GAETA 4-6 SETTEMBRE

IARG-24

SCUOLA DI DOTTORATO

CONSOLIDAMENTO DEI TERRENI E DELLE ROCCE

Lunedì 2 settembre, ore 14-18

Paolo Croce	Obiettivi e tecniche di consolidamento dei terreni
Giuseppe Modoni	Progettazione degli interventi colonnari basata su evidenze sperimentali
Erminio Salvatore	Sperimentazione di laboratorio per lo sviluppo e l’ottimizzazione delle tecniche di consolidamento

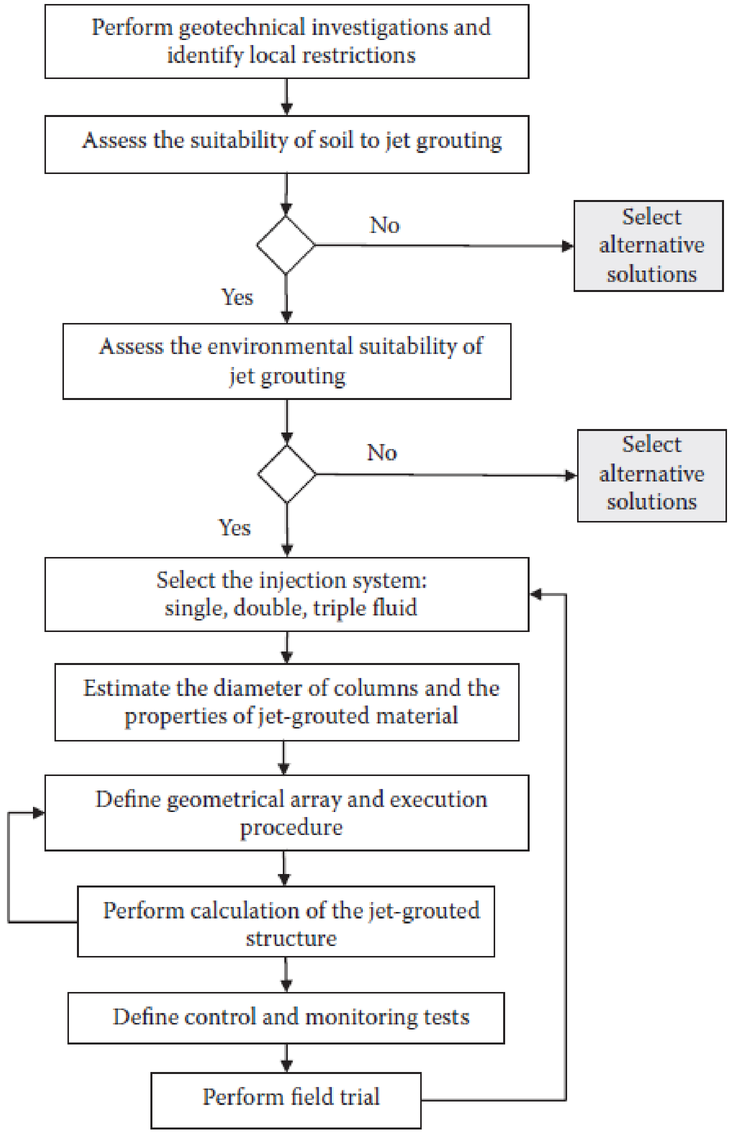
NORME TECNICHE PER LE COSTRUZIONI

Approvate con Decreto Ministeriale 17 gennaio 2018

6.9. MIGLIORAMENTO E RINFORZO DEI TERRENI E DEGLI AMMASSI ROCCIOSI
6.9.1. SCELTA DEL TIPO DI INTERVENTO E CRITERI GENERALI DI PROGETTO
6.9.2. MONITORAGGIO

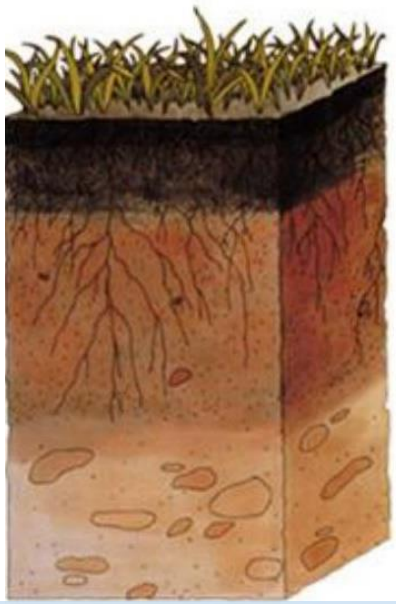
I criteri generali di progetto e controllo indicano la necessità di:

– evidenziare i caratteri geotecnici del sito mediante indagini sperimentali;
– per gli interventi di miglioramento (par.6.1) giustificare mediante analisi meccaniche l'inadeguatezza delle proprietà originarie dei terreni e gli obiettivi delle modifiche;
– accertare mediante un piano di indagini l'avvenuto raggiungimento degli effetti meccanici attesi;
– per gli interventi di maggiore importanza, supportare le analisi progettuali con una fase preliminare di verifica sperimentale e messa a punto delle modalità esecutive dell'intervento (il cosiddetto campo prove);
– definire nel progetto un piano di monitoraggio per valutare l'efficacia degli interventi, verificare la rispondenza dei risultati ottenuti con le ipotesi progettuali, controllare il comportamento nel tempo del complesso opera-terreno trattato maggiormente se gli interventi di miglioramento e di rinforzo possano condizionare la sicurezza e la funzionalità dell'opera in progetto o di opere circostanti.

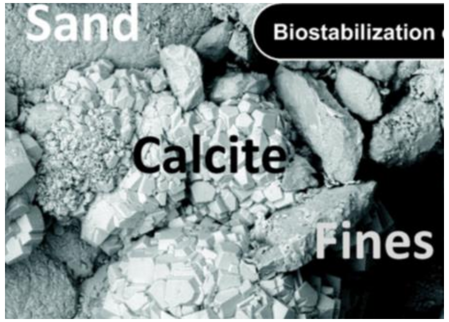


Ingegneria del consolidamento

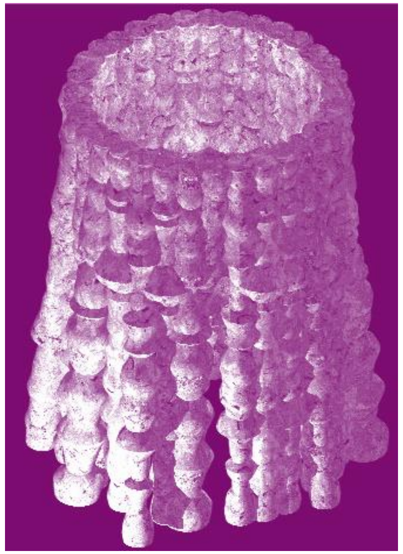
Terreno naturale



Elementi di terreno trattato



Struttura di rinforzo



Setup del trattamento
(sistema, parametri)

←

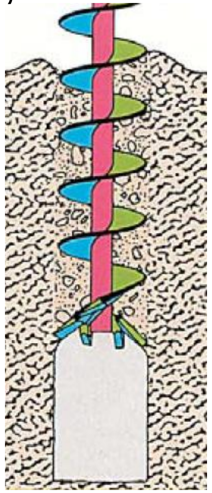
Proprietà del terreno trattato
(estensione, resistenza, conducibilità idraulica)

←

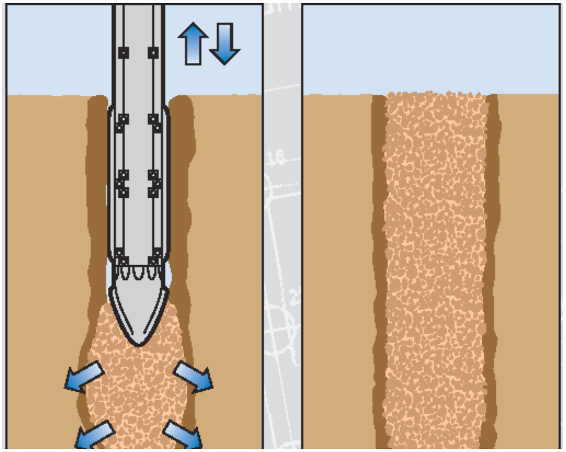
Funzione
(statica, idraulica, …)

Interventi colonnari

Pali per spostamento, sostituzione, intermedi



Vibrosostituzione



Jet grouting

Deep Soil Mixing

Ingegneria del consolidamento

Setup del trattamento

(sistema, parametri)

← - - - - - - - - - →

Proprietà del terreno trattato

(estensione, resistenza, conducibilità idraulica)

Jet grouting

High Speed Injection:

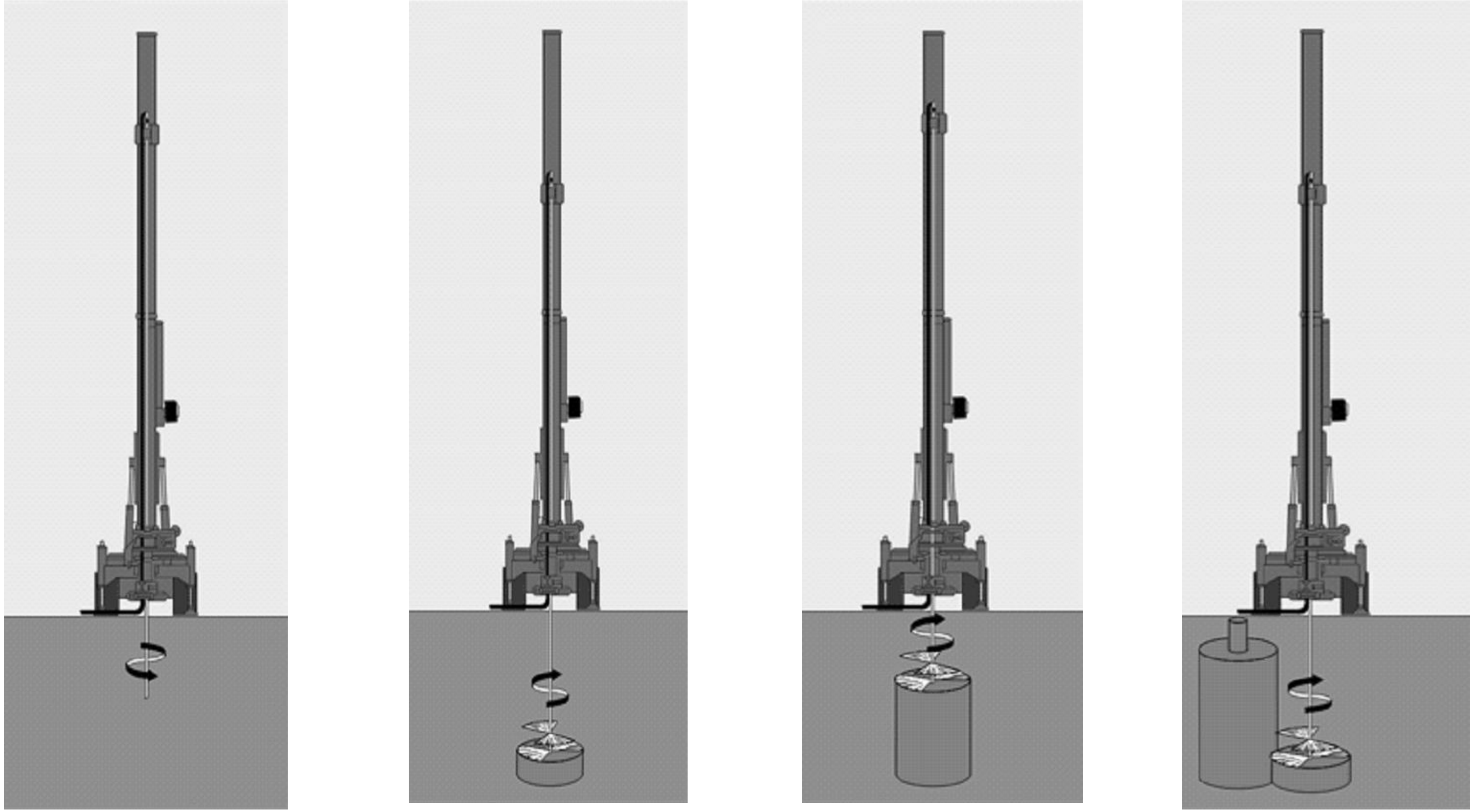
•Feeding pressure: 300-420 bar

•Outlet velocity: 190-234 m/s

•Flow rate: 37-700 lt/min

•Equivalent force: 200-4000 N

Jet grouting



•DRILLING

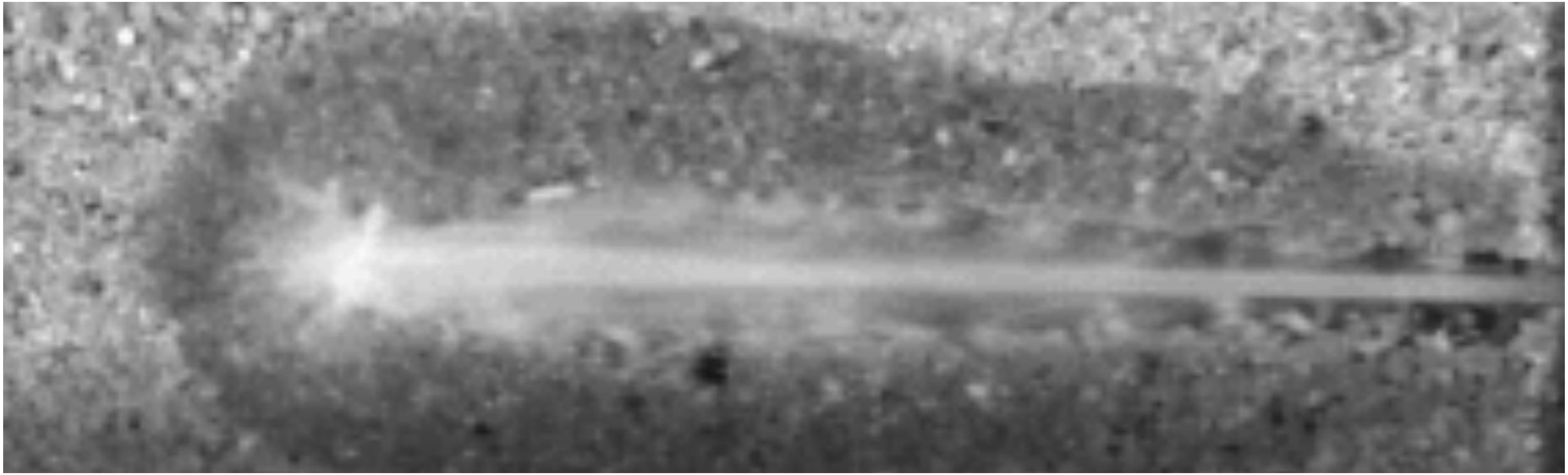
•EXTRACTION, INJECTION

Deep Soil Mixing

(Courtesy of Keller)

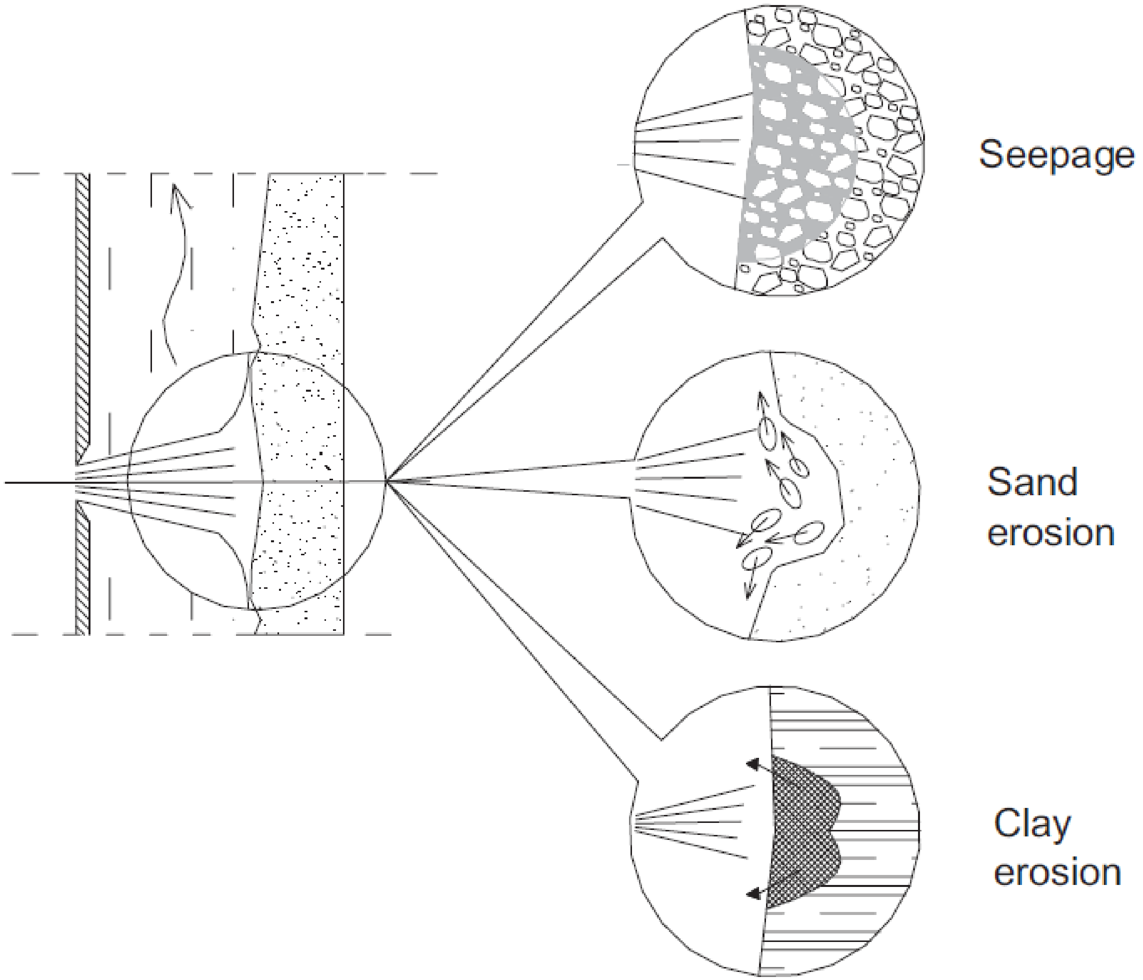
(Courtesy of Bauer)

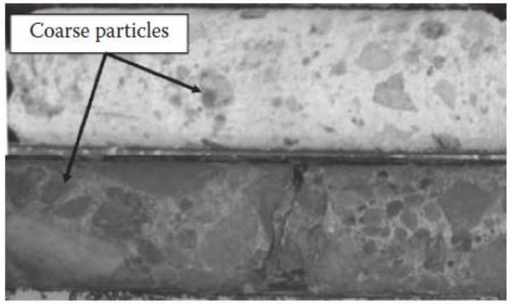
Jet grouting

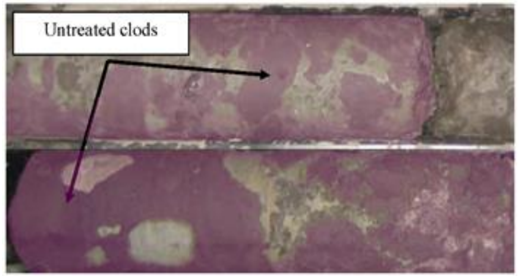


Seepage → Erosion → Cementation

Jet grouting: observation

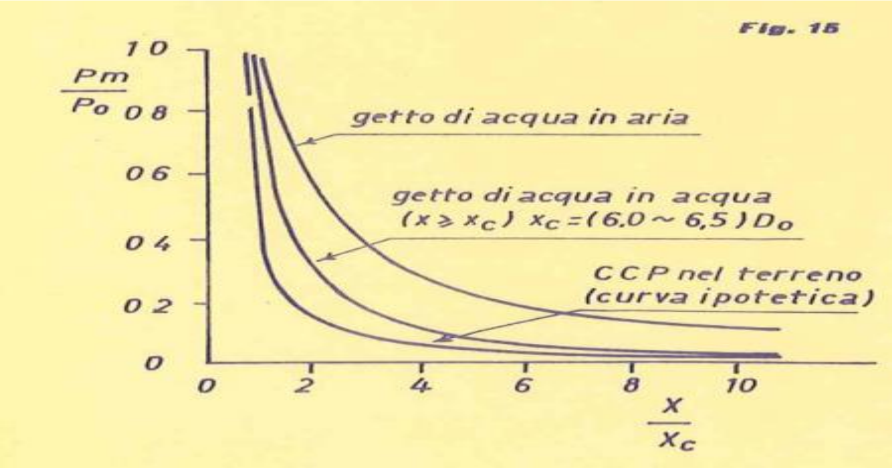


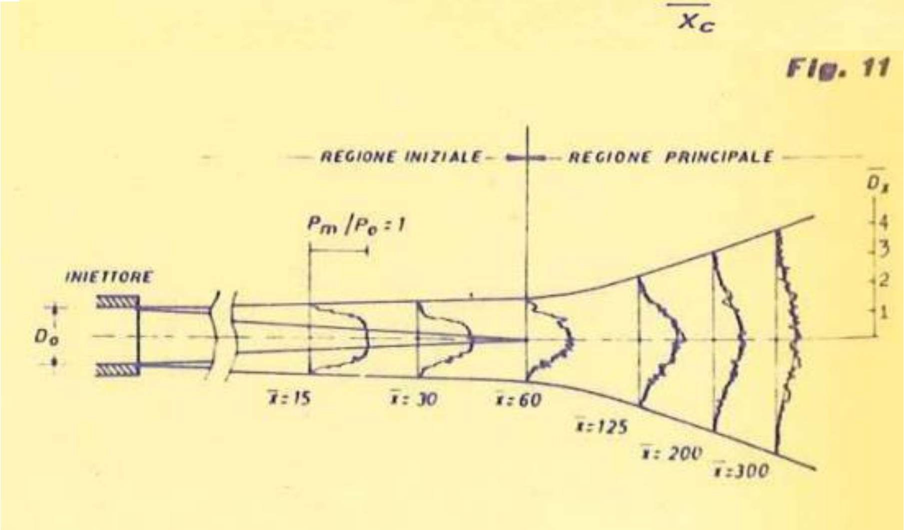




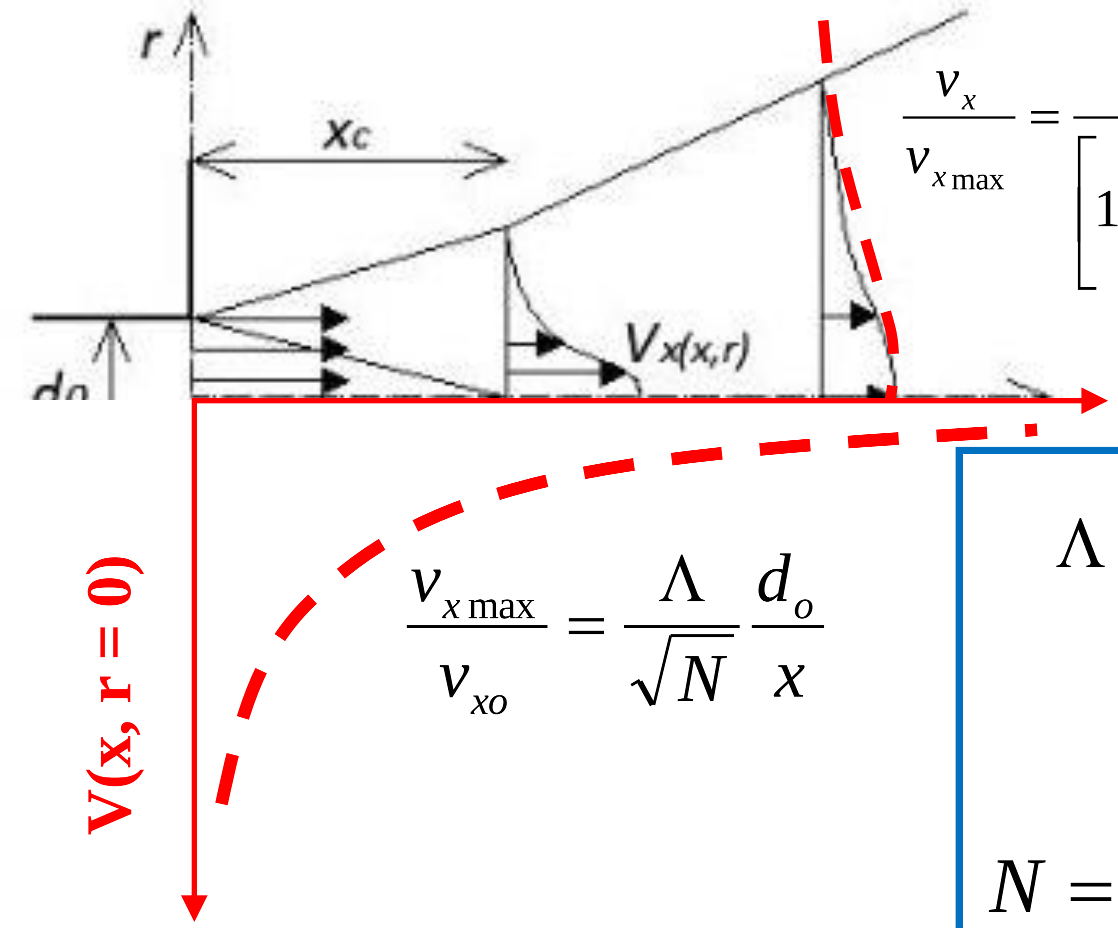
JET GROUTING: observation and analytical modelling

Submerged jets: the Hinze's 1948 theory





Yanaida (1973) from Ventriglia (1975)



