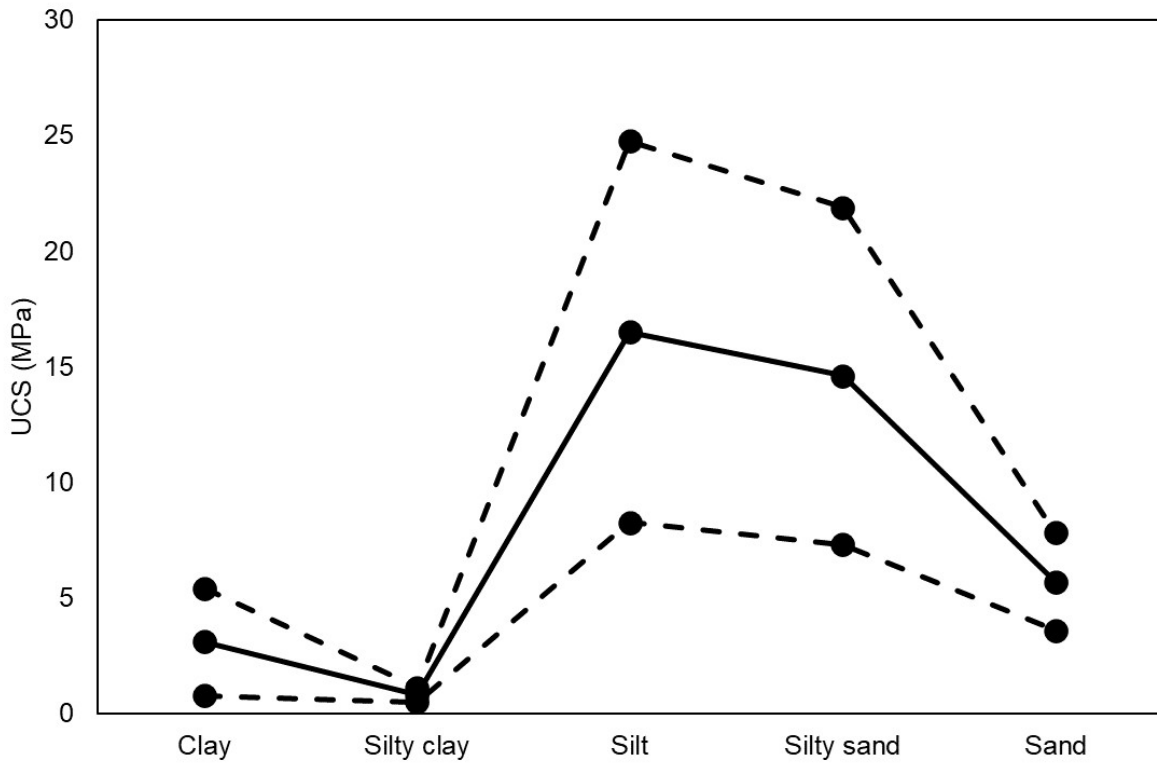
264

265 Fig. 9. Single-fluid technology. Trend of the E/UCS ratio in the three identified types of soil
266 (cohesive, intermediate, coarse): average value and variability range that is able to include
267 90% of the available data. Key: solid line: average value; dotted lines: minimum and
268 maximum value of the variability range.