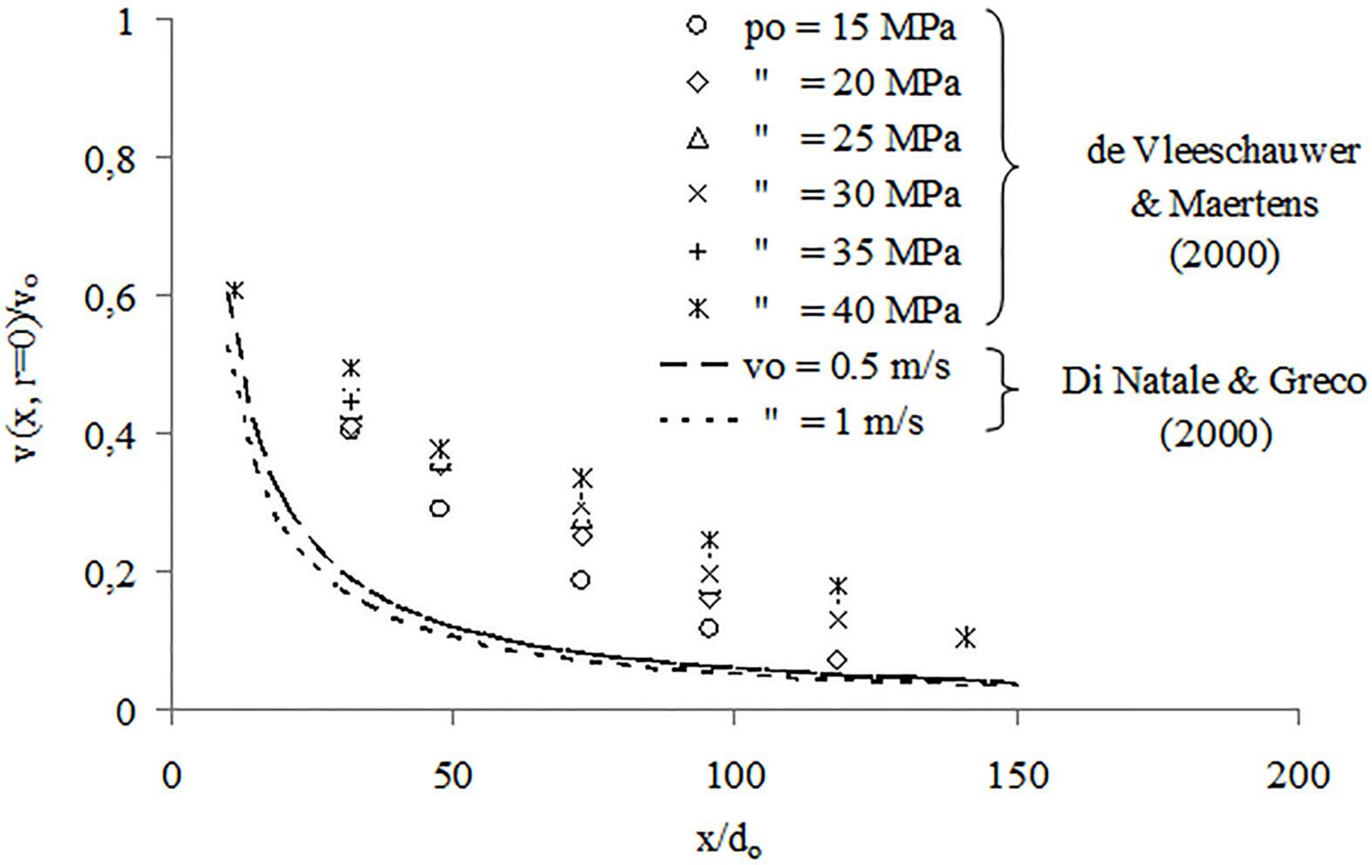
$$\frac{v_x}{v_{x\max}} = \frac{1}{\left[1+\frac{1.33\cdot\Lambda^2\cdot(r/x)^2}{N}\right]^2}$$

$$\frac{v_{x\max}}{v_{xo}} = \frac{\Lambda}{\sqrt{N}}\frac{d_o}{x}$$

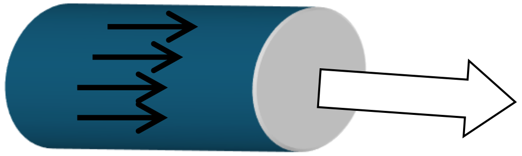
$$\Lambda = \frac{1}{\sqrt{\frac{8}{6}\kappa'}}$$

$$N = \frac{\varepsilon_g}{\varepsilon_w} = \frac{\nu_g}{\nu_w}$$

JET GROUTING: observation and analytical modelling



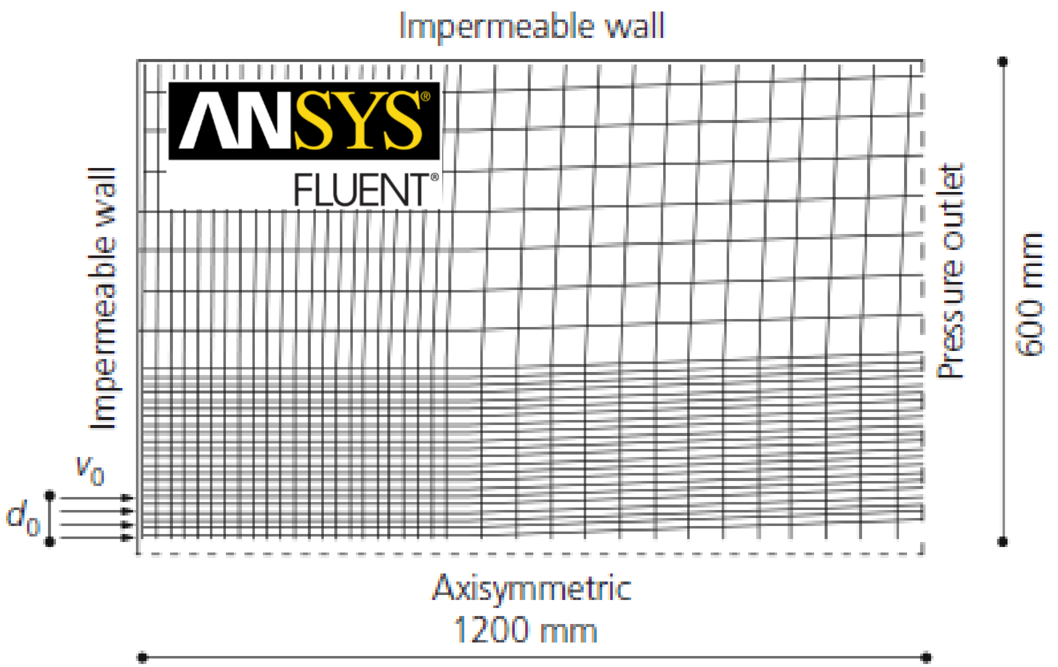
$$S \propto \mu \cdot \pi \cdot d_o \cdot v_o$$

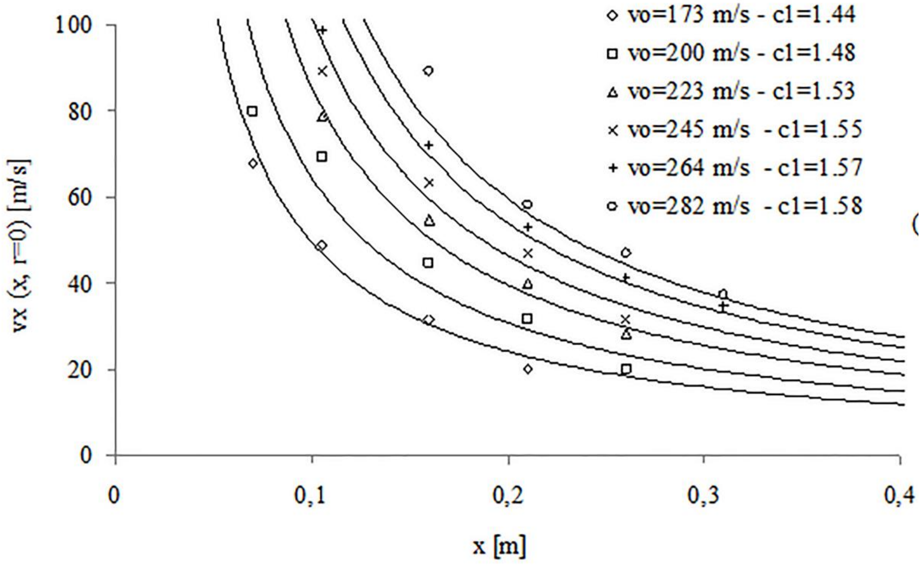


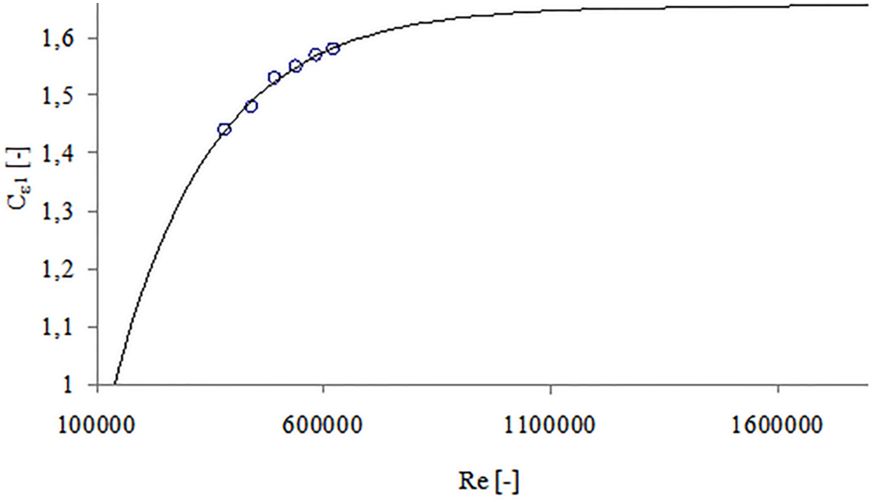
$$M \propto \rho \cdot \frac{\pi \cdot d_o^{\,2}}{4} \cdot v_o^{\,2}$$

$$\mathrm{Re} = \frac{M}{S} = \frac{\rho \cdot v_o \cdot d_o}{\mu}$$

JET GROUTING: numerical modelling

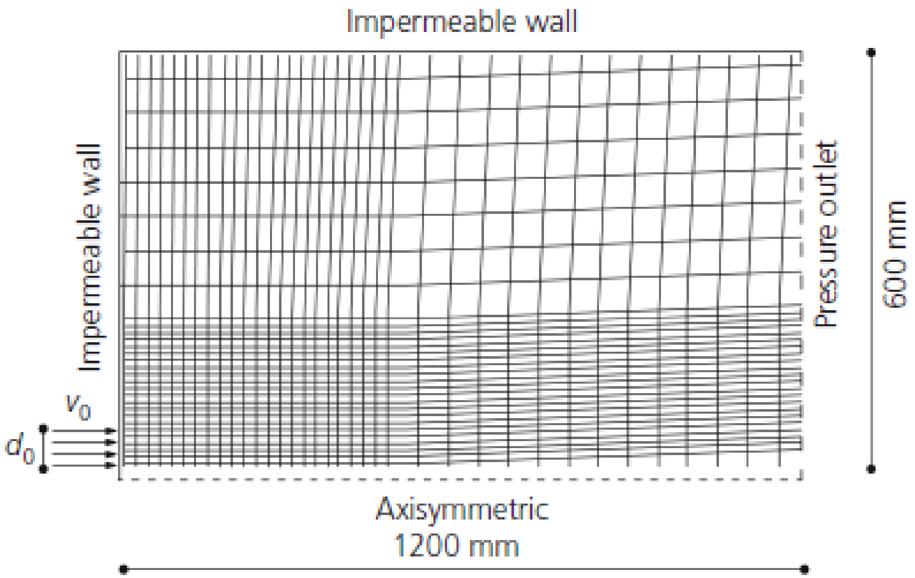


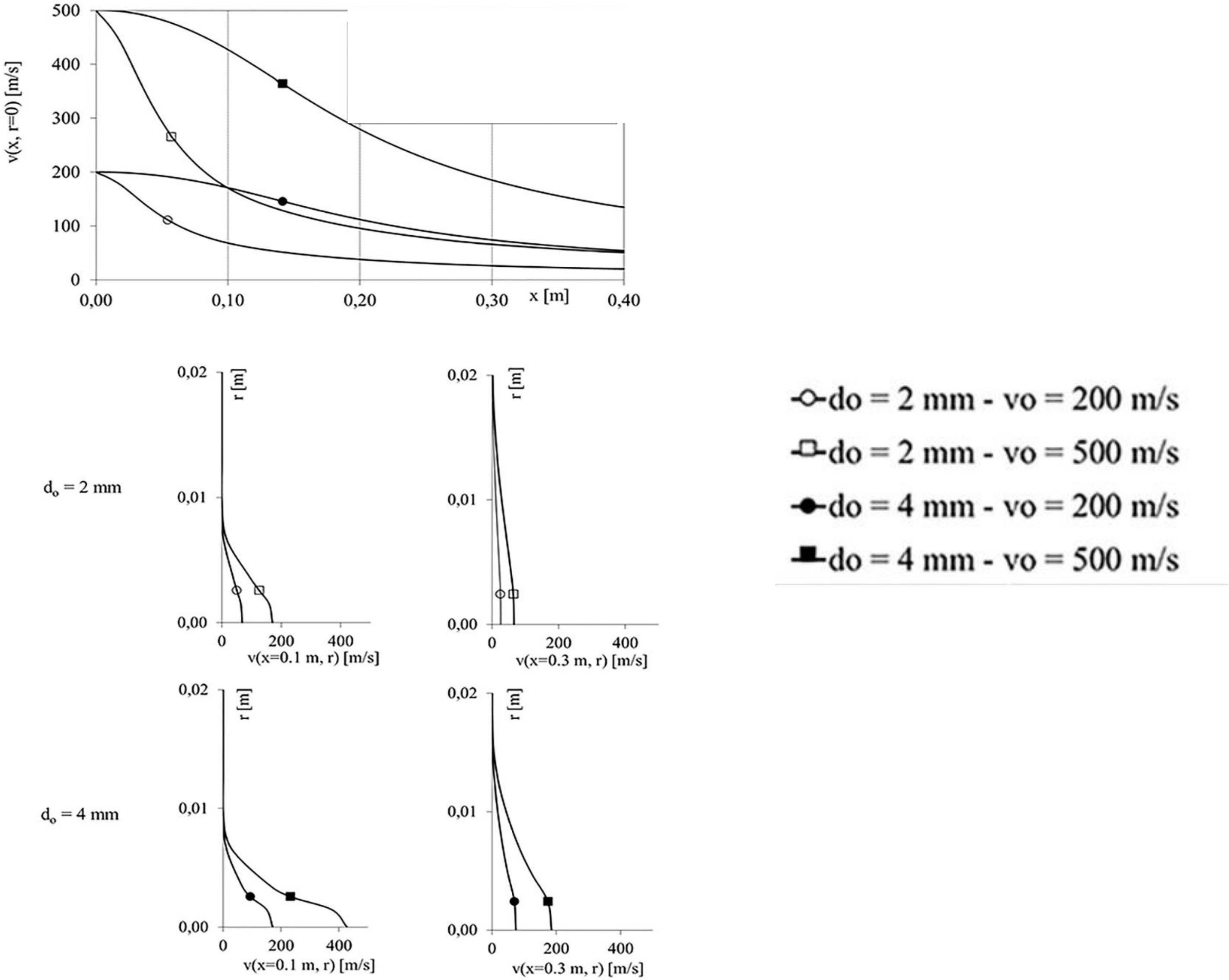




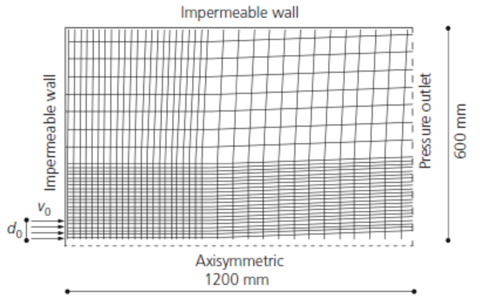
$$Re = \frac{M}{S} = \frac{\rho \cdot v_o \cdot d_o}{\mu}$$

JET GROUTING: numerical modelling



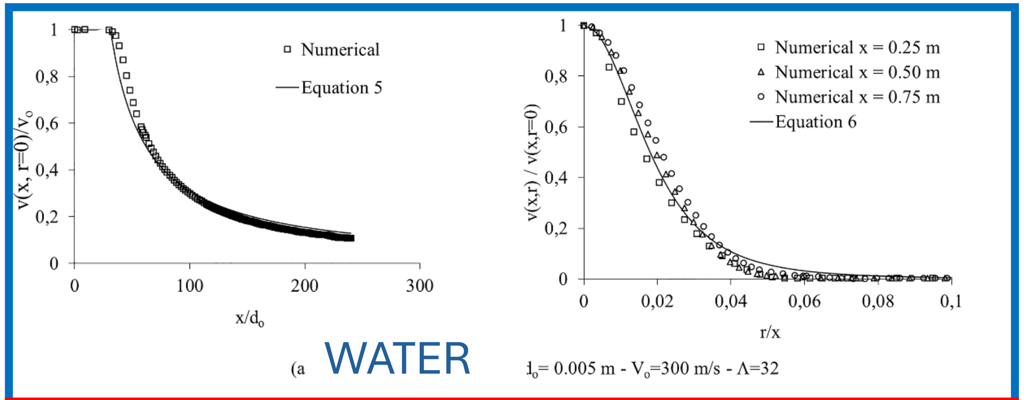


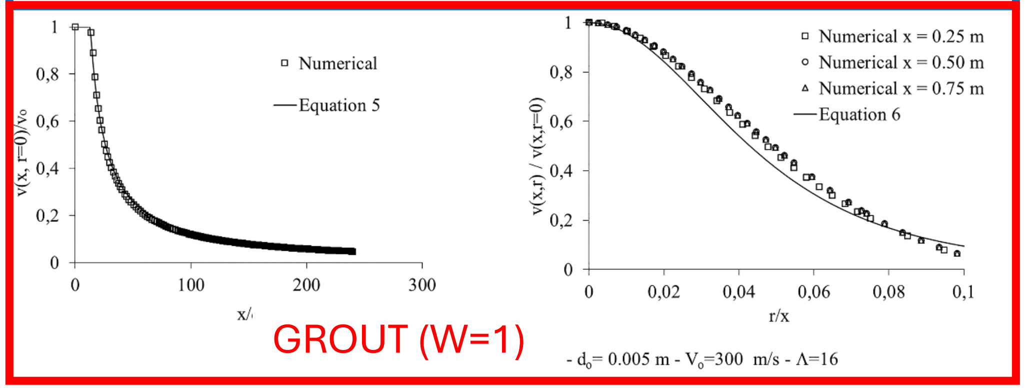
JET GROUTING: numerical modelling

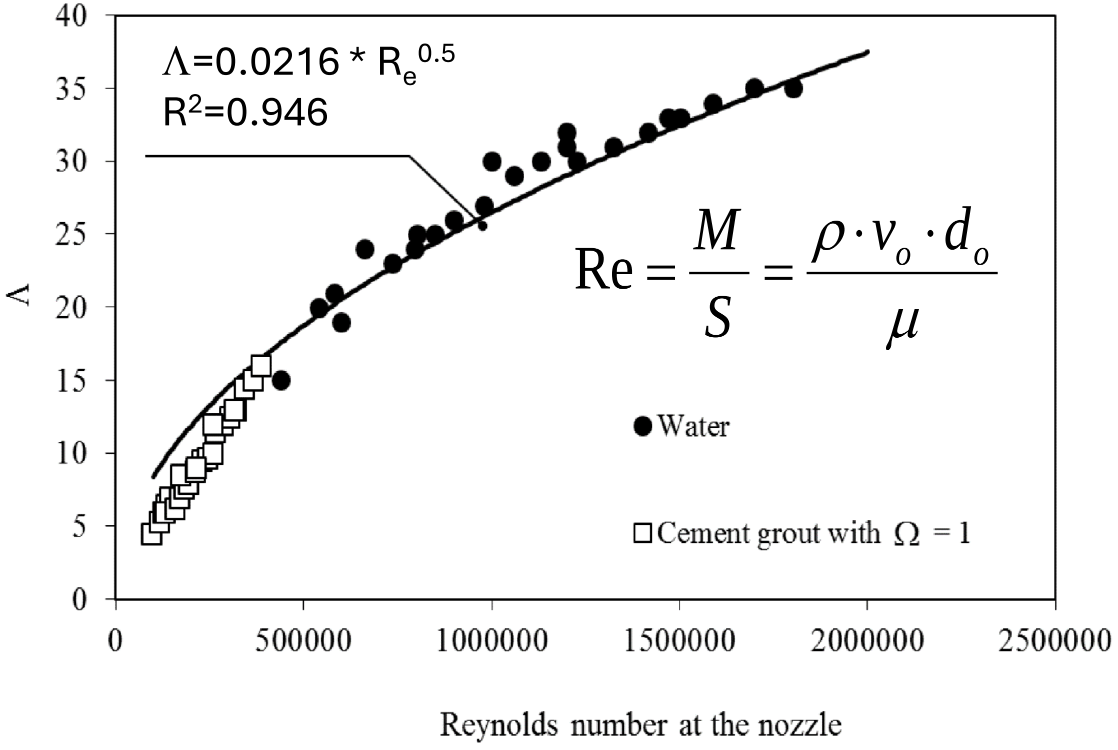


$$\frac{v(x,r=0)}{v_o} = \Lambda \frac{d_o}{x}$$

$$\frac{v(x,r)}{v(x,r=0)} = \frac{1}{\left[1+1.33\cdot\left(\Lambda\frac{r}{x}\right)^2\right]^2}$$

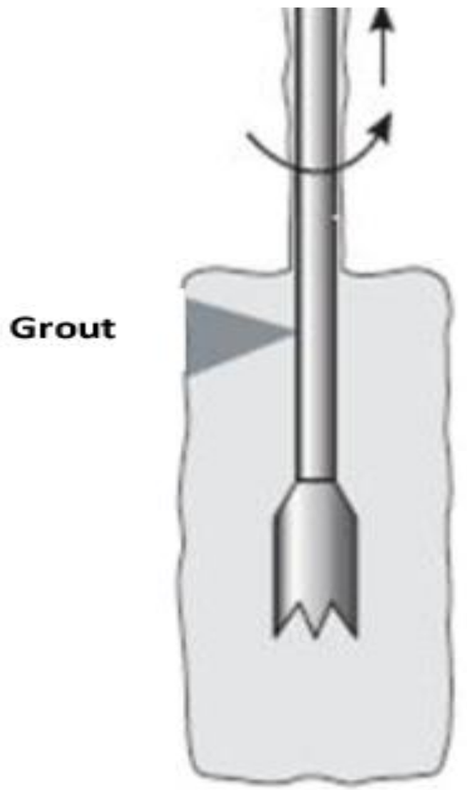




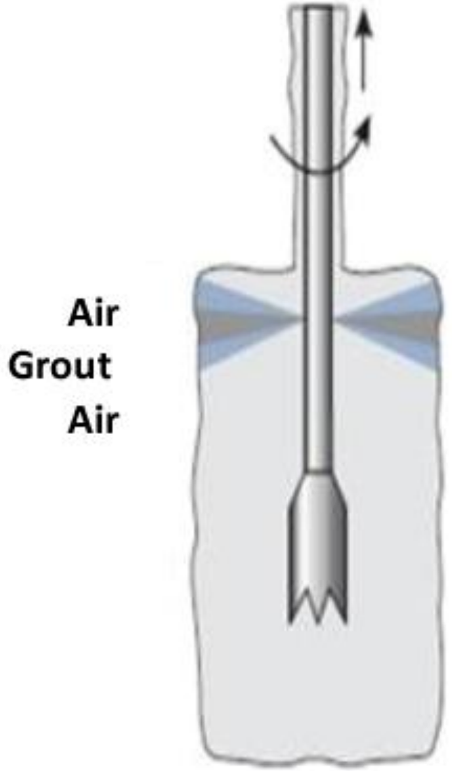


JET GROUTING: injection systems

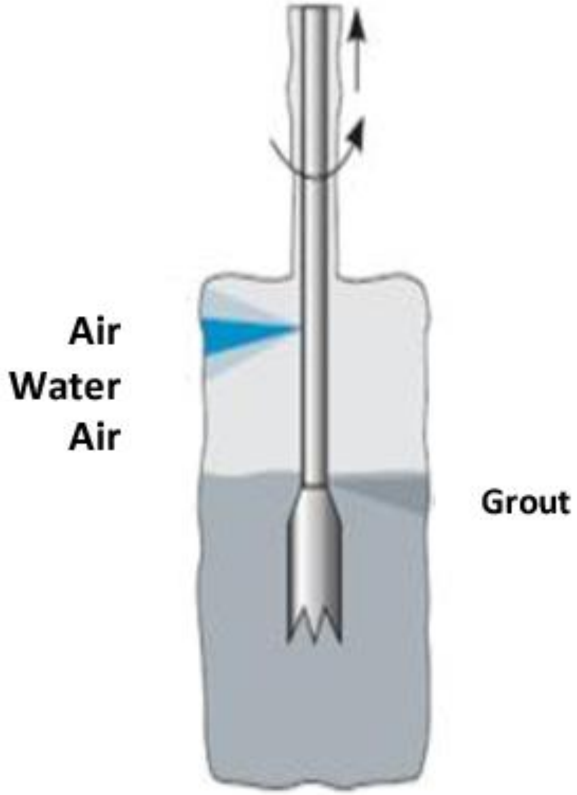
Single fluid
C.C.P.
(*Chemical Churning Pile*).



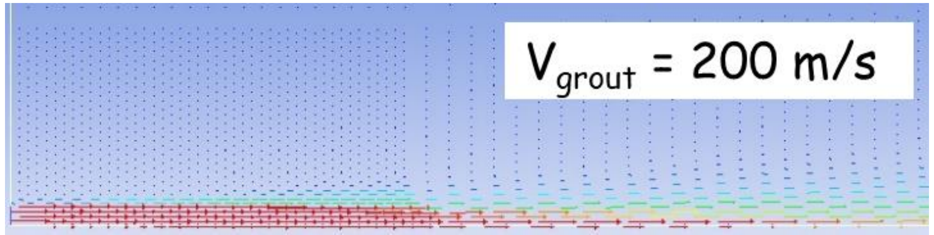
Double fluid
J.S.G.
(Jumbo Jet Special Grout)

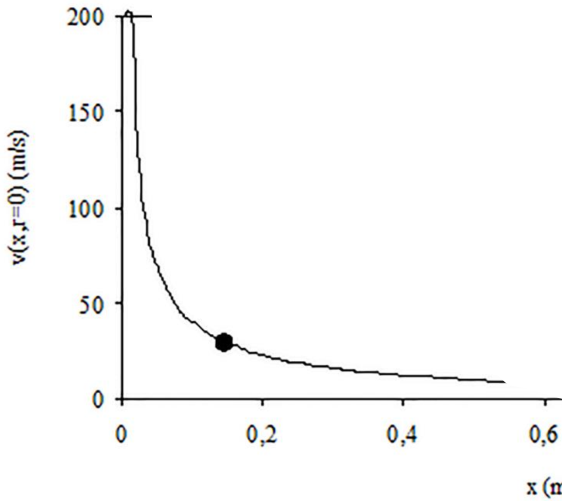


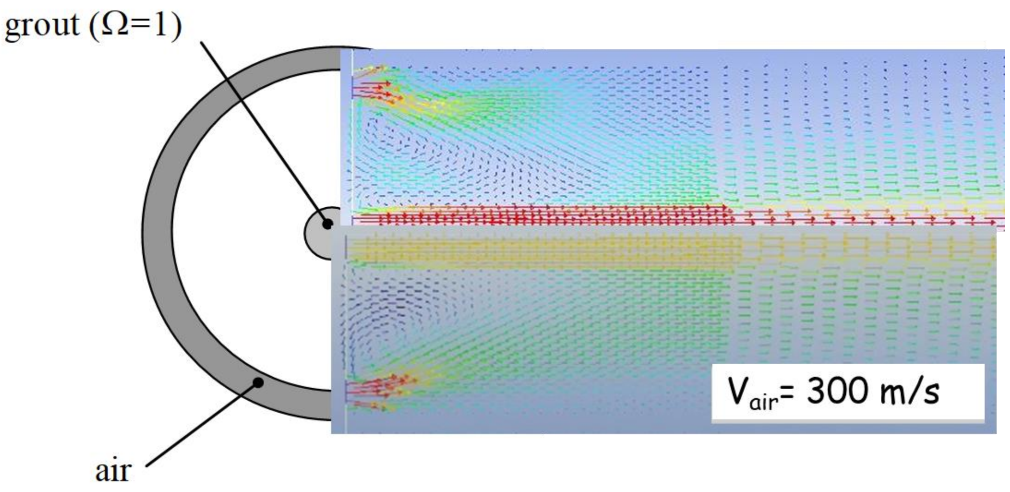
Triple fluid
Kajima method



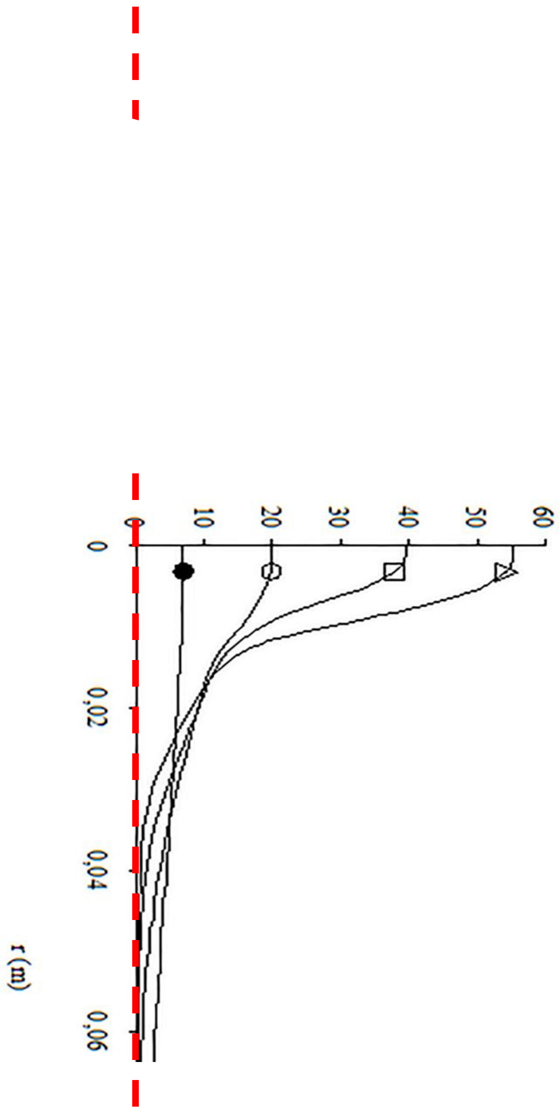
JET GROUTING: numerical modelling



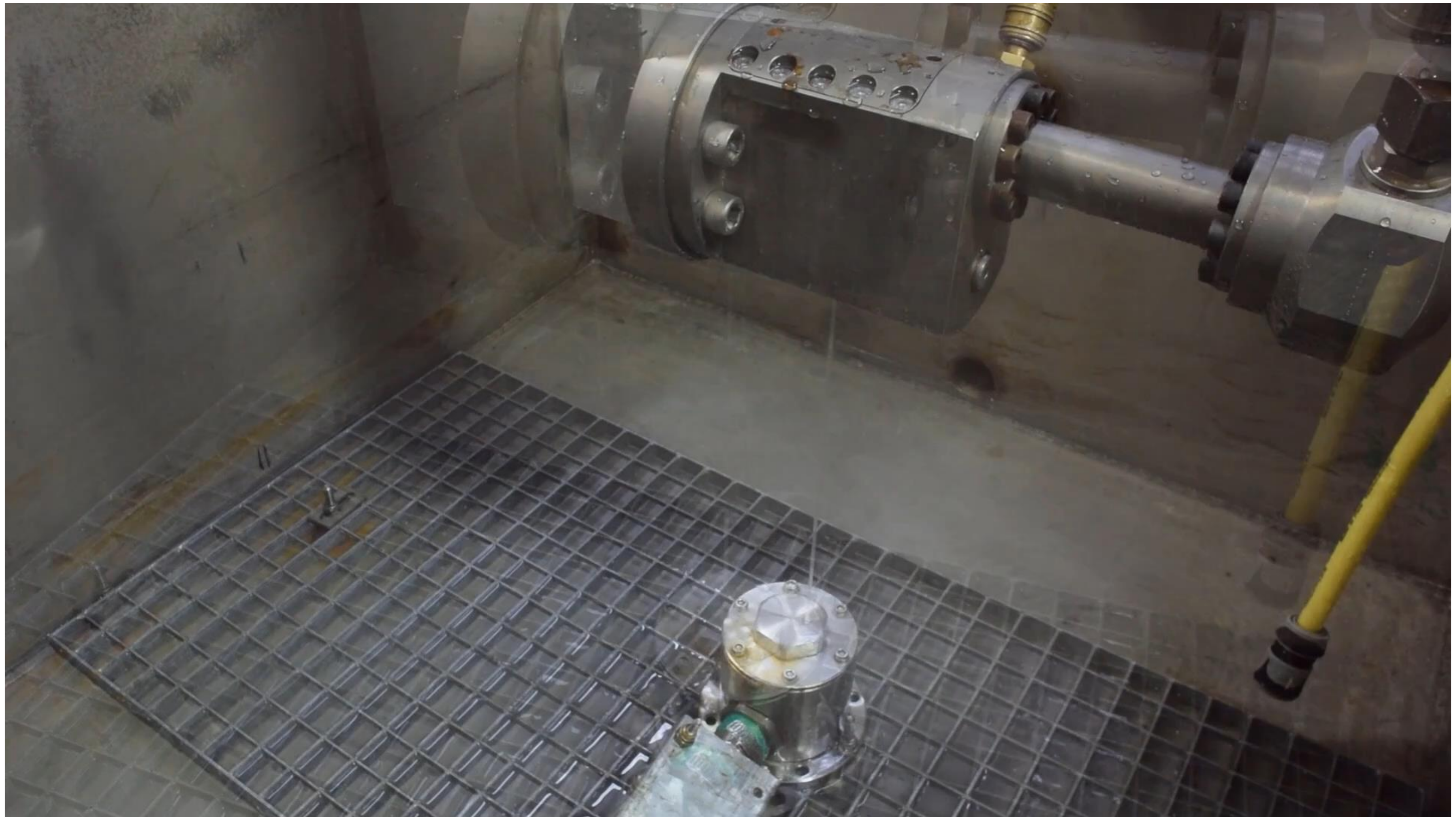


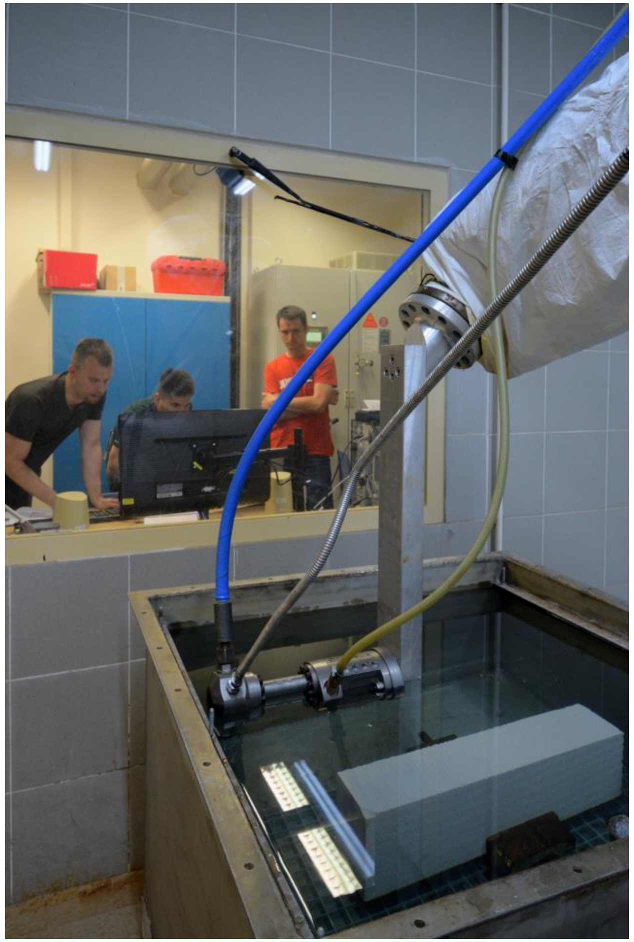


grout



The submerged jet: laboratory observation





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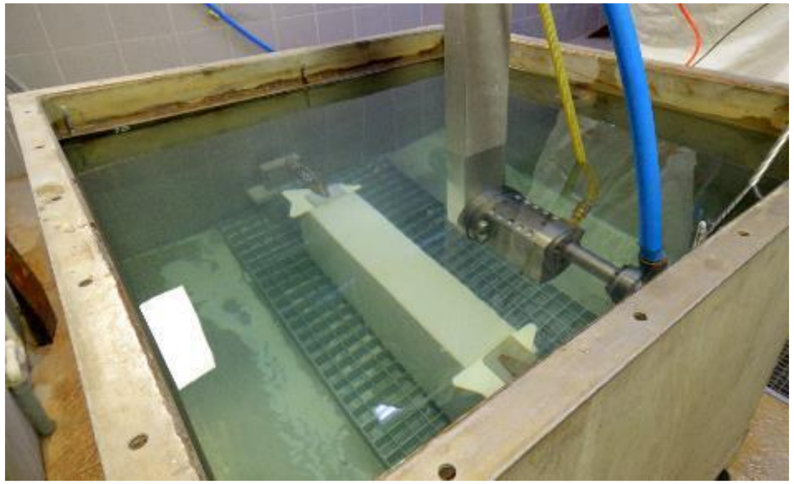
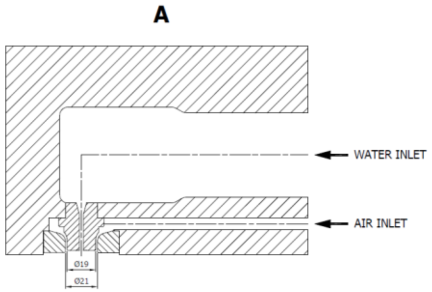
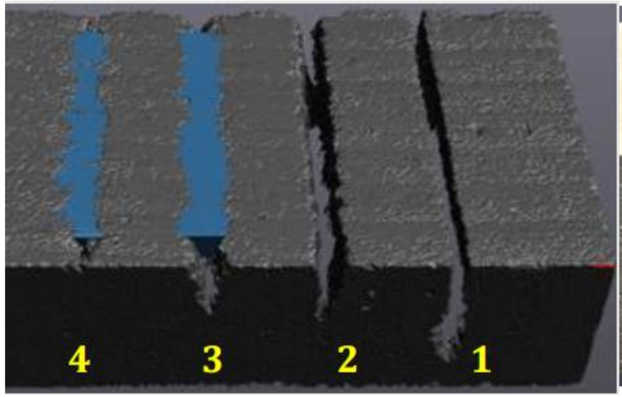
The submerged jet: laboratory observation

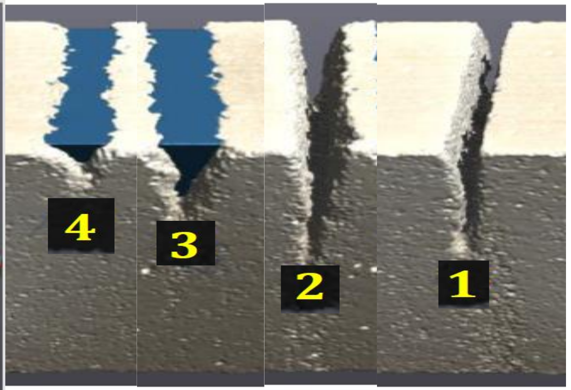




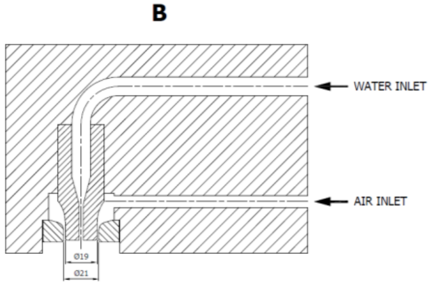
Standard nozzle



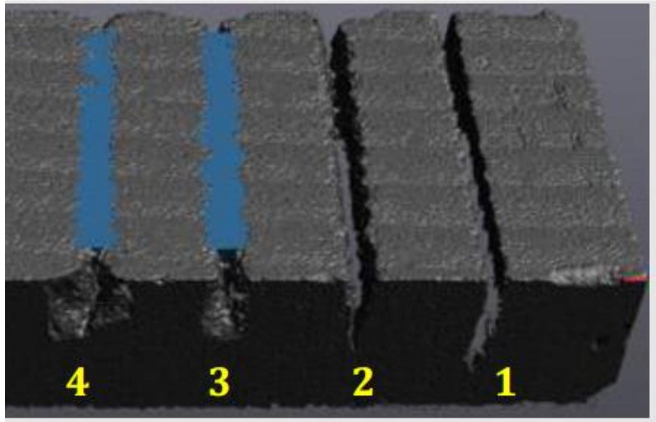
Without air



With air



Strajet nozzle



Without air

1-100 mm standoff distance
2-200 mm
3-300 mm
4-400 mm

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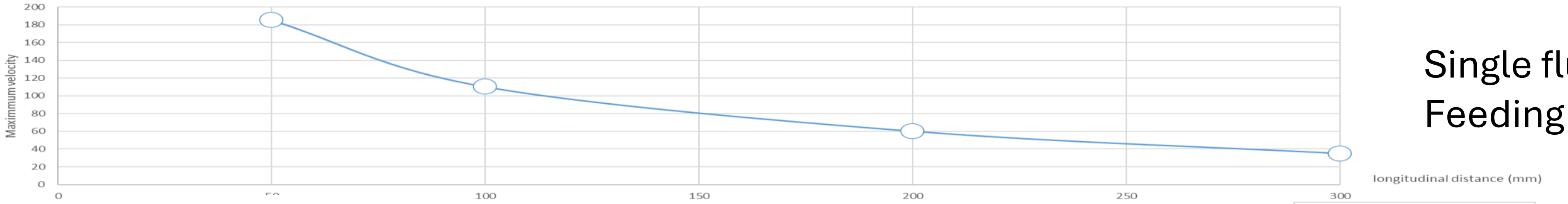
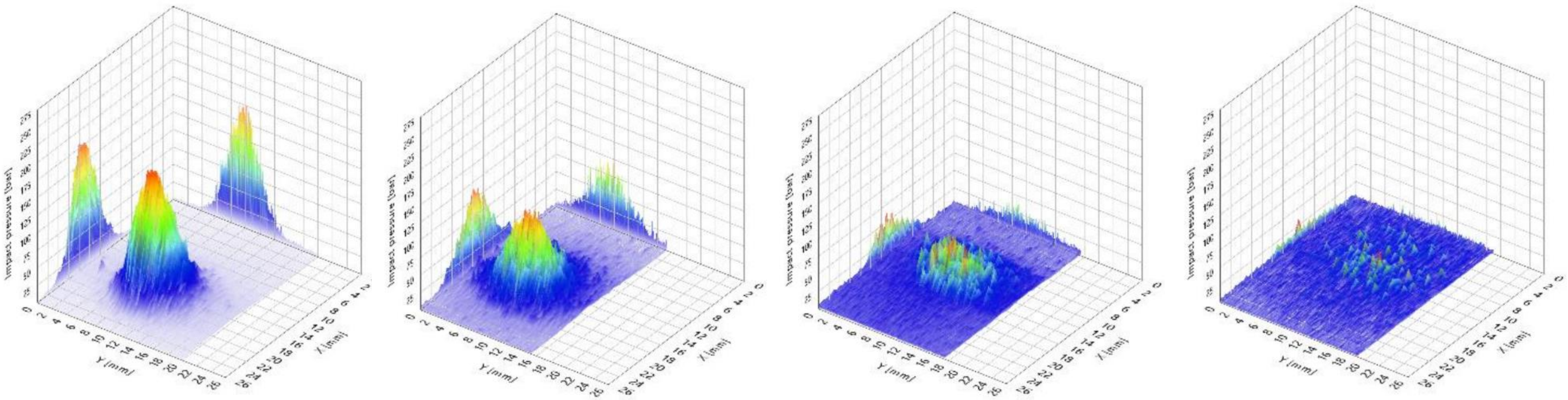
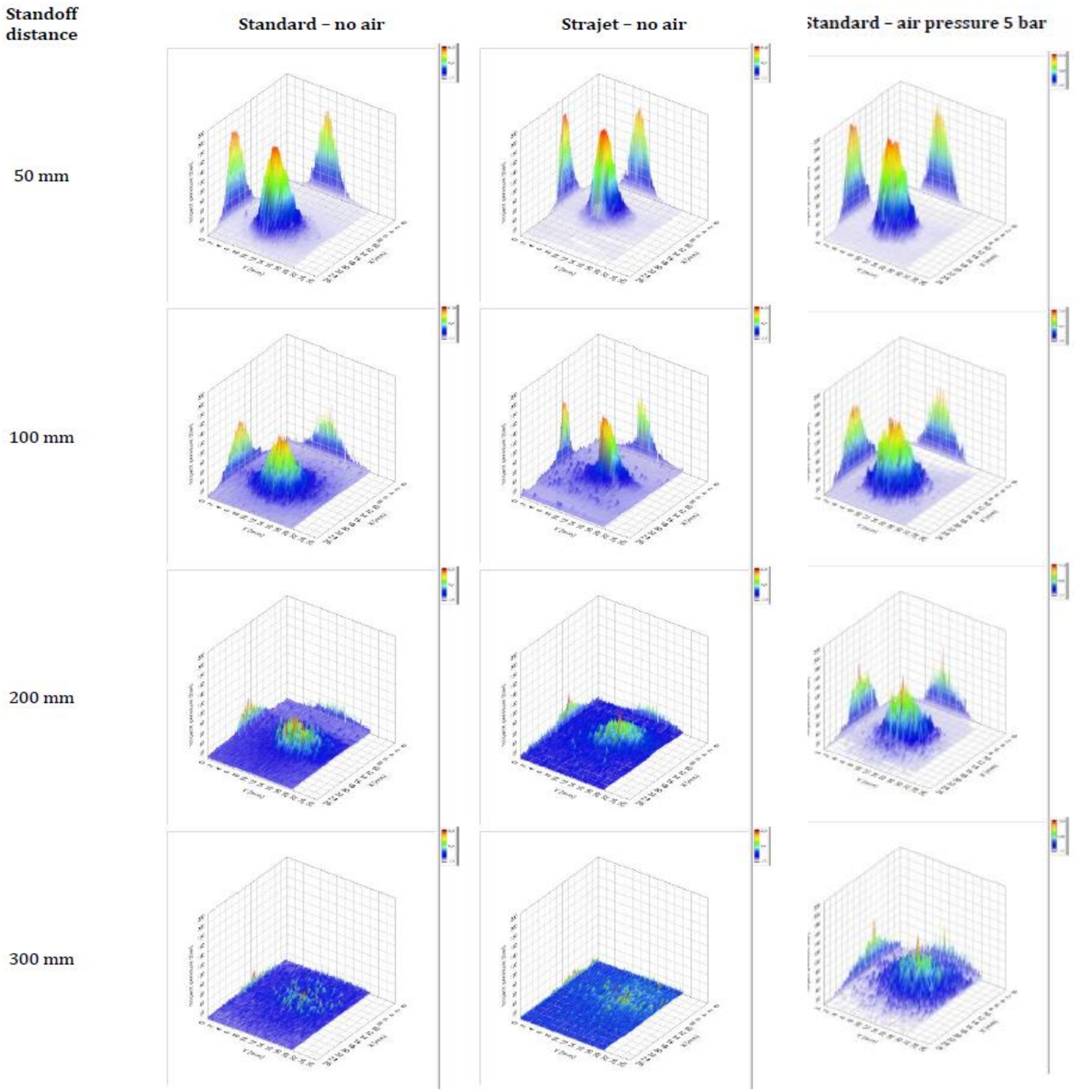
The submerged jet: laboratory observation



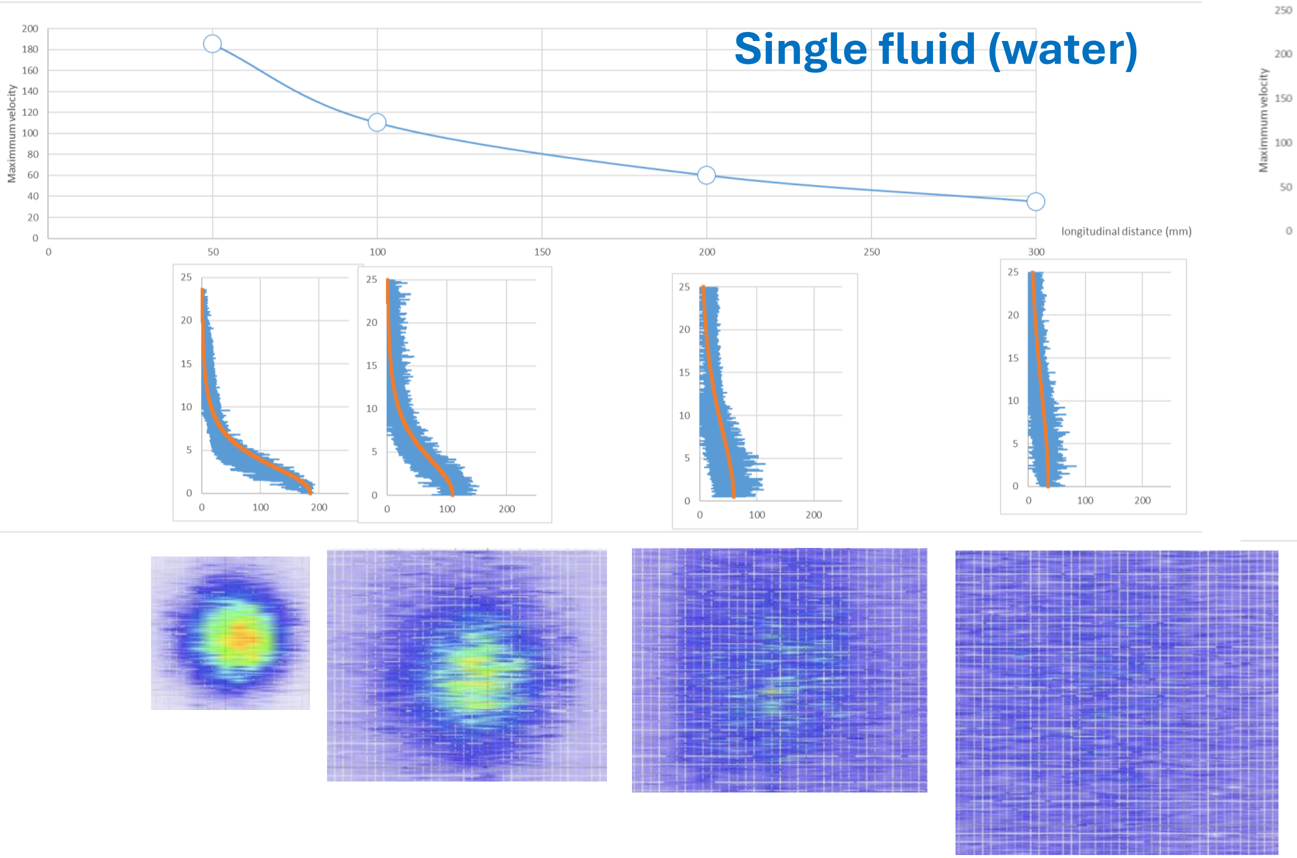
Single fluid (water)
Feeding pressure 380 bar