269

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

272

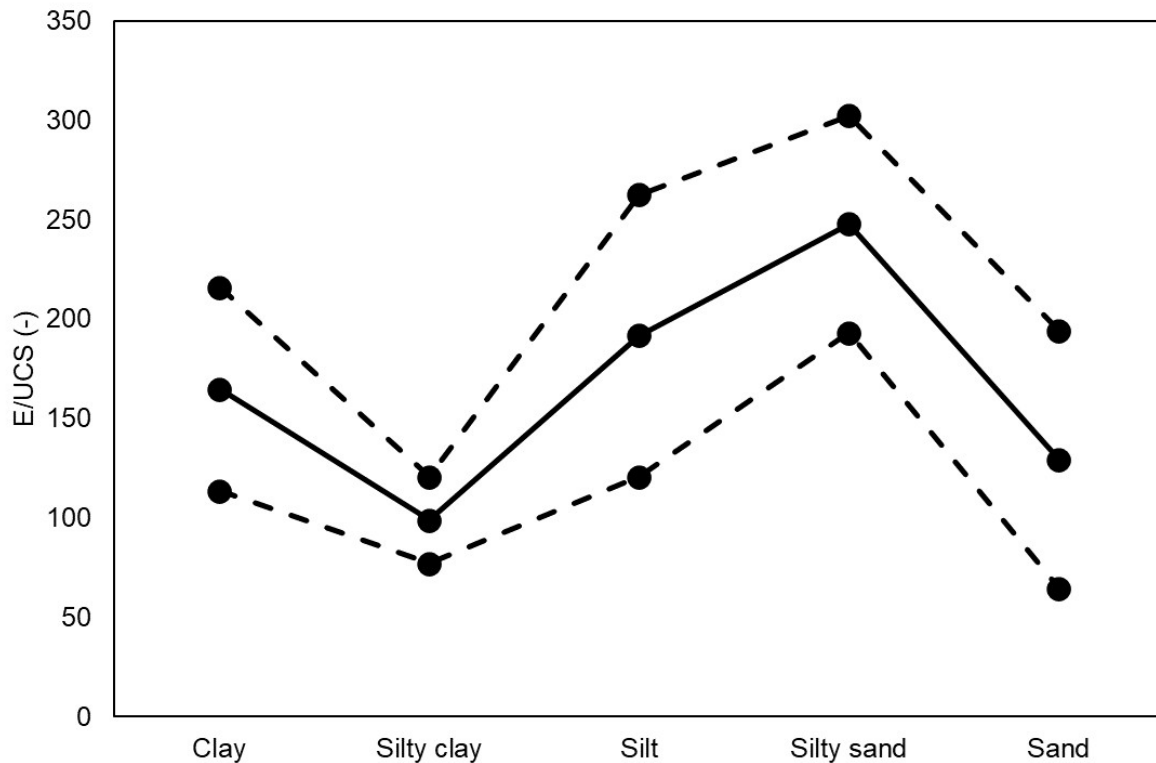


273

274 Fig. 10. Double-fluid technology. Trend of UCS strength in the five identified types of soil
 275 (clay, silty clay, silt, silty sand, sand): mean value and variability range that is able to include
 276 90% of the available data. Key: solid line: mean value; dotted lines: minimum and maximum
 277 value of the variability range.

278

279



280

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

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

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

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

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

313 **Conclusions**

314 Ground improvement using jet-grouting has been very successful in recent decades and
315 represents a widespread methodology for improving the mechanical characteristics of soils.
316 Due to various factors influencing the final result of the treatment, there is uncertainty about
317 the final mechanical parameters of the treated soil, particularly regarding the uniaxial

318 compressive strength (UCS) and the elastic modulus. To manage this uncertainty, it is
319 almost always necessary to create a field test capable of verifying the final outcome of the
320 treatment. However, designing a field test requires a series of preliminary indications, which
321 can be obtained by analyzing collected data based on previous experience in similar soil
322 types. Thanks to the analysis of numerous scientific publications reporting information on
323 the outcome of jet-grouting treatment in different soil types, it was possible to select a series
324 of data on the strength and stiffness of the treated soil, which was then statistically analyzed.
325 The selected sample consisted of 109 cases. For each case, the type of jet-grouting, soil
326 type, UCS, and E values were recorded. The detailed statistical analysis provided further
327 useful information on the selected sample. Furthermore, for each type of intervention (single-
328 fluid and double-fluid), it was possible to determine the trends of the average UCS values
329 as the soil type varies. Along with the average value, a UCS variability interval was identified,
330 centered on the average value, capable of enclosing 90% of the sample cases. The same
331 analysis was then also developed for the E/UCS ratio, which allows determination of the
332 elastic modulus E once the UCS is known. Ultimately, thanks to the four obtained graphs, it
333 is possible to have a preliminary estimate of the strength and stiffness of the treated soil for
334 each adopted type of jet-grouting and for each soil type to be treated. These graphs,
335 therefore, allow for the design of field tests and the correct design of ground improvement
336 interventions.

337 **Conflict of interests**

338 Authors declare they have no conflict of interest. The authors declare that no funds, grants,
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340 **Author contributions**

341 All authors contributed to the study conception and design. Data collection and analysis
342 were performed by Giovanni Spagnoli and Pierpaolo Oreste. The first draft of the manuscript

343 was written by Giovanni Spagnoli and Pierpaolo Oreste commented on previous versions of
344 the manuscript. All authors read and approved the final manuscript.

345 **Data Availability**

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

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