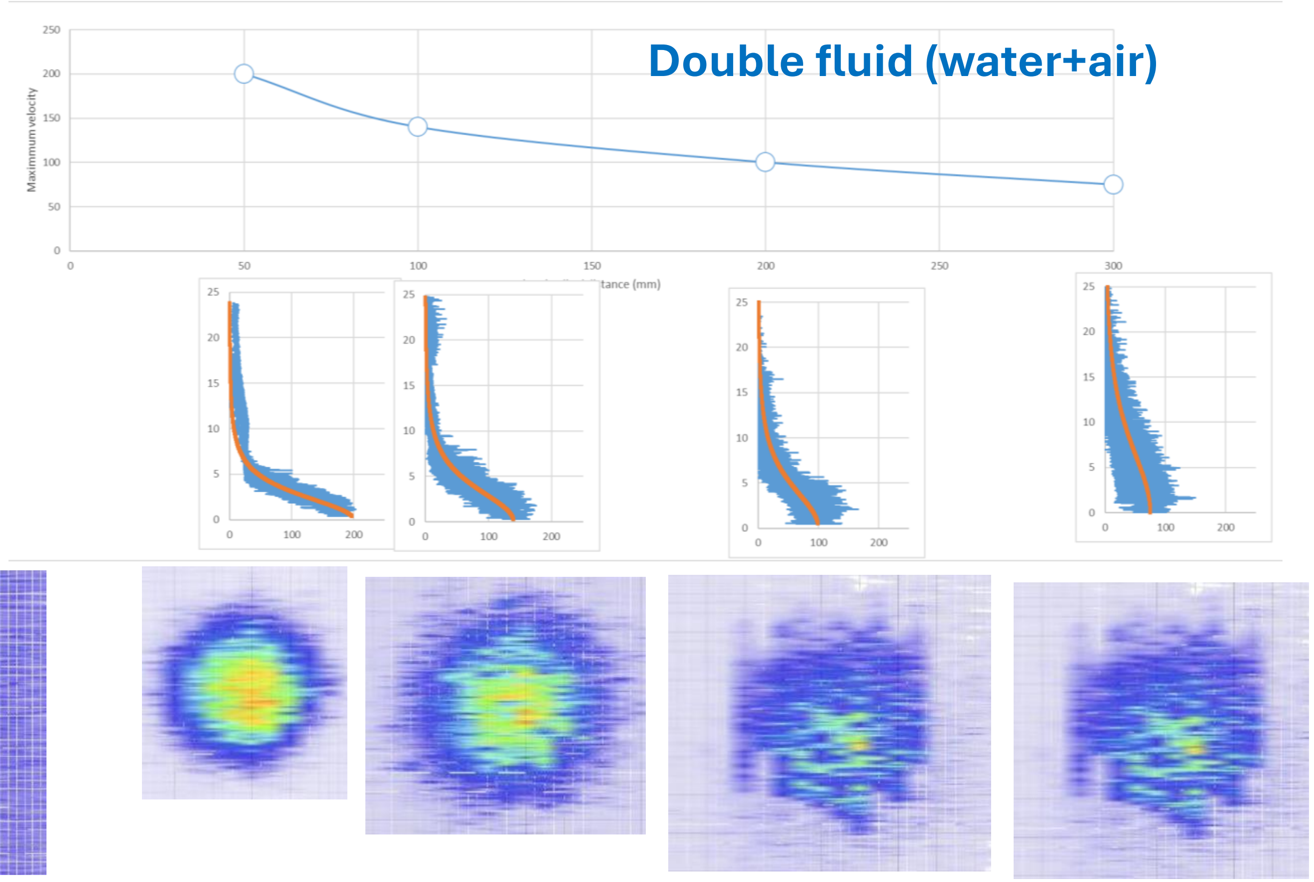


The submerged jet: laboratory observation



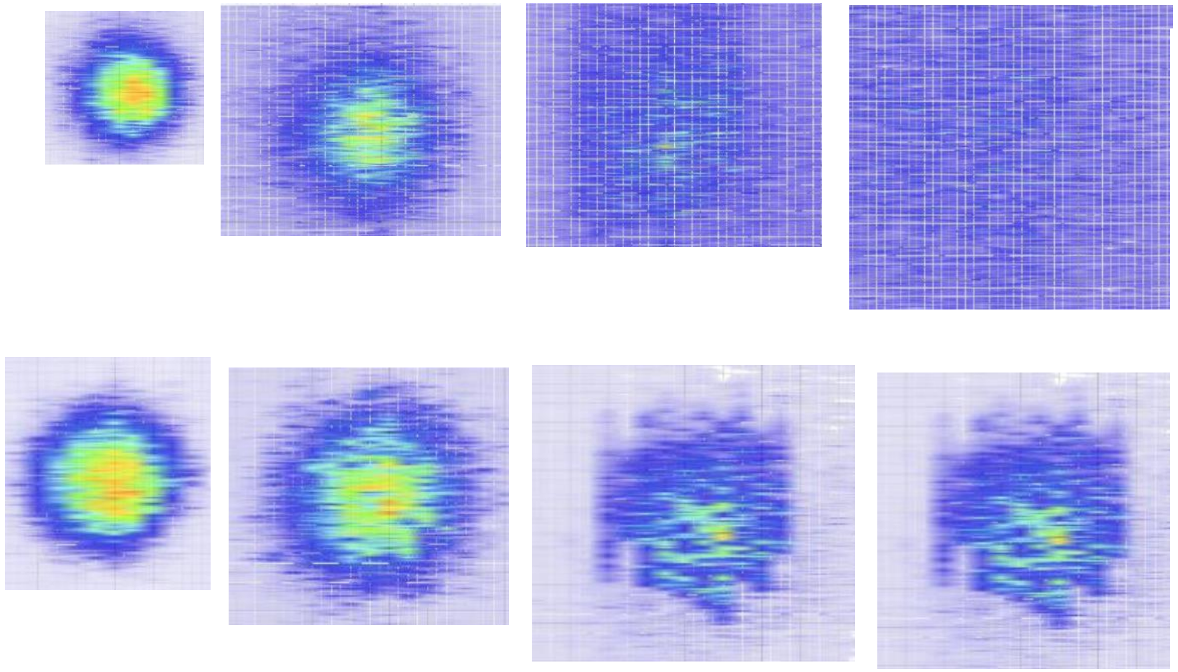
The submerged jet: laboratory observation



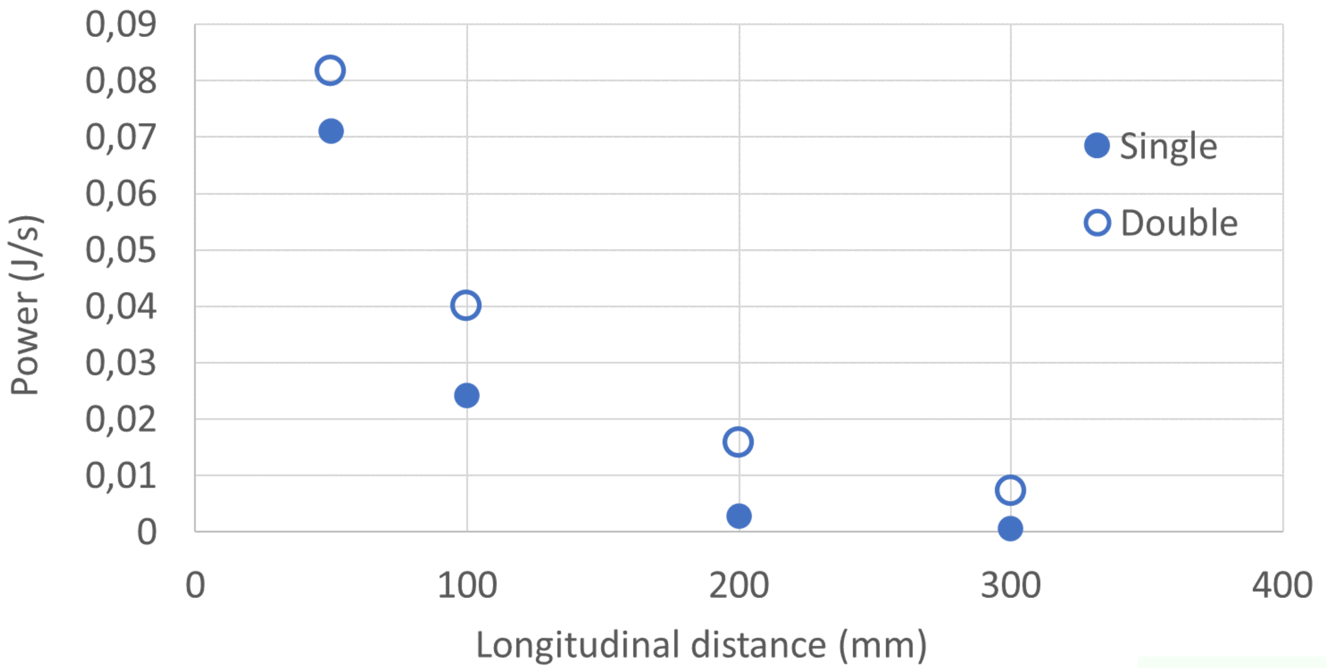


The submerged jet: laboratory observation

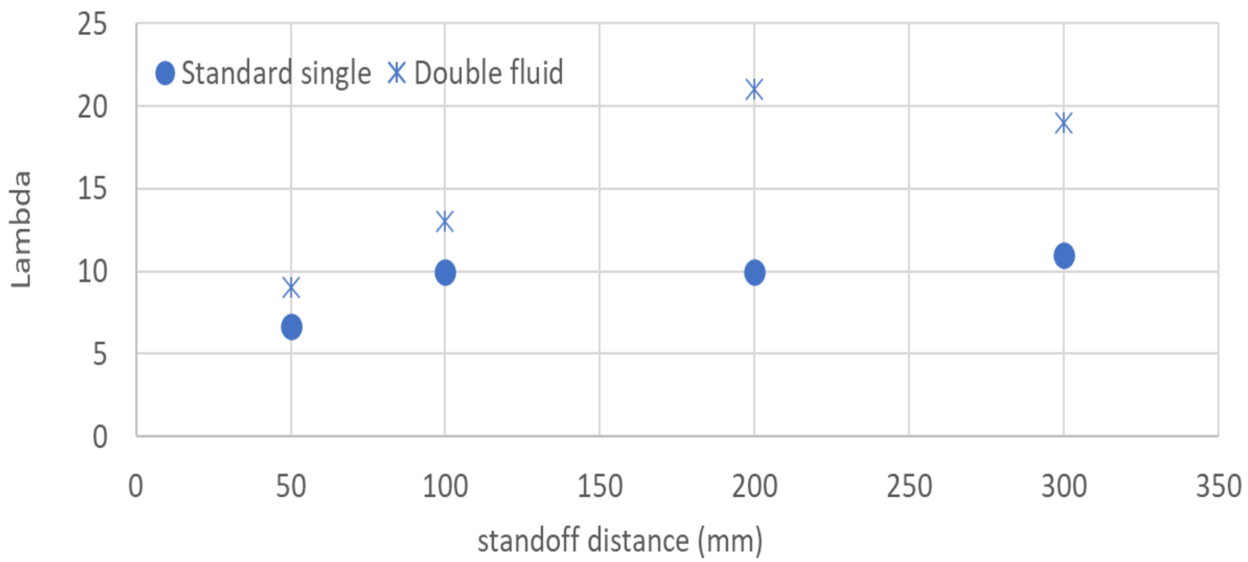
Single fluid (water)



Double fluid (water+air)

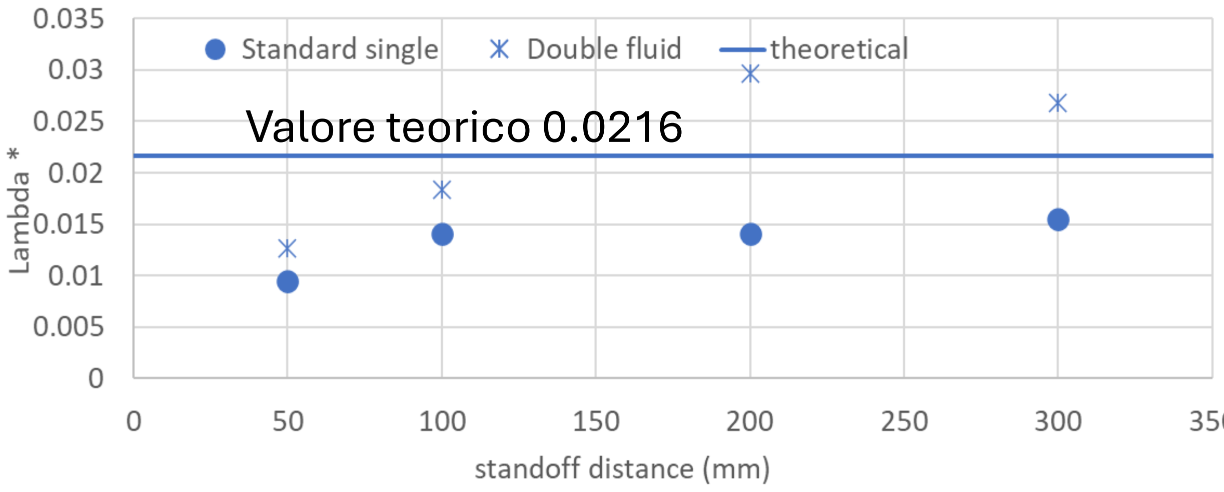


The submerged jet: laboratory observation



$$\frac{v(x, r=0)}{v_o} = \Lambda \frac{d_o}{x} \qquad \frac{v(x,r)}{v(x,r=0)} = \frac{1}{\left[1 + 1.33 \cdot \left(\Lambda \frac{r}{x}\right)^2\right]^2}$$

$$\Lambda = \Lambda^* \cdot R_e^{0.5}$$



Diameter prediction

Jet properties

Soil properties

Modoni, G., Croce, P. & Mongiovì, L. (2006). *Géotechnique* **56**, No. 5, 335–347

Theoretical modelling of jet grouting

G. MODONI*, P. CROCE* and L. MONGIOVÌ†

Theoretical modelling of the mechanical phenomena induced by jet grouting is presented. The analysis is developed for the single-fluid method. The jet propagation across the space included between the injection nozzles and the intact soil is first modelled on the basis of the theory of submerged flows. Different possible interaction modes between jet and soil are then assumed for gravels, sands and clays, according to the results of previous experimental investigations. In the case of gravels, grout seepage is considered to be the most relevant mechanism. For sandy soils, the injected fluid is assumed to penetrate, for a limited extent, into the soil skeleton, producing a considerable increment of the pore pressures and a corresponding reduction of the grain-to-grain contact forces. The removal of the soil particles is then triggered by the dragging action of the fluid threads, and the analysis is developed under drained conditions. For clayey soils, the jet action is considered as a load imposed on the jet–soil interface, and the erosion process is modelled as an evolving sequence of undrained failures. Theoretical results obtained for the different soil types are compared with available experimental data, and the models are thus calibrated by means of back-analysis.

KEYWORDS: design; erosion; grouting; model tests; seepage

Nous présentons une modélisation théorique de phénomènes mécaniques provoqués par la cimentation par injection. Nous développons cette analyse pour la méthode à un seul fluide. Nous modélisons d'abord la propagation du jet dans l'espace inclus entre les tuyères d'injection et le sol intact sur la base de la théorie des flots submergés. Nous supposons ensuite différents modes d'interaction possible entre le jet et le sol pour les graviers, les sables et les argiles, selon les résultats d'investigations expérimentales précédentes. Dans le cas des graviers, nous considérons l'infiltration de ciment liquide comme le mécanisme le plus pertinent. Pour les sols sableux, nous supposons que le fluide injecté pénètre, sur une étendue limitée, dans le squelette du sol, produisant une augmentation considérable des pressions de pores et une réduction correspondante des forces de contact grain à grain. Le retrait des particules de sol est alors déclenché par l'action de dragage des fils de fluide ; l'analyse est développée sous conditions drainées. Pour les sols argileux, l'action de jet est considérée comme une charge imposée sur l'interface jet-sol et le processus d'érosion est modélisé comme une séquence évolutive des défaillances non drainées. Nous comparons les résultats théoriques obtenus pour différents types de sol avec les données expérimentales disponibles ; les modèles sont ainsi calibrés au moyen d'une rétro analyse.

INTRODUCTION

Jet grouting is one of the most popular ground improvement techniques, and is currently used all over the world for many different purposes, such as increasing the bearing capacity and reducing settlements of new and existing foundations, supporting open and underground excavations, and creating water cut-offs for dams. The method is based on high-speed grouting of water–cement mixtures and/or other fluids (air, water) into the subsoil. The fluids are injected through small-diameter nozzles placed on a grout pipe, which is continuously rotated at a constant rate and slowly raised towards the ground surface. The jet propagates radially from the borehole axis and, after some time, the injected mortar solidifies underground, eventually producing a cemented soil body of quasi-cylindrical shape (jet column).

Currently adopted jet grouting methods can be classified according to the number of fluids injected into the subsoil: water–cement grout (single-fluid system), air + grout (double-fluid system), and water + air + grout (triple-fluid system). In the double-fluid system, the grout jet is wrapped by a coaxial air jet, whereas in the triple-fluid system the grout jet is preceded by a jet of water surrounded by air.

Technical improvements are continuously introduced, for each system, in order to increase the dimensions and the mechanical properties of the jet columns (e.g. Shibazaki, 2003). However, in spite of such rewarding developments, there is still a relevant degree of uncertainty at the design stage, arising from the lack of reliable methods for predicting the diameter of the jet columns. In fact, most jet grouting projects are planned on the basis of some empirical rules, which may provide only rough estimates of the column diameter (Croce & Flora, 2000).

Theoretical modelling of the mechanical phenomena induced by jet grouting has thus been attempted. Considering the complexity of the mechanical phenomena involved, the analysis has been restricted to the single-fluid system.

The first step of the analysis is devoted to the jet propagation across the space included between the nozzles and the intact soil. This space is usually filled by some fluid, of various possible origin (natural groundwater, perforation water, previously injected grout, floating soil grains, etc.). At the beginning of treatment this fluid region is relatively thin, because the soil boundary coincides with the borehole surface. However, if soil erosion takes place, the soil boundary will shift, and the fluid region will become larger. The evolution of the geometrical and kinematical characteristics of the jet within this zone are analysed on the basis of the theory of submerged flow (Hinze, 1948).

After reaching the soil face, part of the injected grout may maintain its original direction (radial flow), either by seeping through the soil pores or by displacing the soil grains, while the remaining grout may flow towards the ground surface (vertical flow), passing through the annular space bounded by the perforation hole and the injection stem. The measured percentage of vertical outflow, comprising grout and some eroded soil, increases with decreasing size of the soil grains, ranging between 0% and 80% (Kauschinger *et al.*, 1992).

For very pervious soils, such as coarse gravel, the vertical

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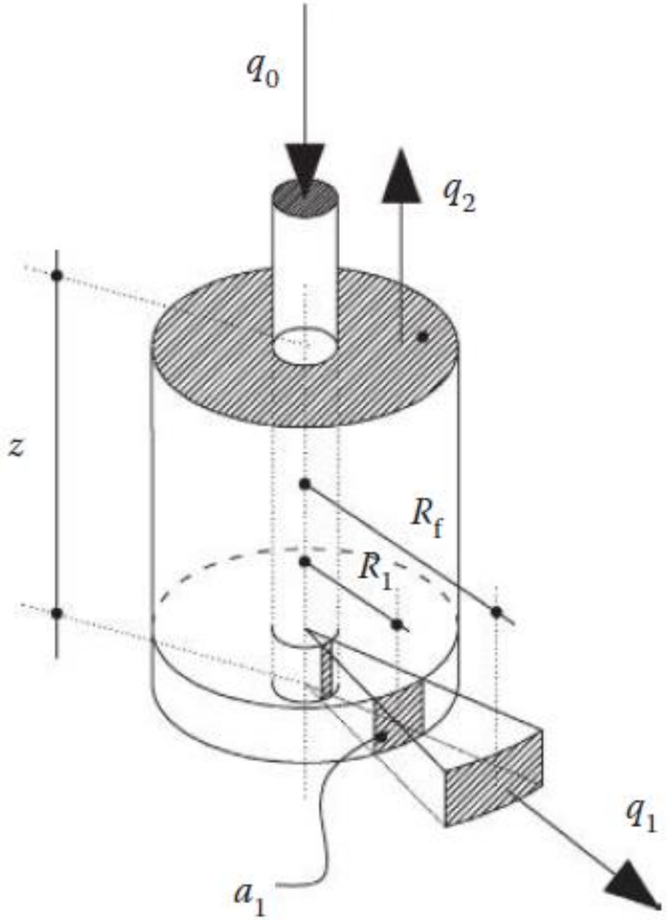
Discussion on this paper closes on 1 December 2006, for further details see p. ii.

* University of Cassino, Cassino, Italy.
† University of Trento, Mesiano, Italy.



Diameter prediction

Jet properties

PARAMETER	UNIT	SINGLE FLUID	DOUBLE FLUID	TRIPLE FLUID
Time interval per step, Δt	s	4÷6	6÷10	8÷80
Uplift step, Δs	10^{-3} m	40÷50	40÷50	40÷50
Uplift speed, v_r	10^{-3} m/s	4÷10	1÷8	0.5÷5
Rotational speed, ω	RPM	5÷40	5÷40	5÷40
Nozzles diameter, d	10^{-3} m	1.2÷4	2÷4	2÷4
Number of nozzles, M	-	1÷2	1÷2	1÷2
Grout pressure, p_m	MPa	40÷55	20÷40	2÷10
Air pressure, p_a	MPa	-	0.5÷2.0	0.5÷2.0
Water pressure, p_w	MPa	-	-	20÷55
Grout flow rate, Q_m	10^{-3} m³/s	1÷10	1÷10	1÷3.5
Air flow rate, Q_a	10^{-3} m³/s	-	70÷150	70÷150
Water flow rate, Q_w	10^{-3} m³/s	-	-	0.5÷2.5
Water cement ratio by weight W/C	-	0.60÷1.5	0.60÷1.5	0.60÷1.5

$$E'_n = \frac{\pi}{8}\frac{M\rho d_0^2 v_0^3}{v_s}$$

$$E'_n = 0{\cdot}9E'_p \qquad E'_p = \frac{pQ}{v_s}$$

Soil properties

$$S = \frac{N_{SPT}}{N_{SPT\ ref}} = \frac{N_{SPT}}{10}$$

for coarse-grained soils

$$S = \frac{q_c}{q_{c\ ref}} = \frac{q_c}{1{\cdot}5} \qquad (q_c \text{ in MPa})$$

for fine-grained soils.

Diameter prediction

Theoretical model

Treatment parameters

$$E'_n = \frac{\pi}{8}\frac{M\rho d_0^2 v_0^3}{v_s}$$

$$E'_n = 0{\cdot}9E'_p \qquad E'_p = \frac{pQ}{v_s}$$

$$J = \frac{E'(x)}{E'_{ref}(x)} = \frac{\alpha\Lambda^* E'_n}{\alpha_{ref}\Lambda^*_{ref}E'_{n,ref}} \qquad (12)$$

In the present work, the reference term $E'_{ref}(x)$ has been calculated assuming a single fluid jet grouting treatment ($\alpha_{ref} = 1$), with a cement to water ratio by weight ω equal to 1 ($\Lambda^*_{ref} \approx 7{\cdot}5$) and a specific energy at the nozzles $E'_{n,ref} = 10$ MJ/m.

Soil properties

$$S = \frac{N_{SPT}}{N_{SPT\ ref}} = \frac{N_{SPT}}{10}$$

for coarse-grained soils

$$S = \frac{q_c}{q_{c\ ref}} = \frac{q_c}{1{\cdot}5} \qquad (q_c \text{ in MPa})$$

for fine-grained soils.

Empirical determination of the parameters

$$D_a = D_{ref} J^{\beta} S^{\delta}$$

Parameters D_{ref}, α, β, δ

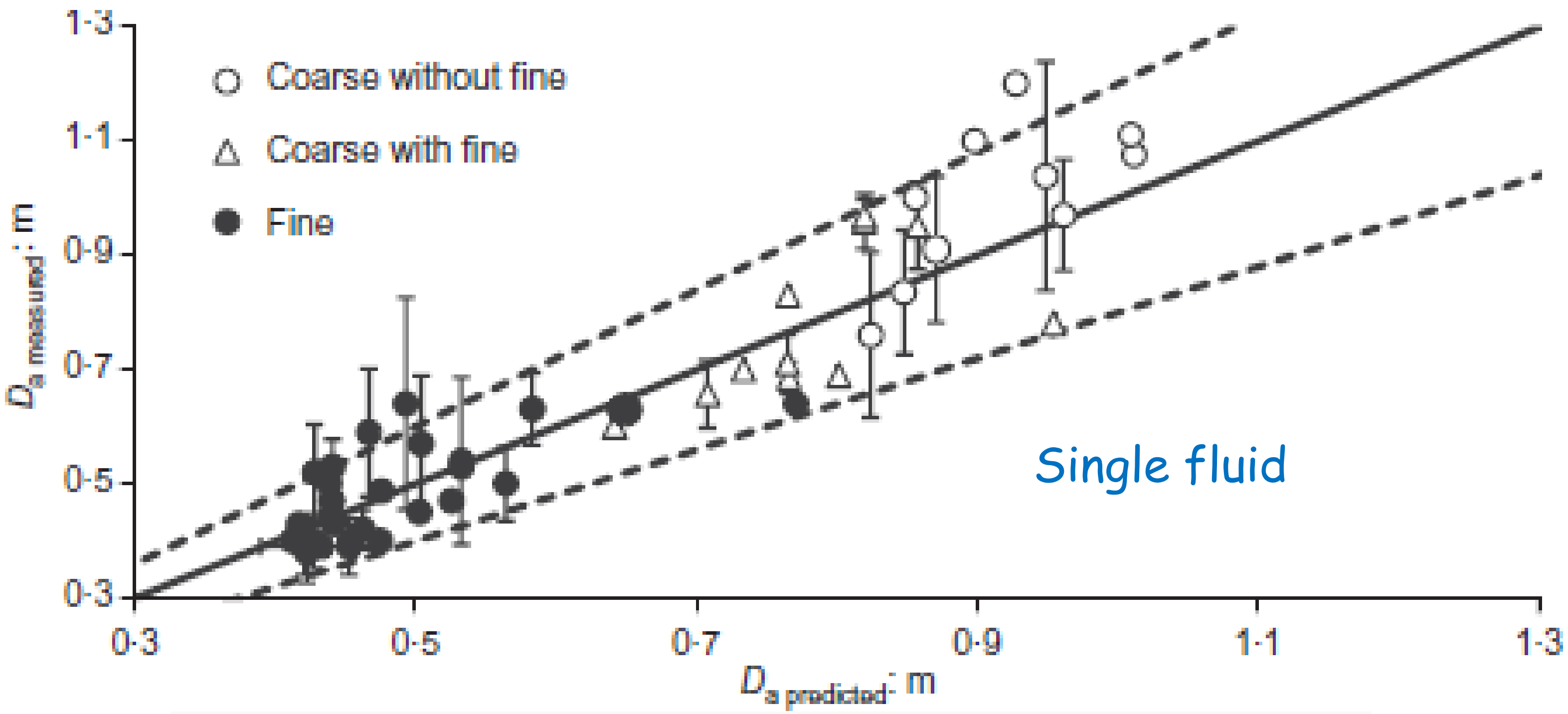
Diameter prediction

$$D_a = D_{ref} J^{\beta} S^{\delta}$$

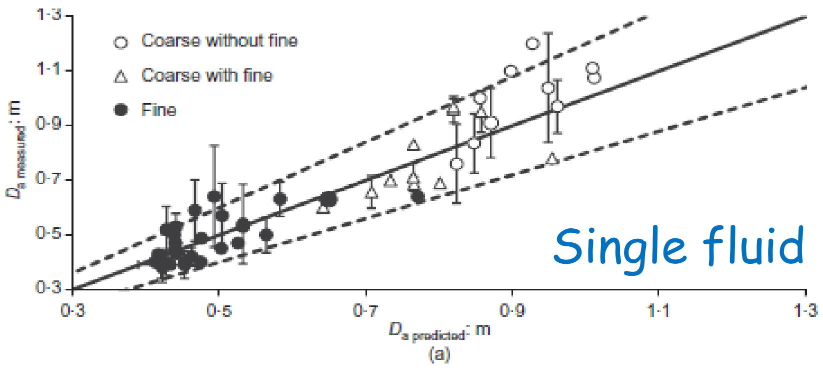
Table 4. Values of the parameters to be adopted in equations (14), calibrated on the experimental data collected in the field trials

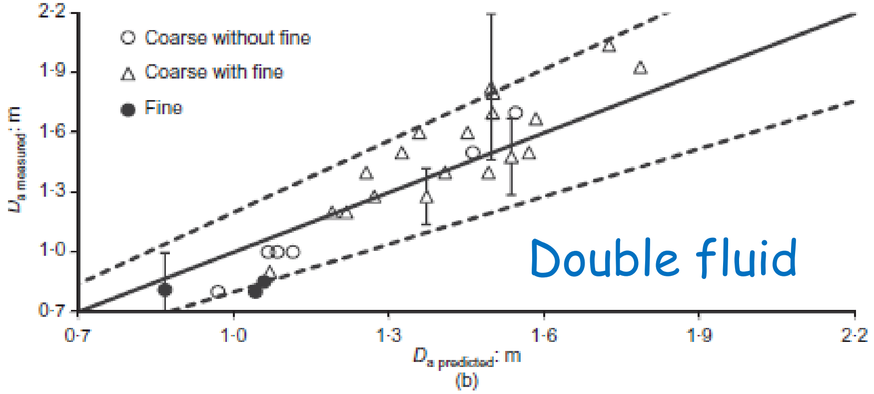
Soil type		ASTM D2487 classification*	D_{ref}: m	β	δ	α, single fluid	α, double and triple fluid
Coarse grained	Without fine	Gravels and sands with less than 5% fines, GW-GP-SW-SP	1·00	0·2	−0·25	1	6
	with fine	Gravels and sands with more than 5% fines, GM-GC-SM-SC	0·80				
Fine grained		Silts, clay and organic soils, CL-ML-OL-CH-MH-OH-Pt	0·50				

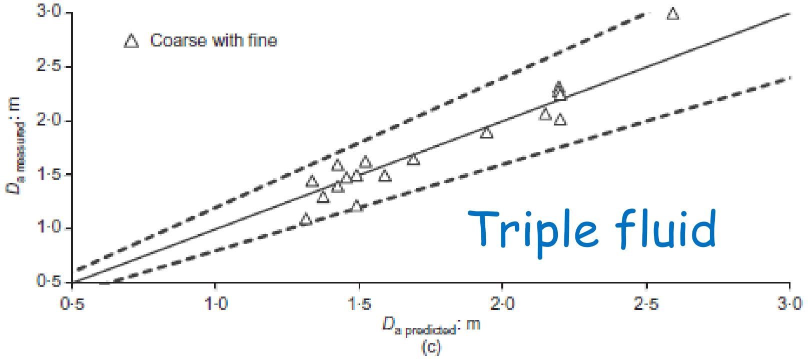
*ASTM (2011b).



Diameter prediction







$$D_a = D_{ref} J^{\beta} S^{\delta}$$

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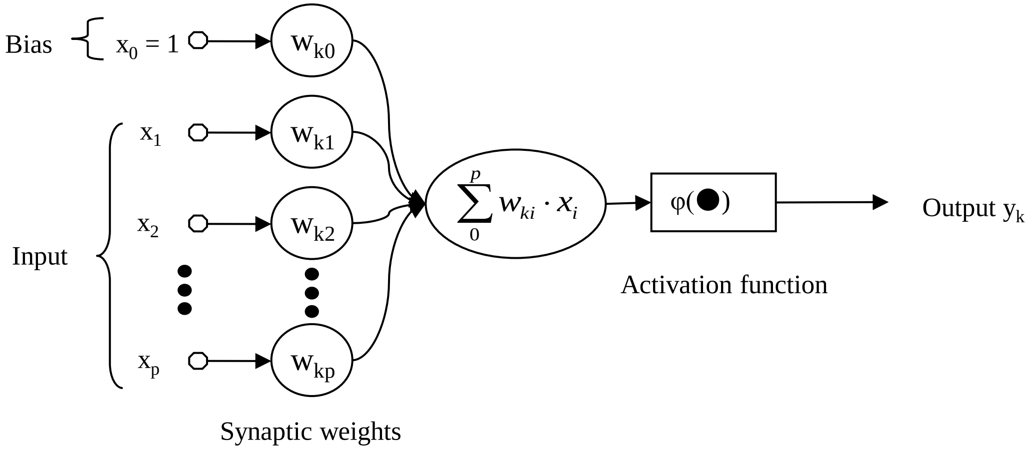
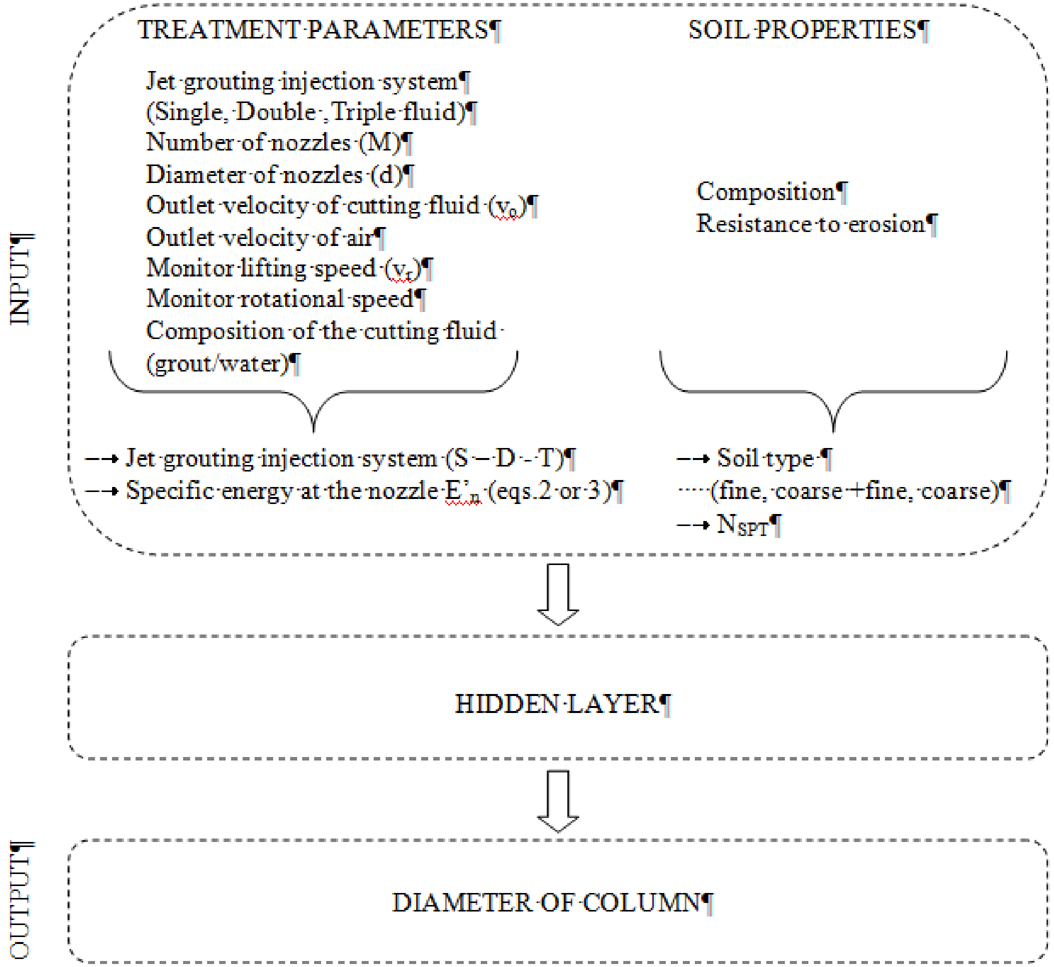
Fine grained		Silts, clay and organic soils, CL-ML-OL-CH-MH-OH-Pt	0·50				

*ASTM (2011b).

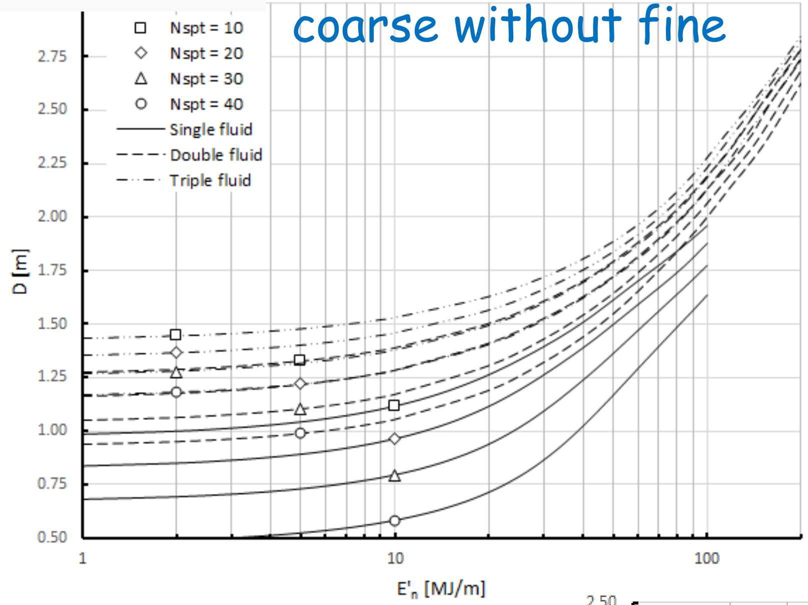
Diameter prediction

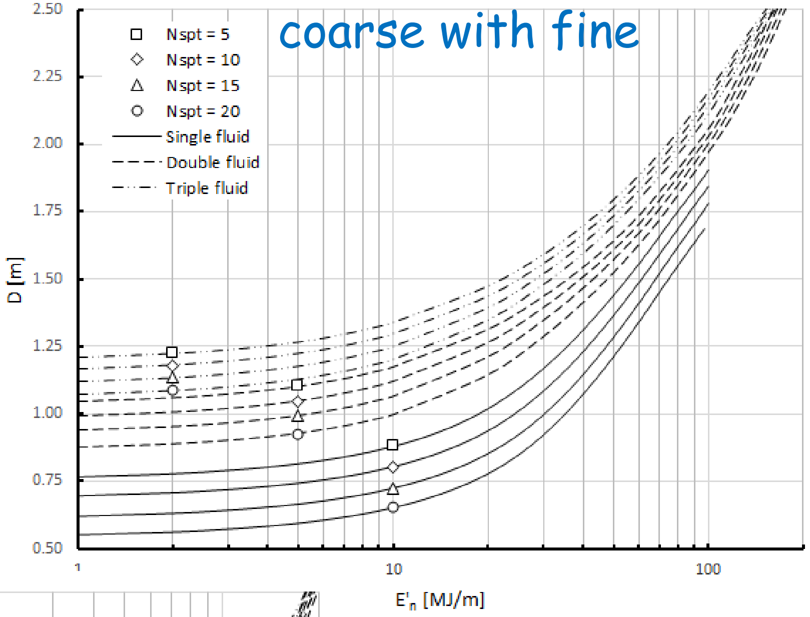
Artificial neural networks

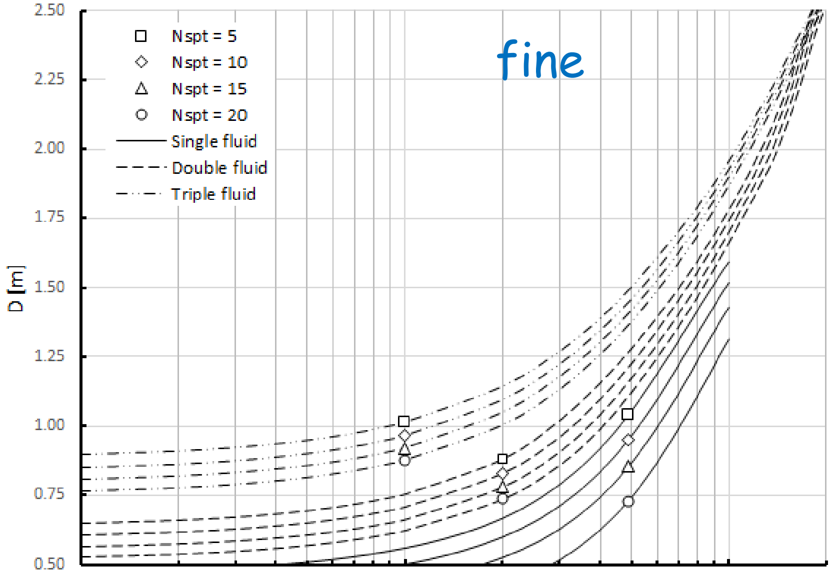




Diameter prediction

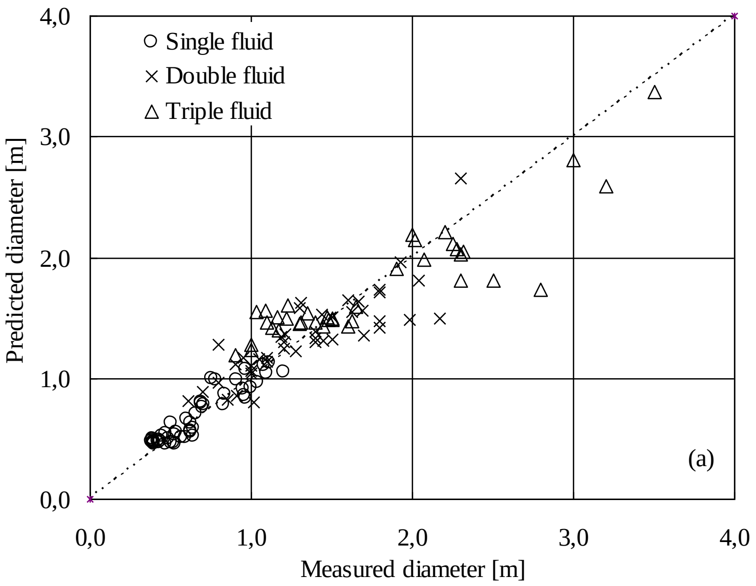




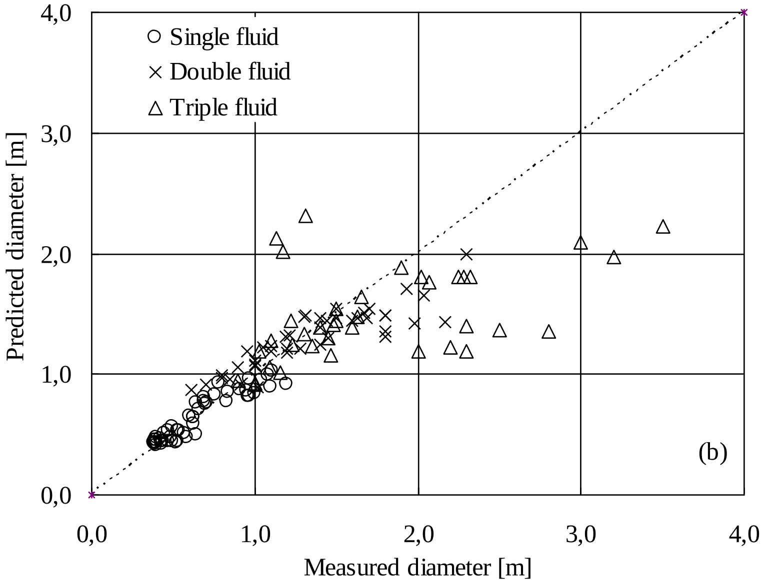


Diameter prediction

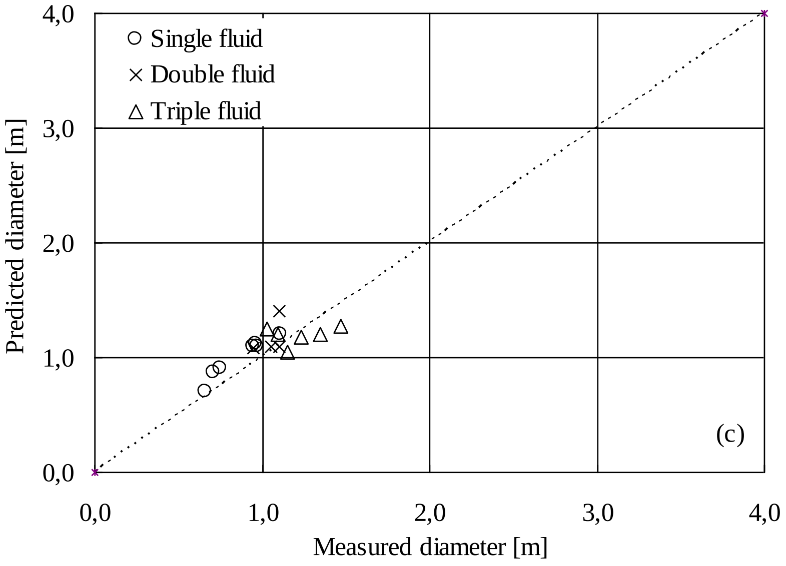
Measurement vs prediction



ANN (Ochmanski et al., 2014)



Flora et al. (2013) (b)

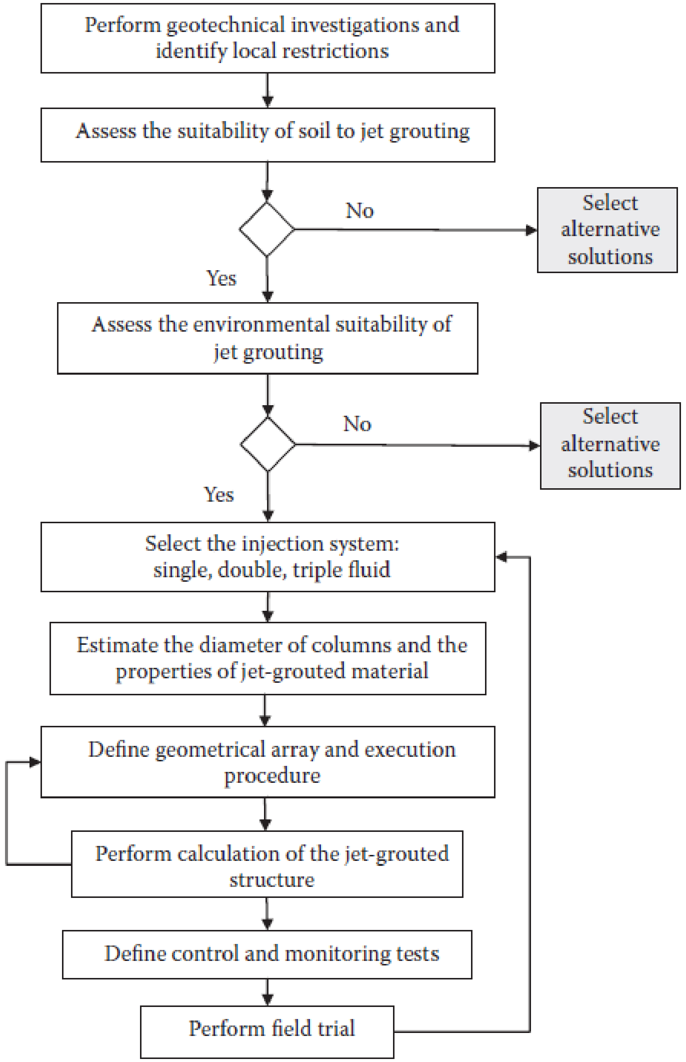


Shen et al. (2013) (c).

Proprietà del terreno trattato (estensione, resistenza, conducibilità idraulica) ←- - - - - - - - - - - -→ Funzione (statica, idraulica, …)

DESIGN OF JET GROUTED STRUCTURES

WARNING
The variability of the geometrical and mechanical proerties affects design



DESIGN OF JET GROUTED STRUCTURES: variability

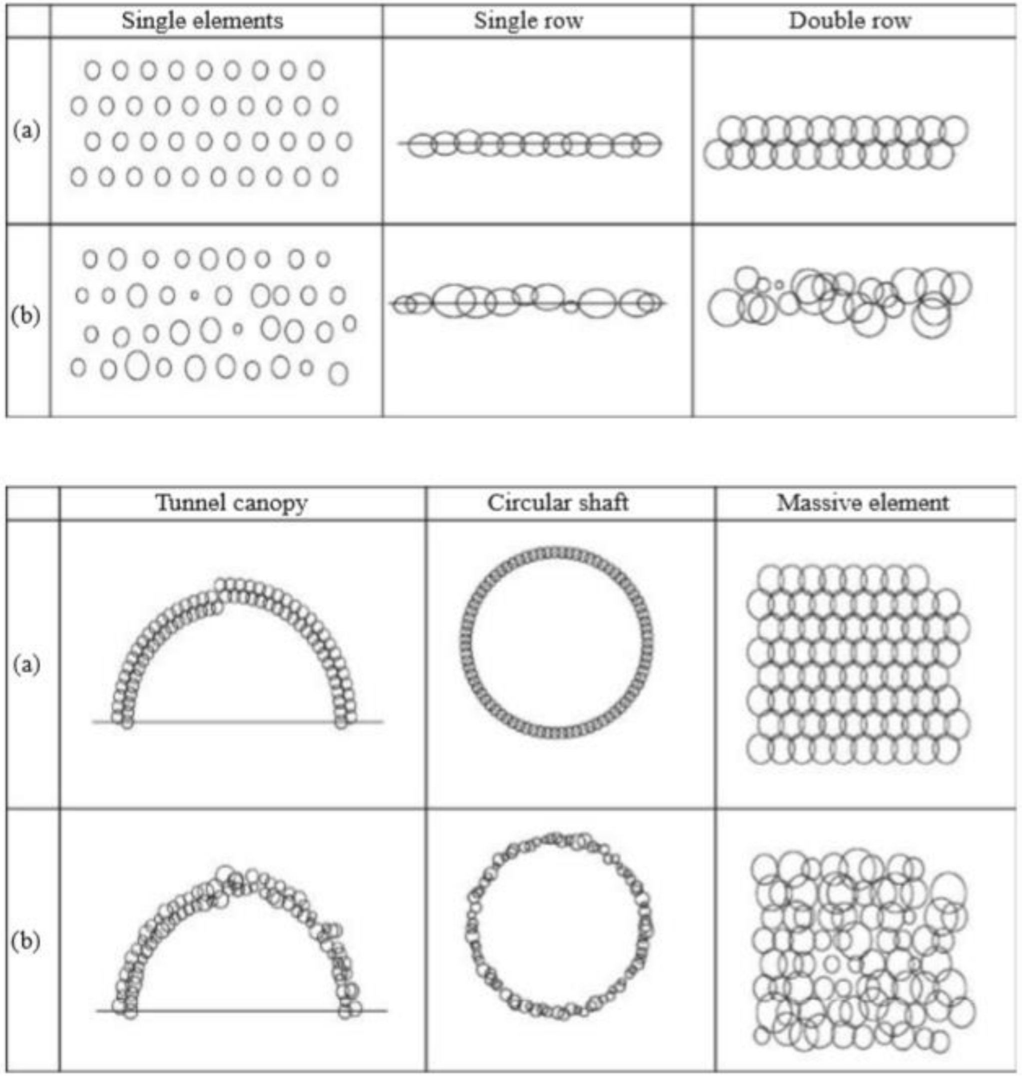


Figure 6.6 Typical layouts of jet-grouted elements: (a) no variability (ideal condition);

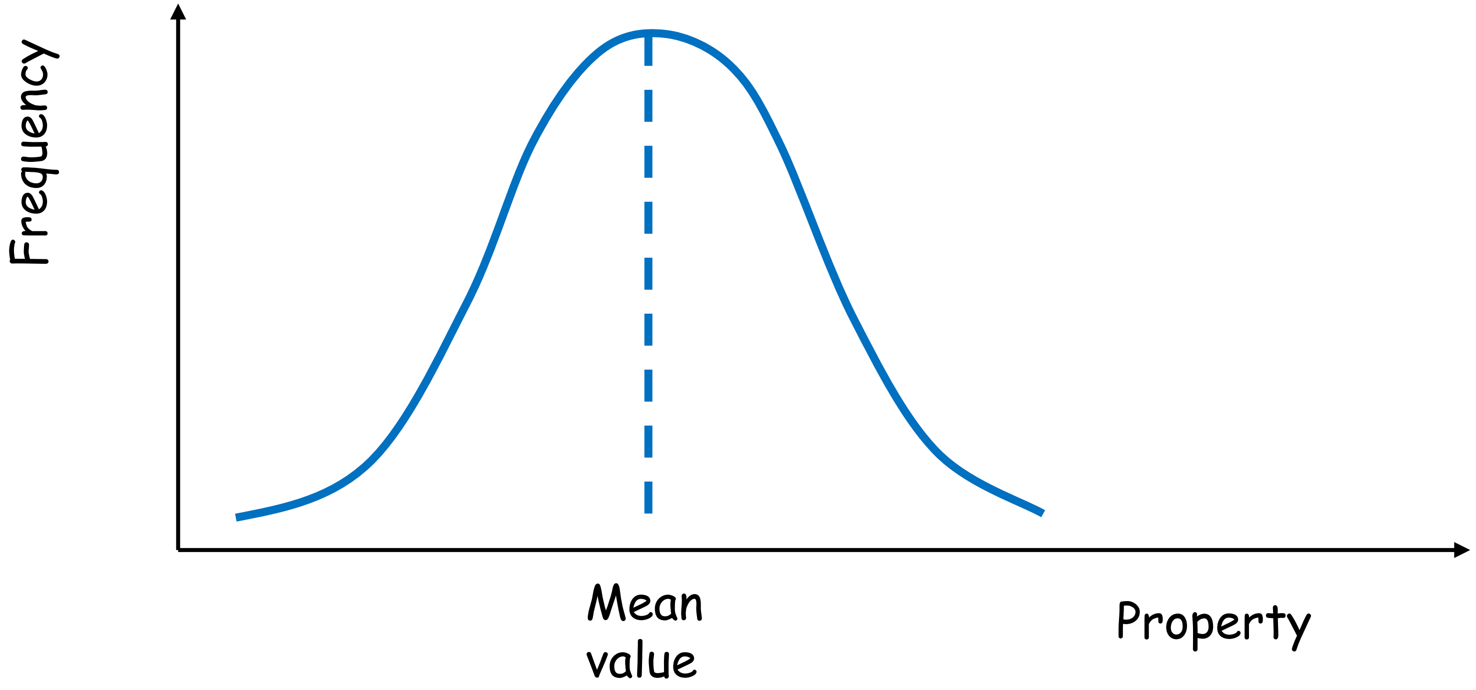
FACTORS

Diameter of columns

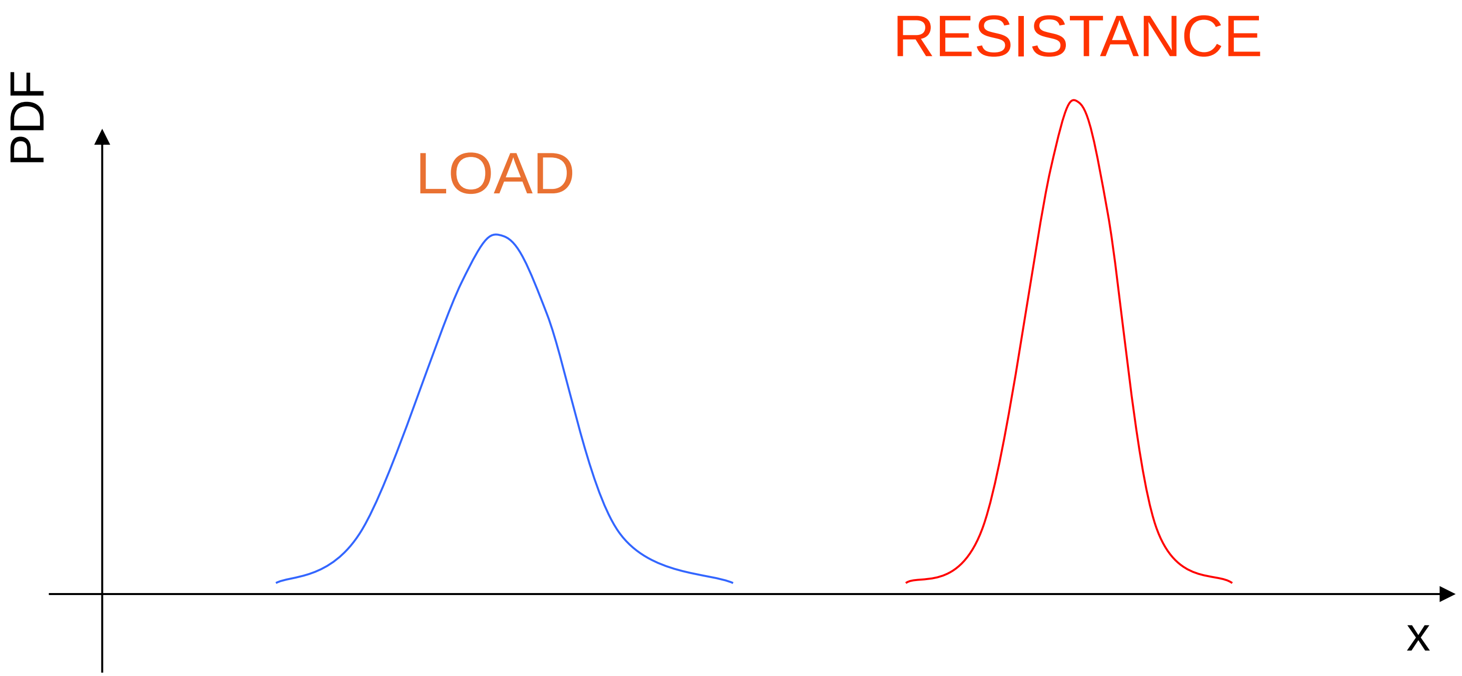
Inclination of columns

Resistance of jet grouted material

PROPERTIES OF COLUMNS



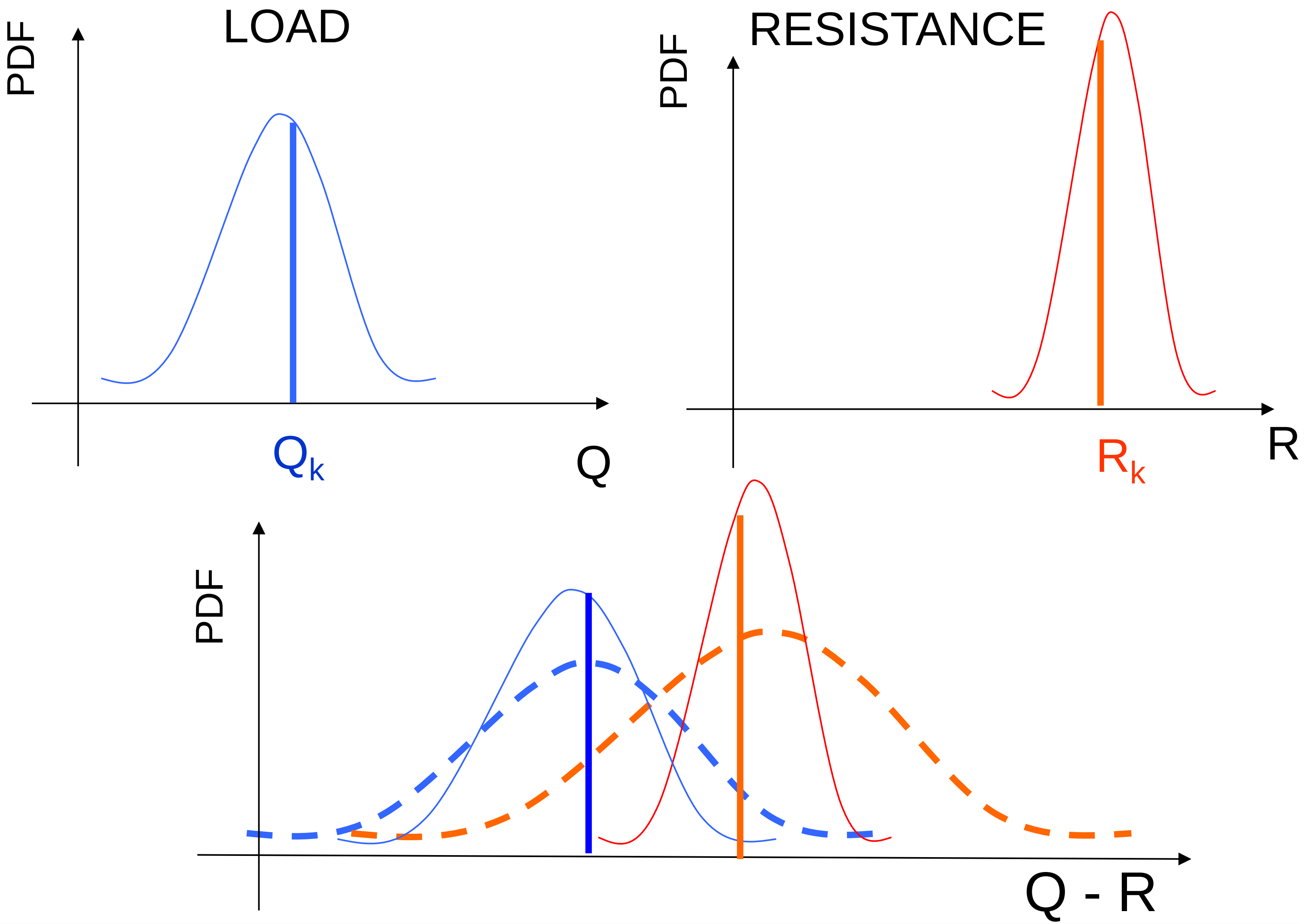
LOAD-RESISTANCE-RELIABILITY PROBLEMS



LOAD-RESISTANCE-RELIABILITY PROBLEMS

Global Safety Factor
(deterministic approach)

$$Q_k = \frac{R_k}{F}$$



DESIGN APPROACHES

Global Safety Factor (deterministic approach)

$$Q_k = \frac{R_k}{F}$$

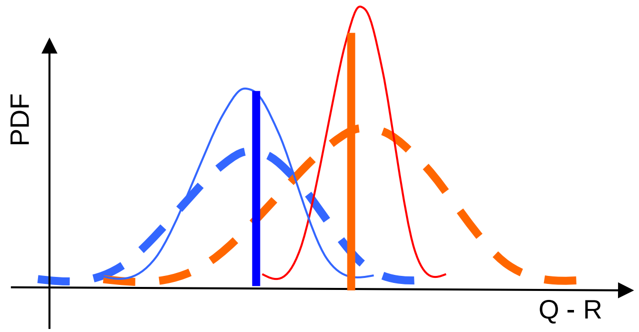


Table 6.3 Safety factors for different jet-grouted structures

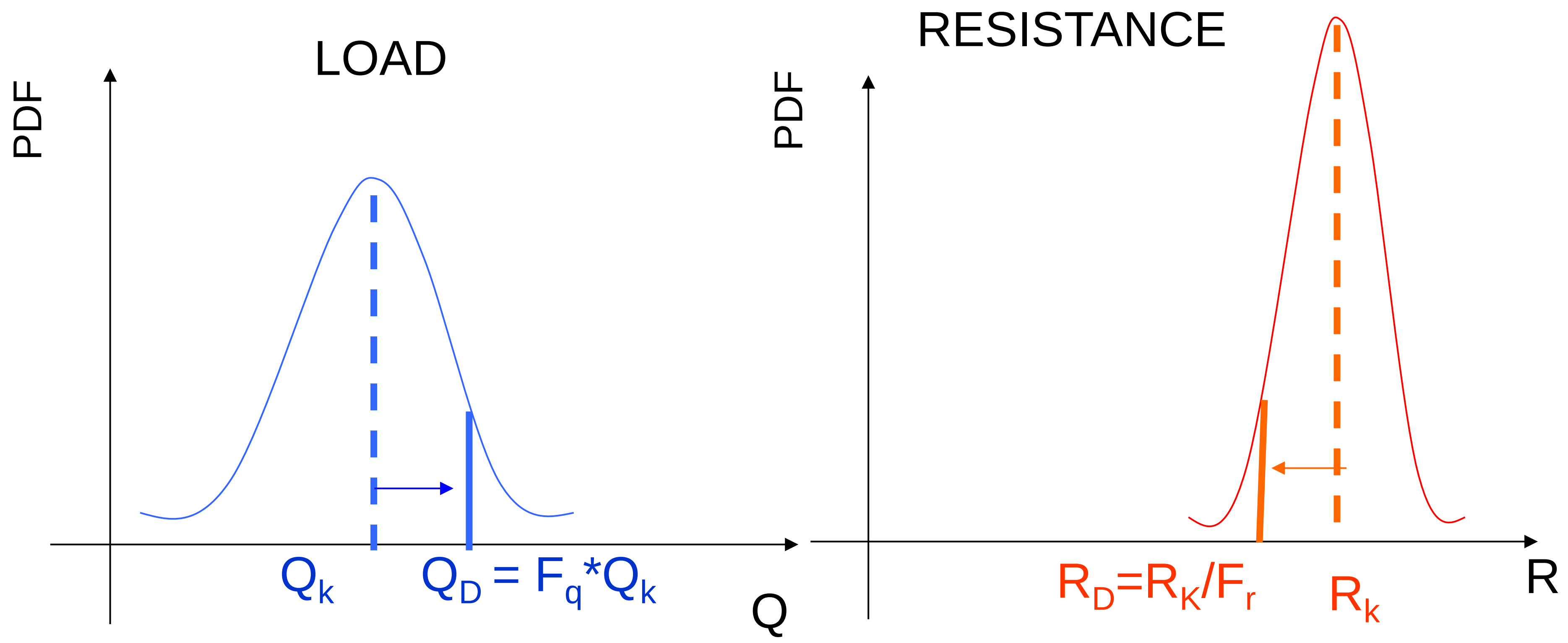
Application	*Objectives of improvement*	*Factor of safety*	*Note*
Improvement at the bottom of open-cut excavation	Heaving protection	1.5	Factor of safety for the permanent structure should be equal to three or more
	Boiling protection	1.5	
	Designing the penetration depth	1.5	
Starting section of shield tunnelling	Protection of cutting face or reaction wall	1.5	
Arrival section of shield tunnelling	Cutting face protection	1.5	
	Tail section protection	1.0	
Soil protection at the gap between earth-retaining walls	Combined with soldier beam	1.0	
	Jet grouting only	2.0	
Caisson-type pile	Reinforcement of sidewall	1.5	
	Cutting face protection	2.0	

Source: Modifed from JJGA, *Jet Grouting Technology: JSG Method, Column Jet Grouting Method.* Technical Information of the Japanese Jet Grouting Association, 13th ed. (English translation), October 2005: 80 p.

Accompanied by a very strict regulation for design and execution

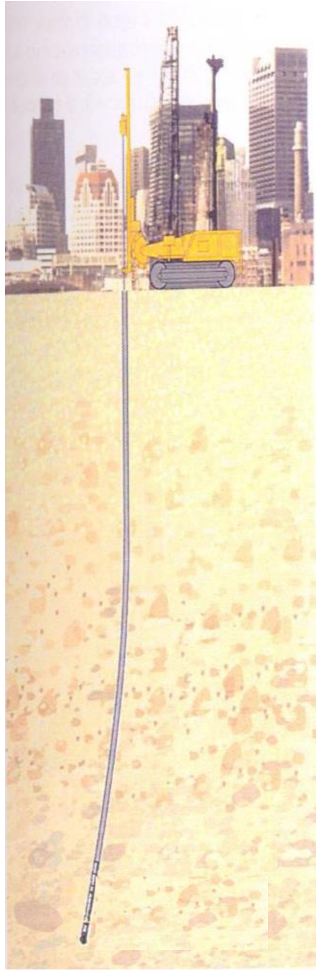
DESIGN APPROACHES

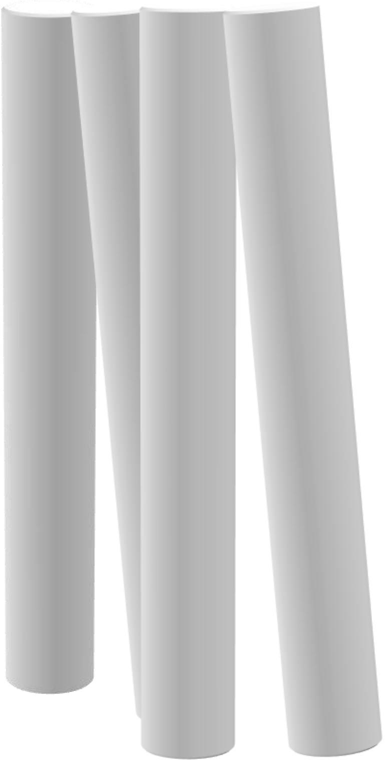
LOAD RESISTANCE FACTORS DESIGN (LRFD)



$$Q_D \leq R_D$$

PROPERTIES OF COLUMNS: alignment





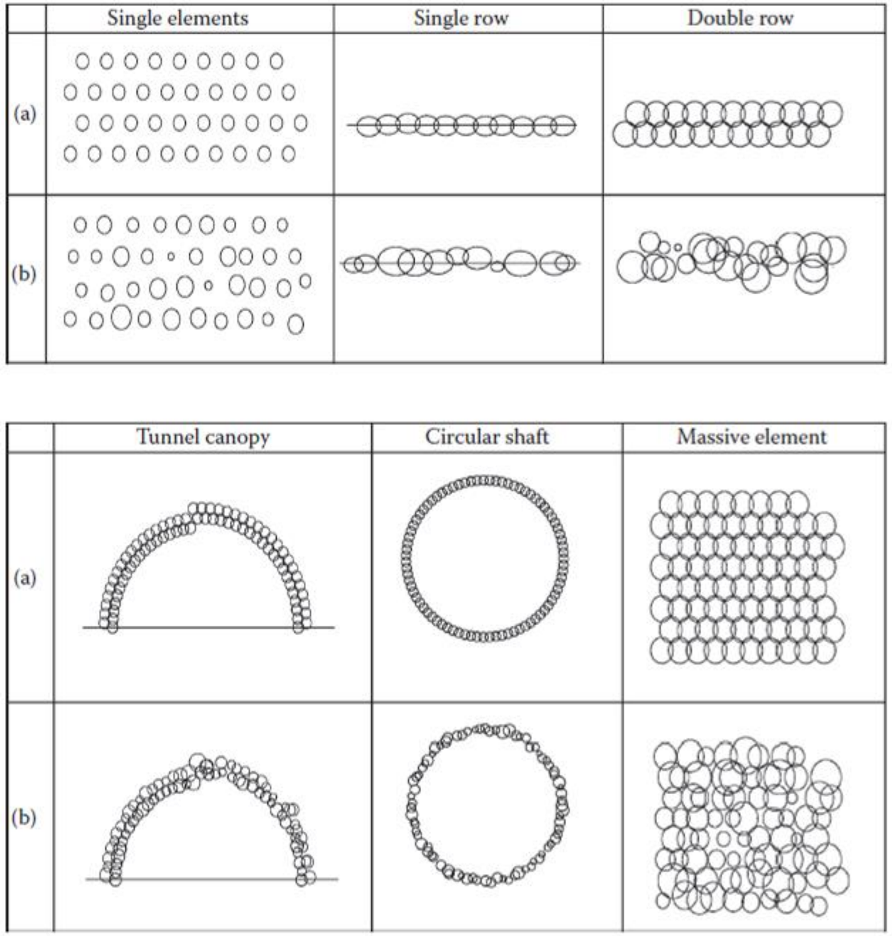
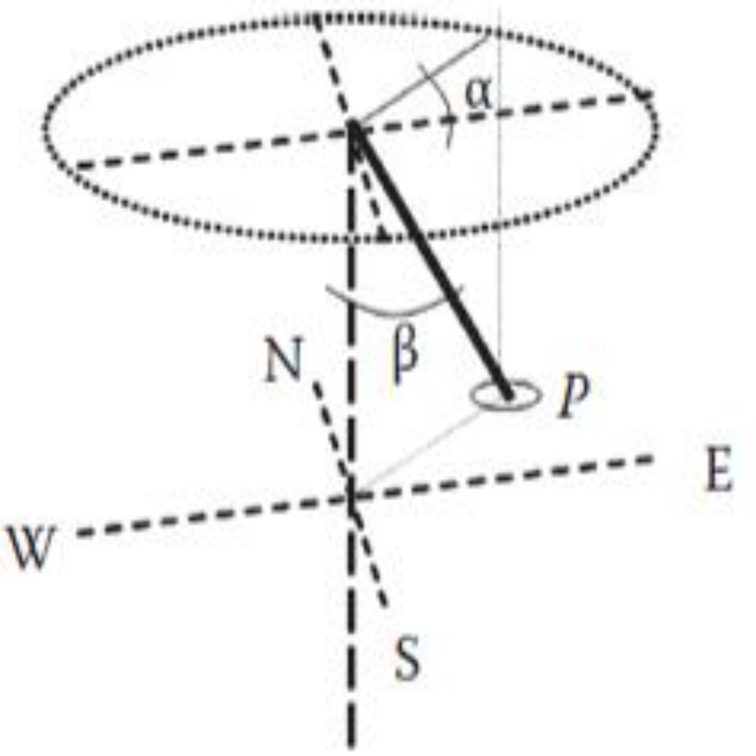
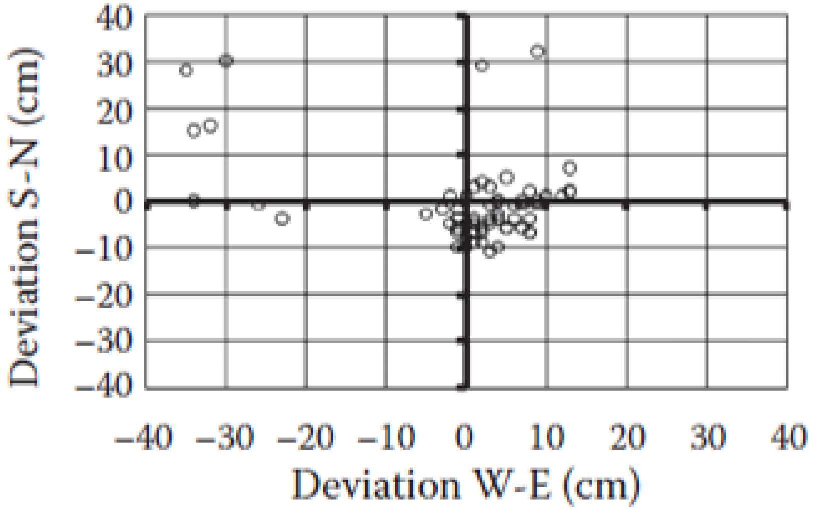


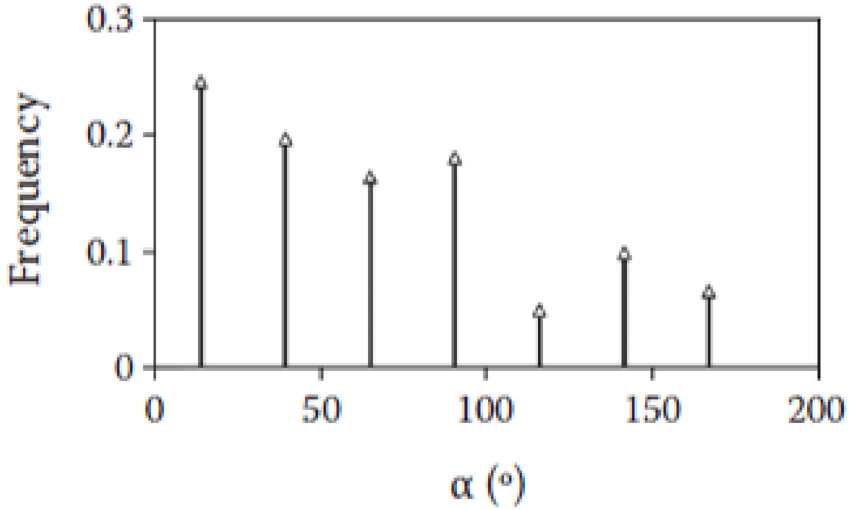
Figure 6.6 (a) Typical layouts of jet-grouted elements: (a) no variability (ideal condition); (b) with variability (SD(β) =1°; CV(*D*) = 0.2).

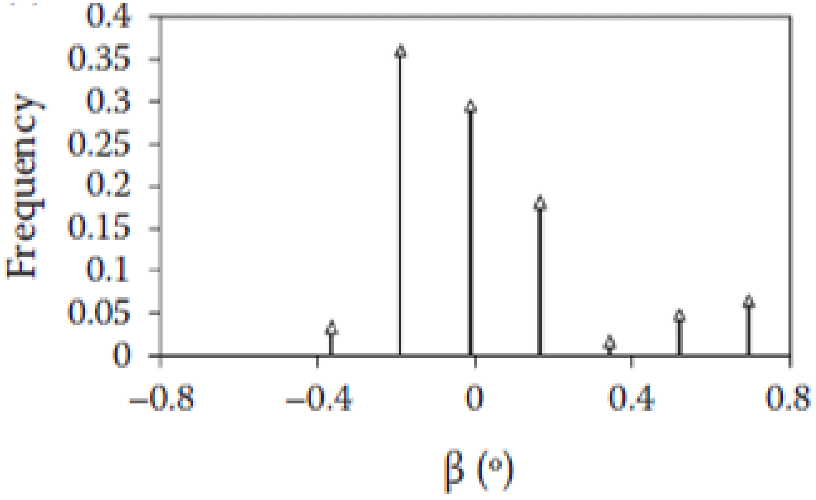
PROPERTIES OF COLUMNS: alignment

ALIGNMENT   Sub-vertical columns



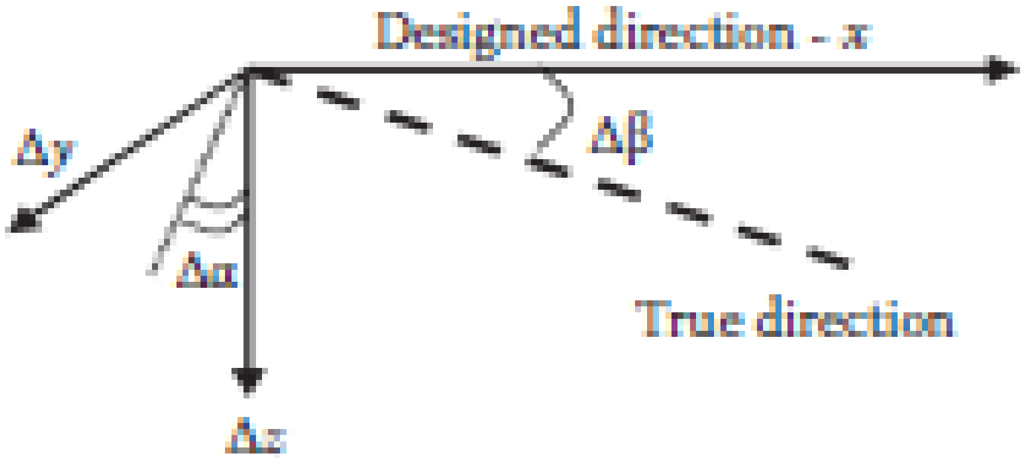


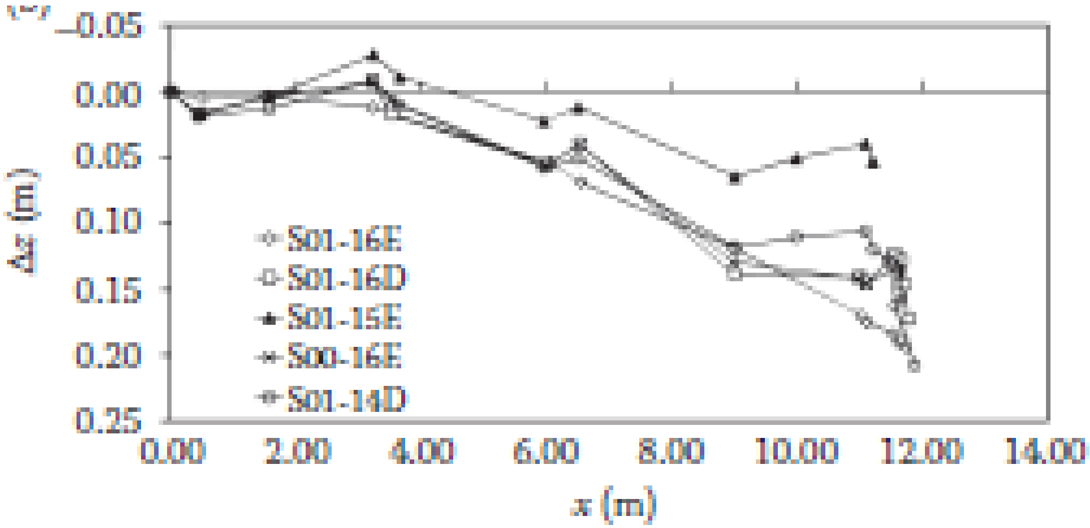


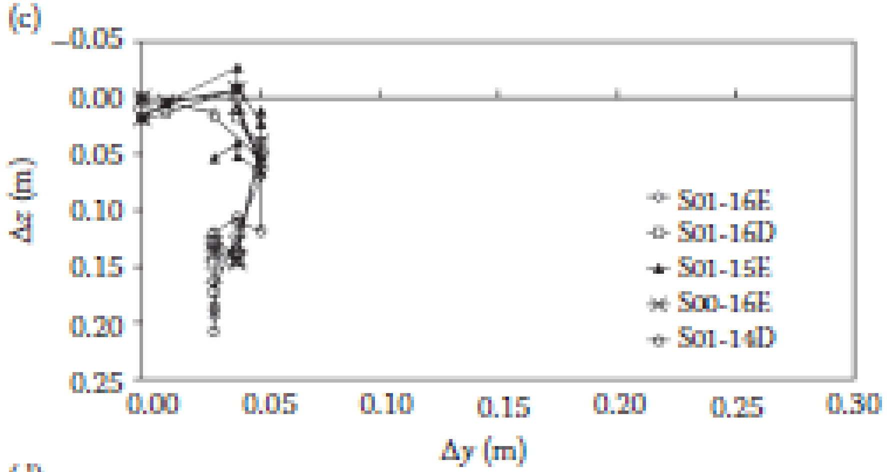


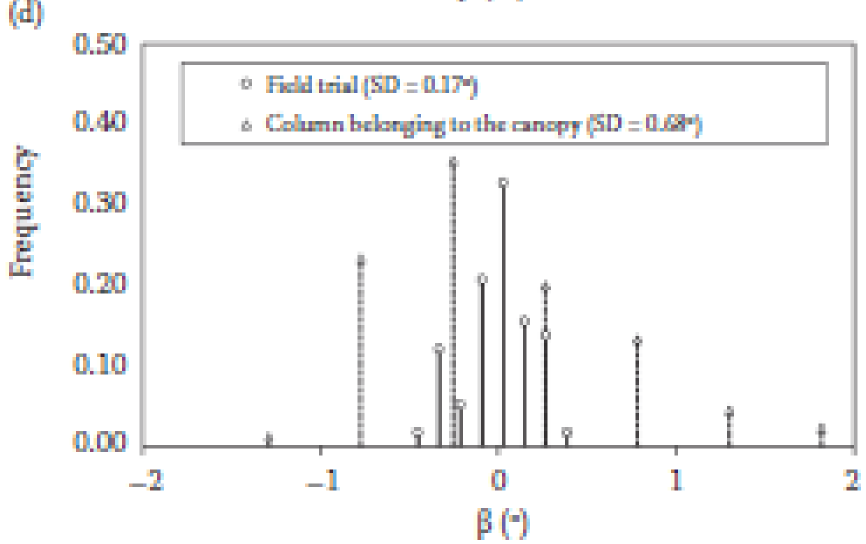
PROPERTIES OF COLUMNS: alignment

Sub-horizontal columns





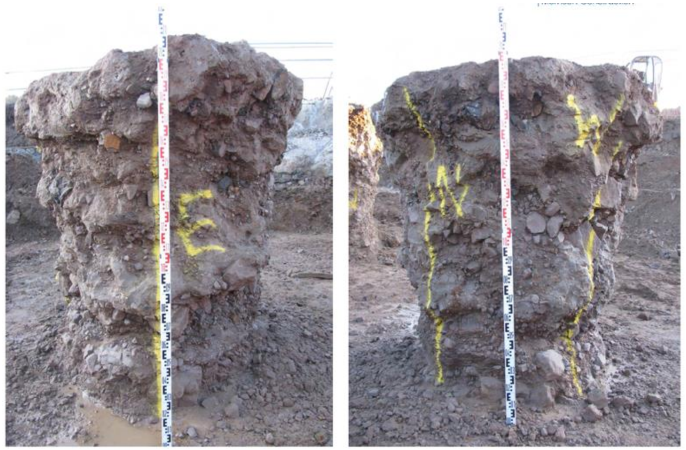


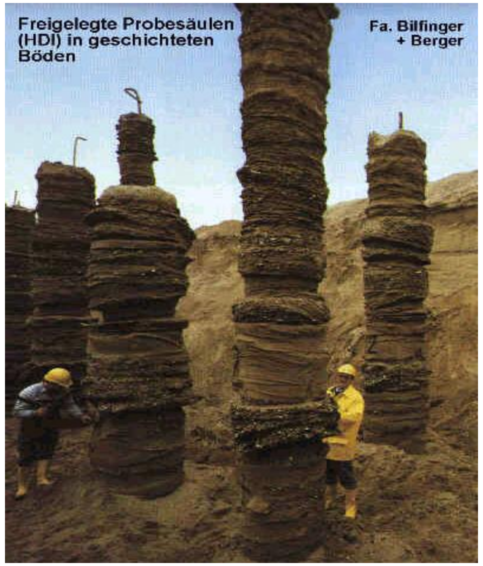


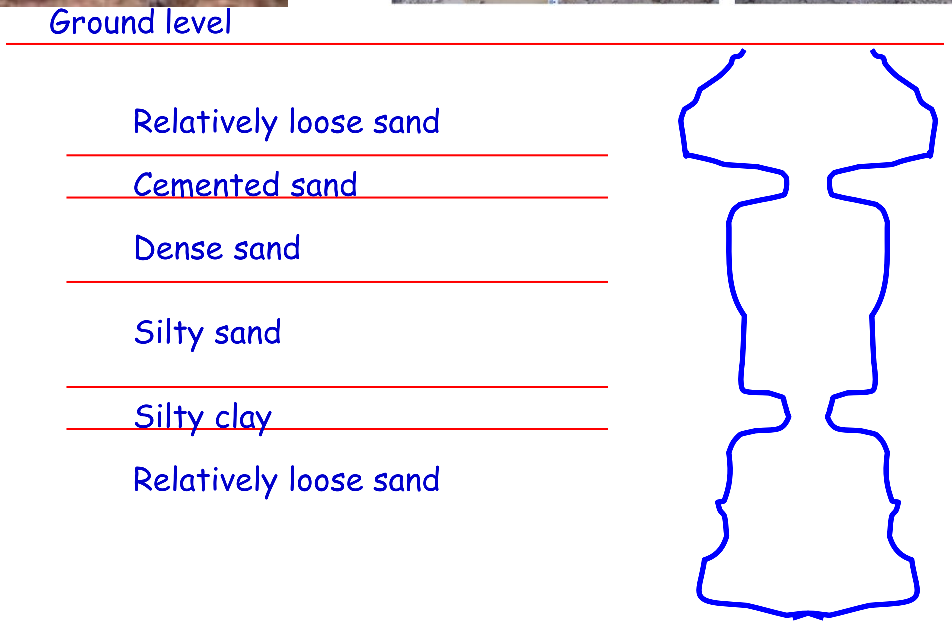
β = 0.2 - 0.6 ° (tanβ = 0.3 - 1 %)

Depending on the quality of execution

PROPERTIES OF COLUMNS: diameter

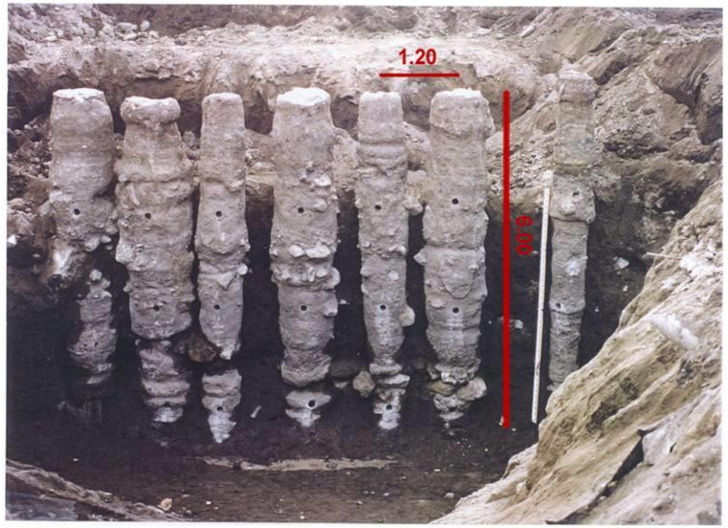


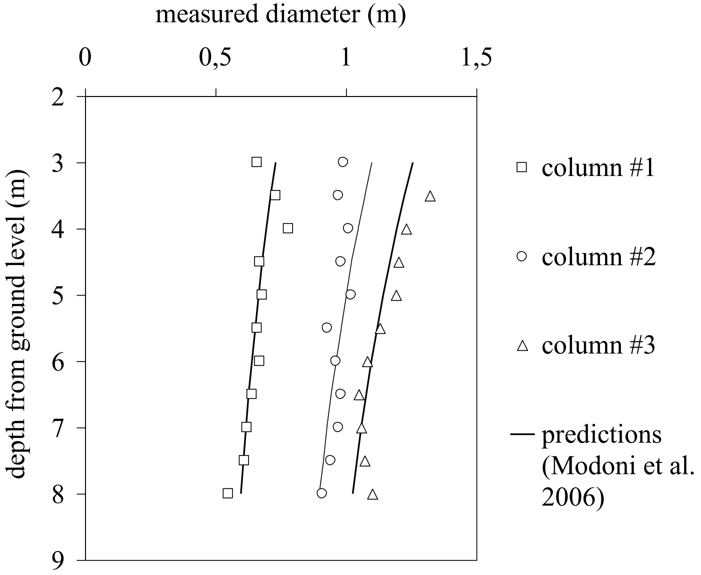




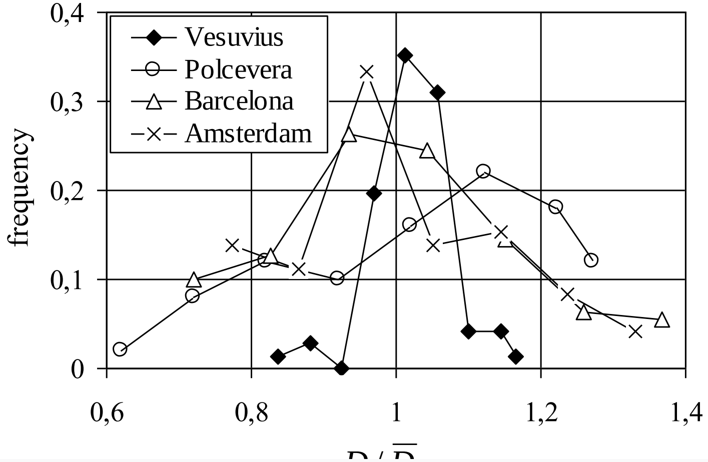
PROPERTIES OF COLUMNS: diameter

Systematic

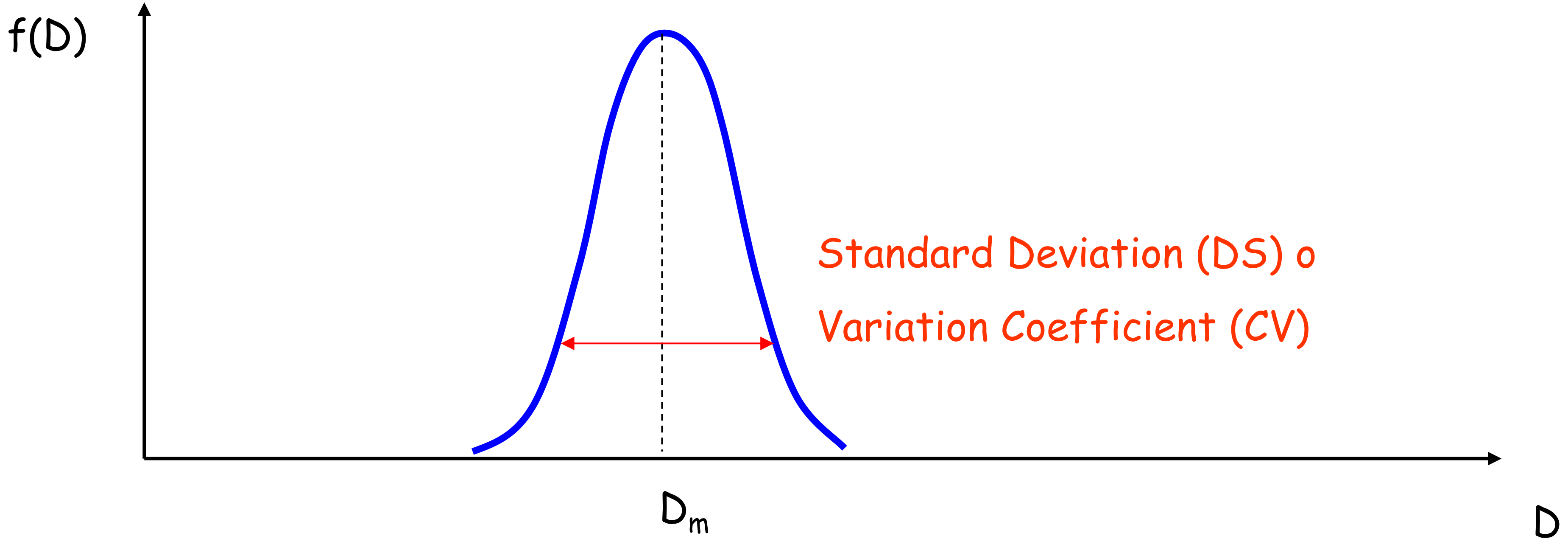




Random



PROPERTIES OF COLUMNS: diameter



Dati sperimentali

Table 4.8 Statistical analysis of column diameters

Case study	*Soil*	*Number of data*	$\bar{D}_{min} - \bar{D}_{max}(m)$	$CV(D/D_m)$	*Kolmogorov–Smirnov test*
Vesuvius	Pyroclastic silty sand	71	0.55–1.35	0.06	0.09 (0.13)
Polcevera	Alluvial sandy gravel	50	1.06–1.20	0.19	0.12 (0.15)
Barcelona	Alluvial sandy clay	97	0.35–0.64	0.18	0.06 (0.11)
Amsterdam	Stratified sandy clay and clay	72	0.72–1.37	0.16	0.10 (0.13)

Source: Adapted from Modoni, G. and J. Bzówka, *ASCE Journal of Geotechnical and Geoenvironmental Engineering* I

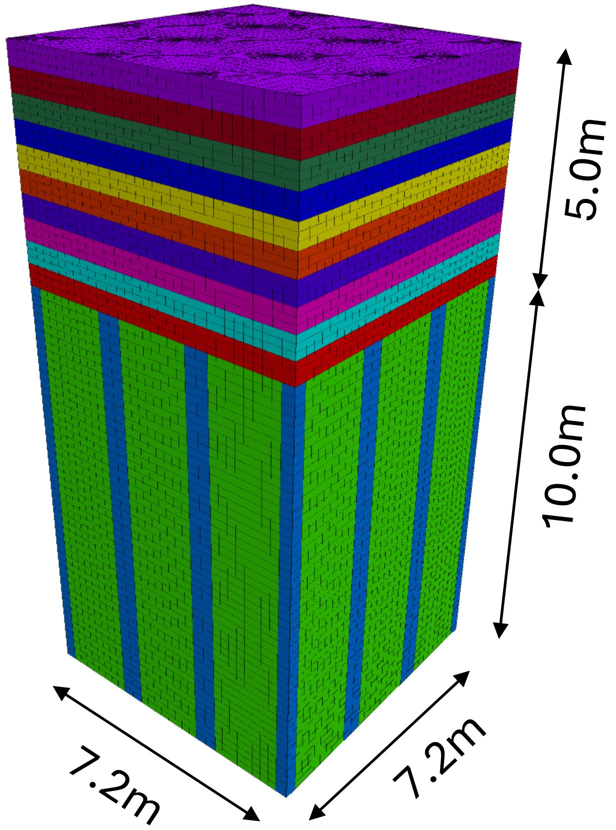
Valori suggeriti

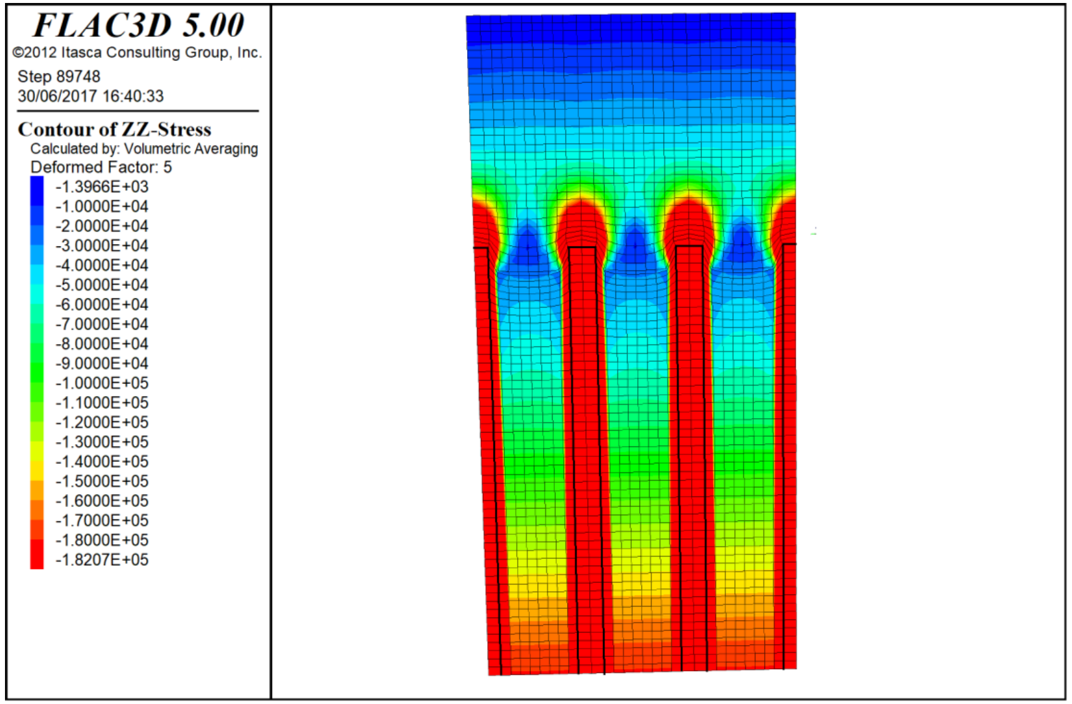
Table 4.9 Coefficients of variation CV(D) of the diameter of columns for soils without significant discontinuities

	Soil heterogeneity		
	Low	*Medium*	*High*
CV(D)	0.02–0.05	0.05–0.10	0.05–0.20

PROPERTIES OF COLUMNS: strength

Foundation



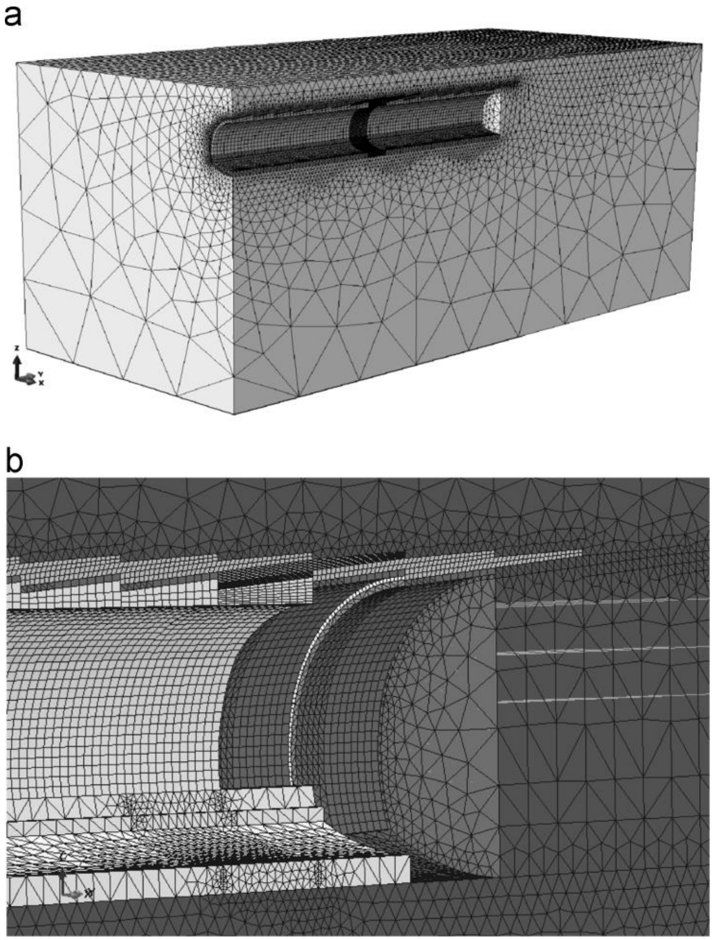


Maximum deviator stress
1.8 MPa

Croce P., Spacagna R.L., Salvatore E., 2017, Interventi di adeguamento dei rilevati stradali e

PROPERTIES OF COLUMNS: strength

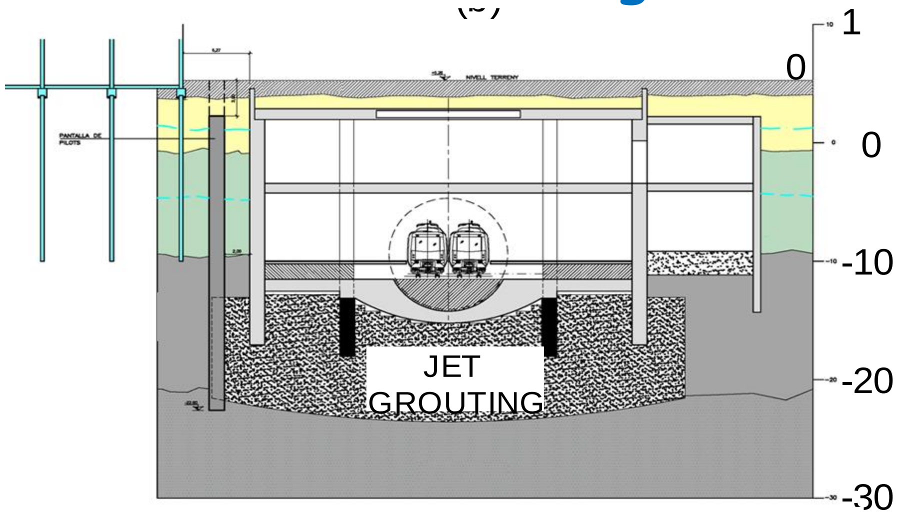
Tunnelling

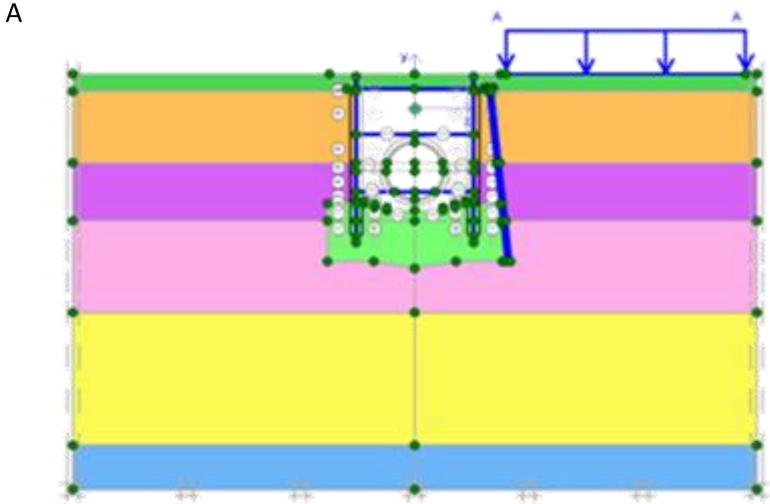


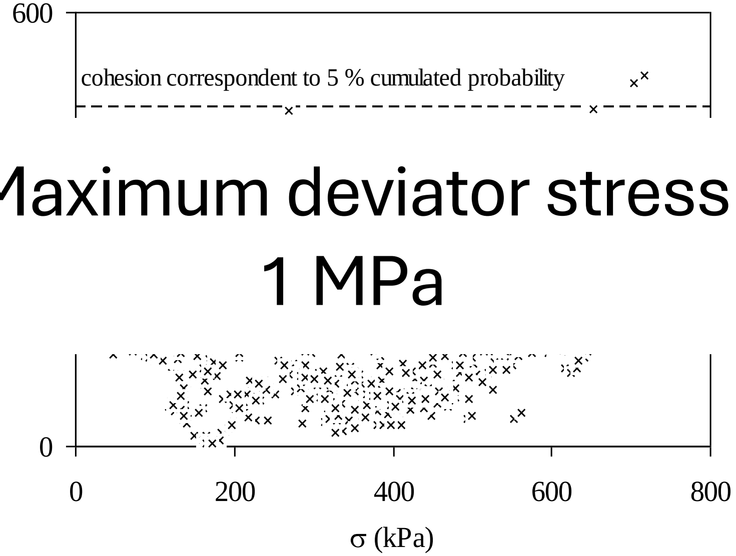
Maximum deviator stress
2 MPa

Ochmański M., Modoni G., Bzòwka J., (2015), Numerical analysis of tunnelling with jet-grouted canopy, Soils and Foundations, Volume 55, Issue 5, October 2015, Pp. 929–942.

PROPERTIES OF COLUMNS: strength





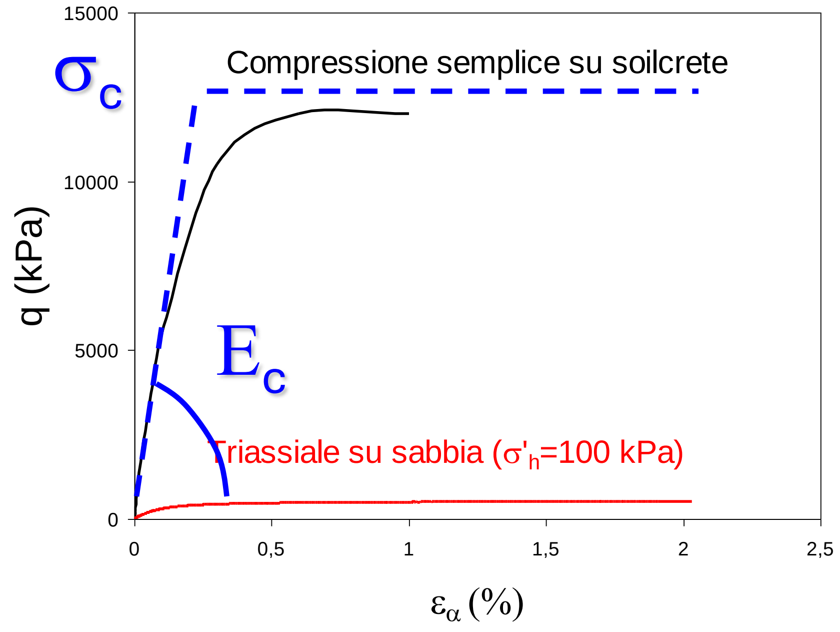


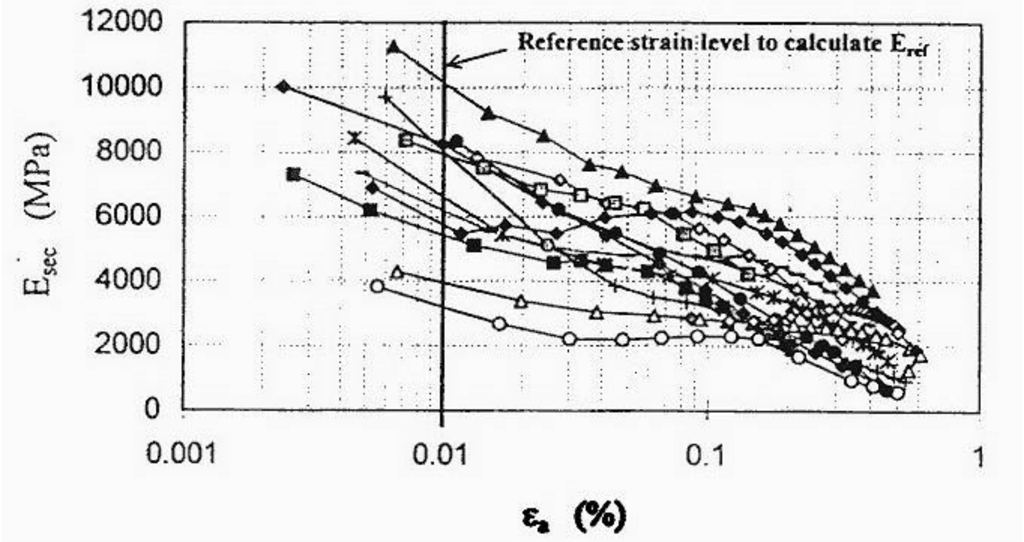
Maximum deviator stress

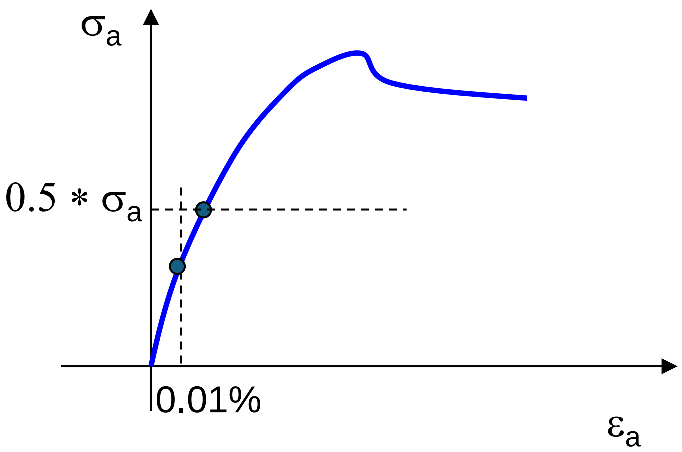
1 MPa

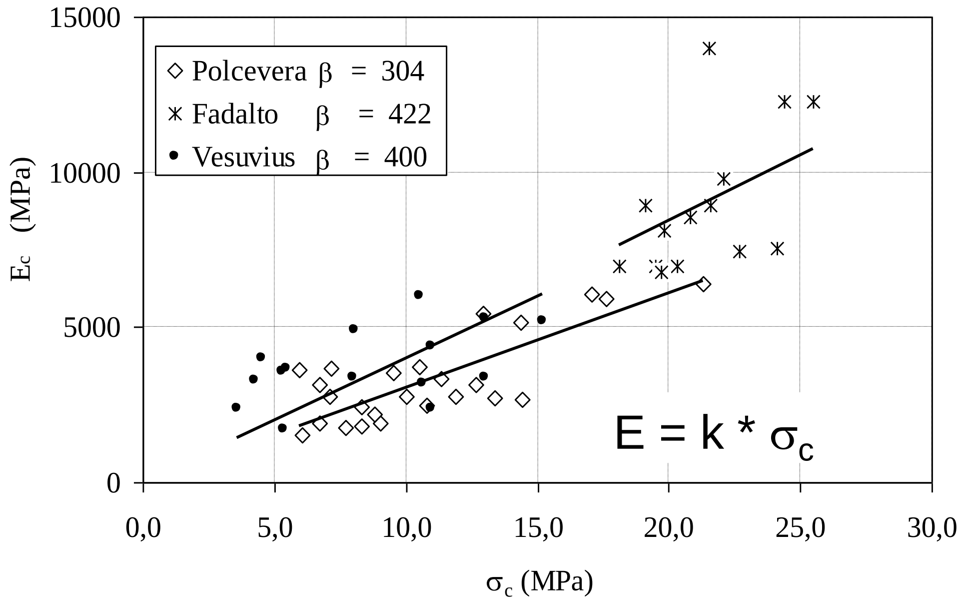
Eramo, N., Modoni, G., Arroyo, M. (2012), Design control and monitoring of a jet grouted excavation bottom plug, VII Int. Symp. on Geotech. Aspects of Undergr. Constr. in Soft Ground, TC28 IS Rome, pp.611-618.

PROPERTIES OF COLUMNS: strength



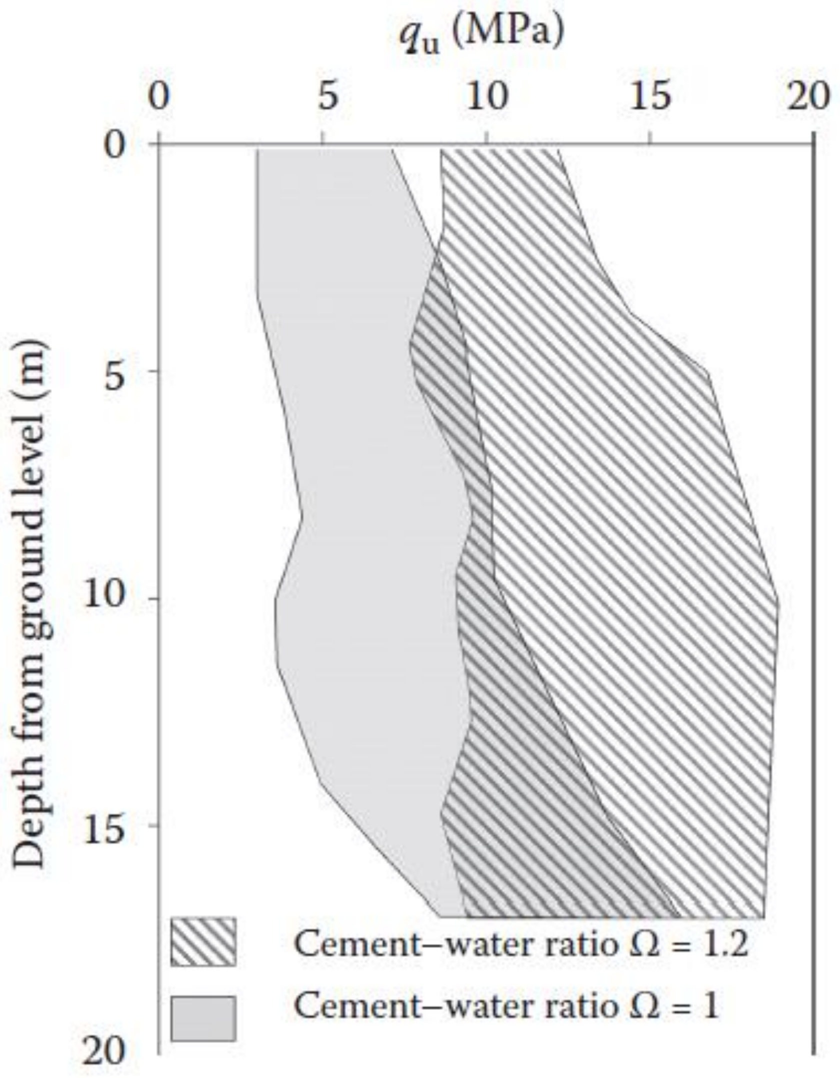






PROPERTIES OF COLUMNS: strength

Single fluid system



PROPERTIES OF COLUMNS: strength

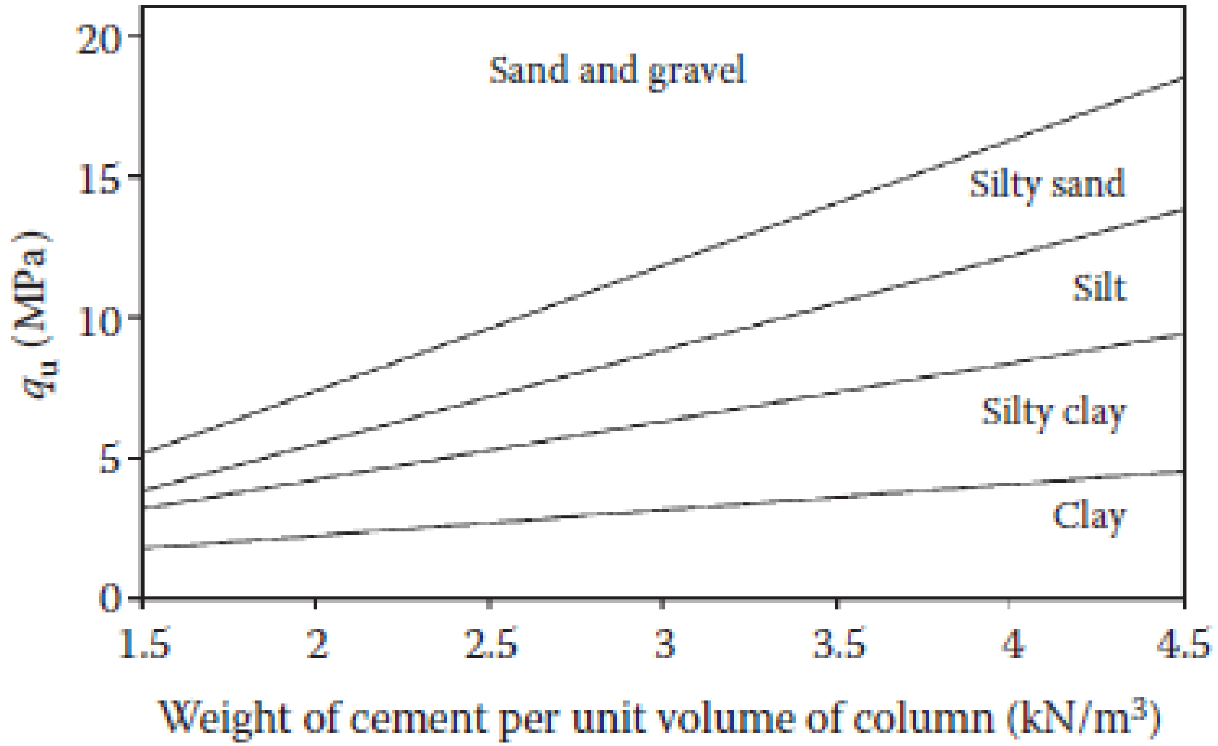


Figure 4.18 Indicative ranges of uniaxial compressive strength for different soil types and variable injected amounts of cement. (Modified from Fiorotto, R., *Improvement of the Mechanical Characteristics of Soils by Jet Grouting*, personal communication, 2000.)

PROPERTIES OF COLUMNS: strength

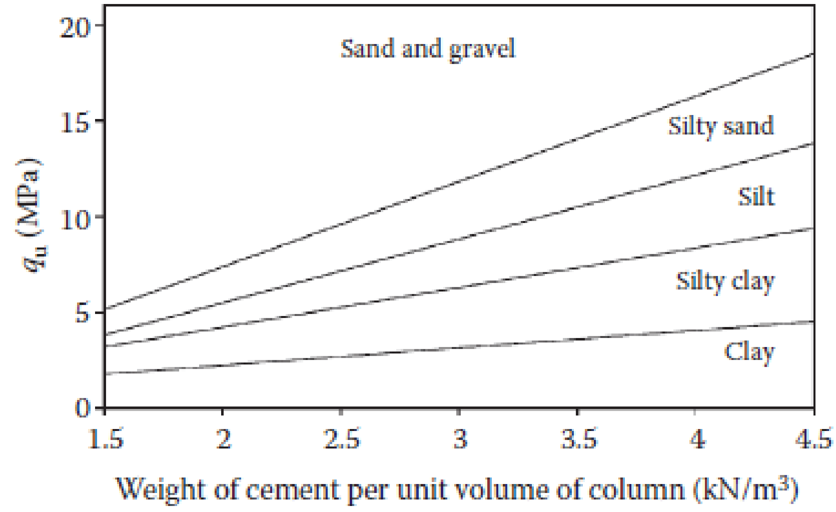
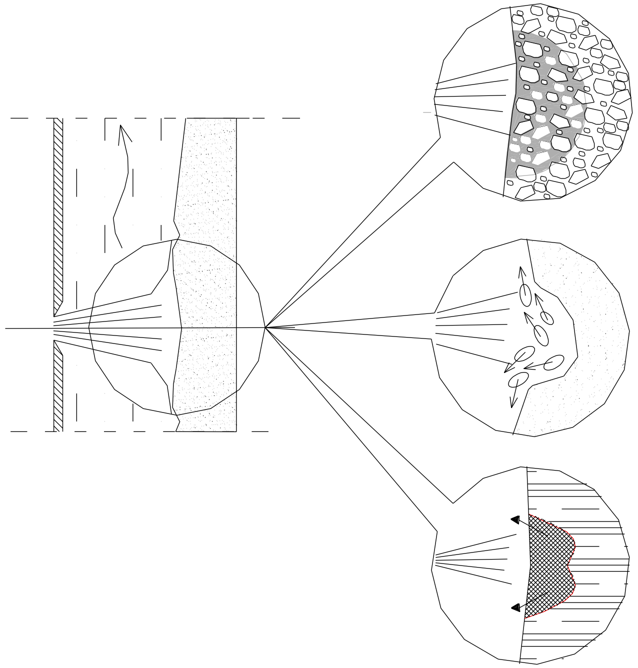
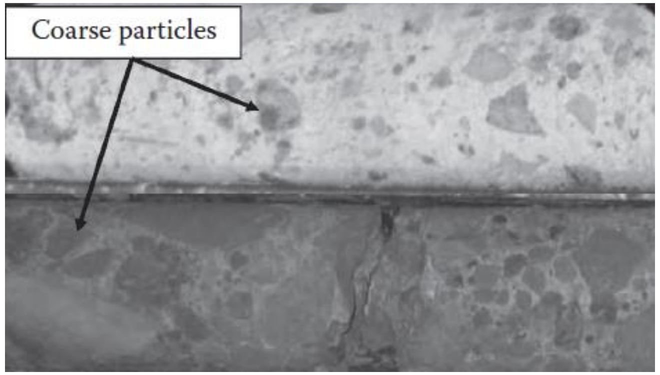
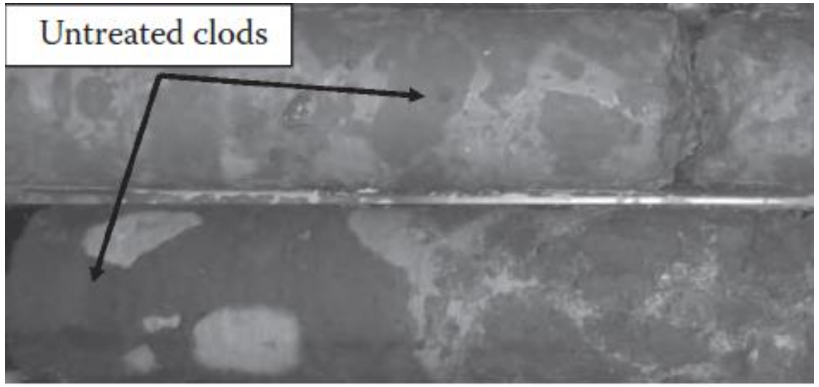


Figure 4.18 Indicative ranges of uniaxial compressive strength for different soil types and variable injected amounts of cement. (Modified from Fiorotto, R., *Improvement of the Mechanical Characteristics of Soils by Jet Grouting*, personal communication, 2000.)

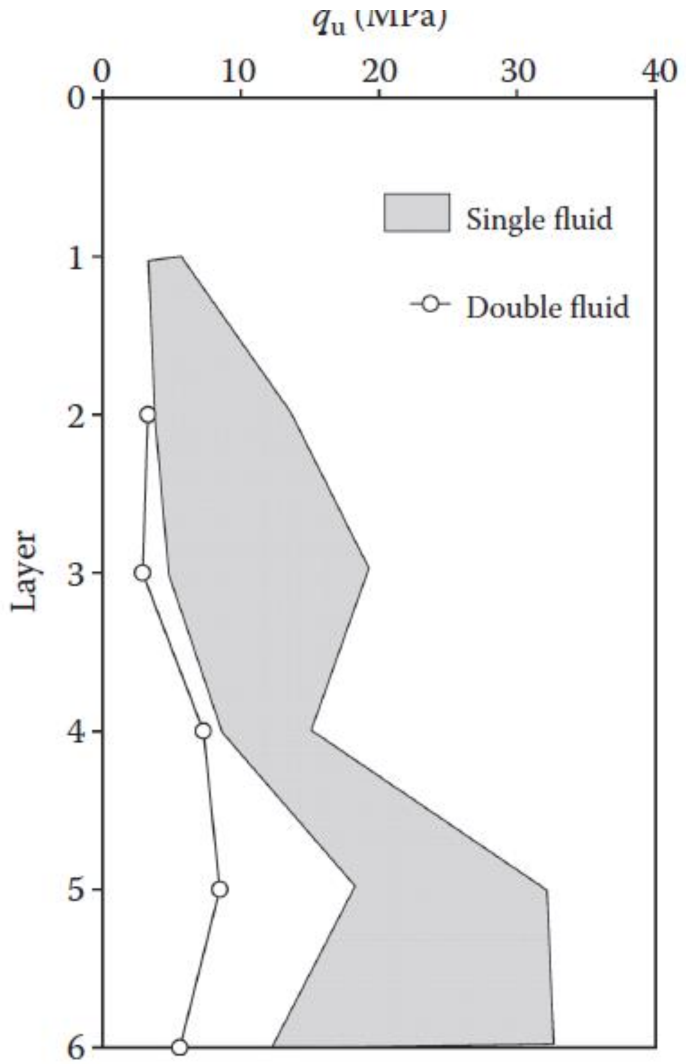






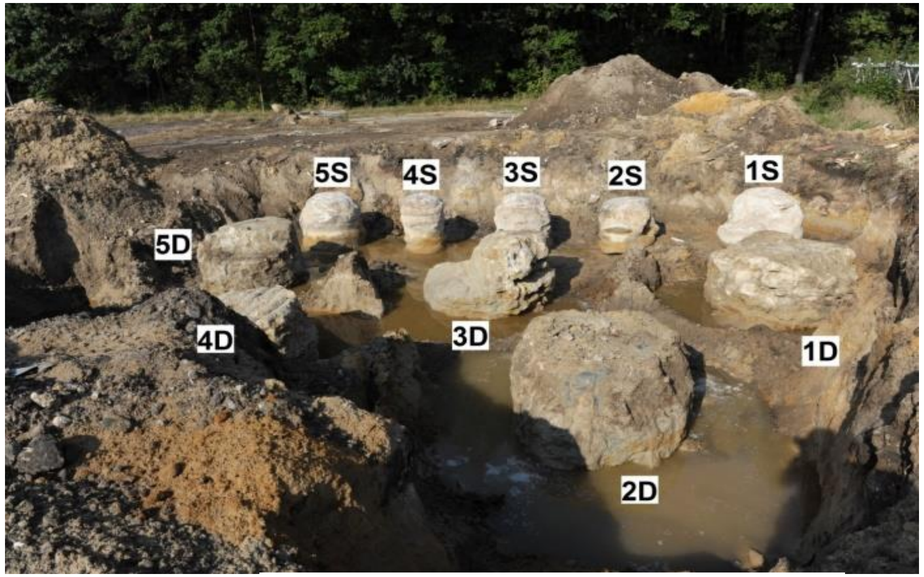
PROPERTIES OF COLUMNS: strength

Single vs double fluid

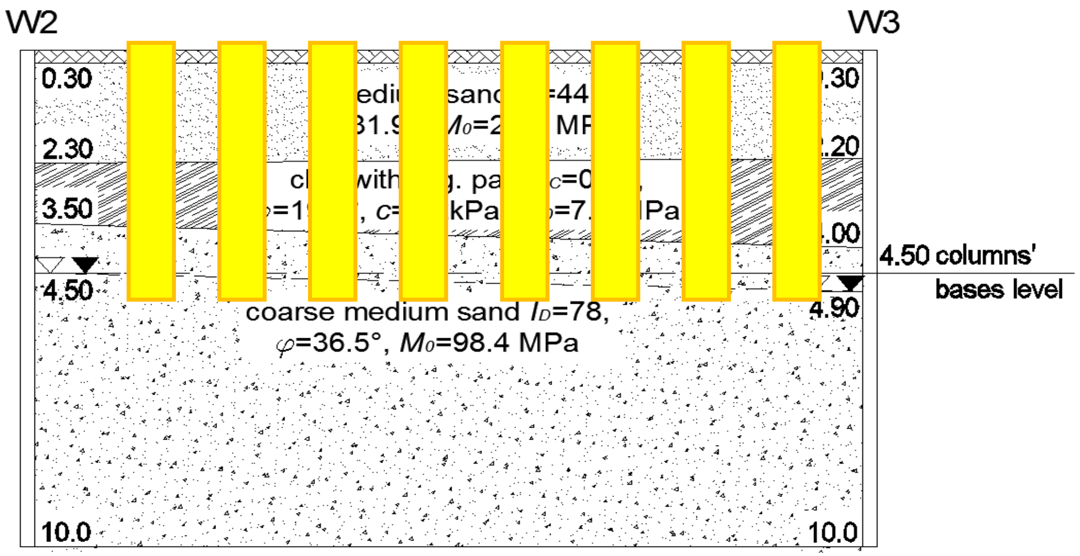


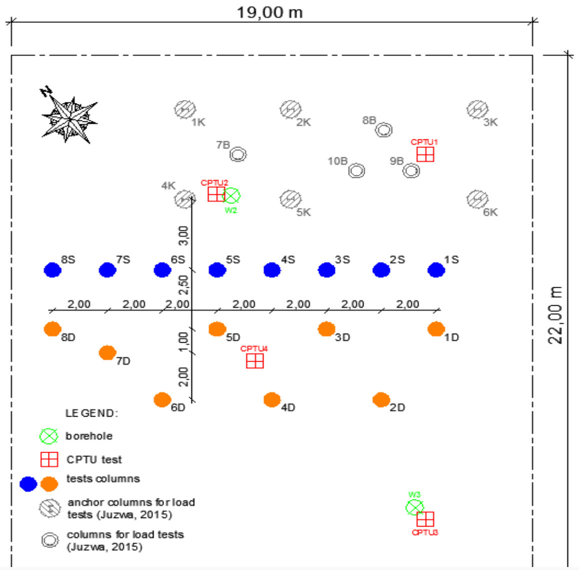
PROPERTIES OF COLUMNS: strength

Single vs double fluid



Sandy soils
(Bojszowy Nowy - Poland)
Wanik (2017)





PROPERTIES OF COLUMNS: strength

Single vs double fluid

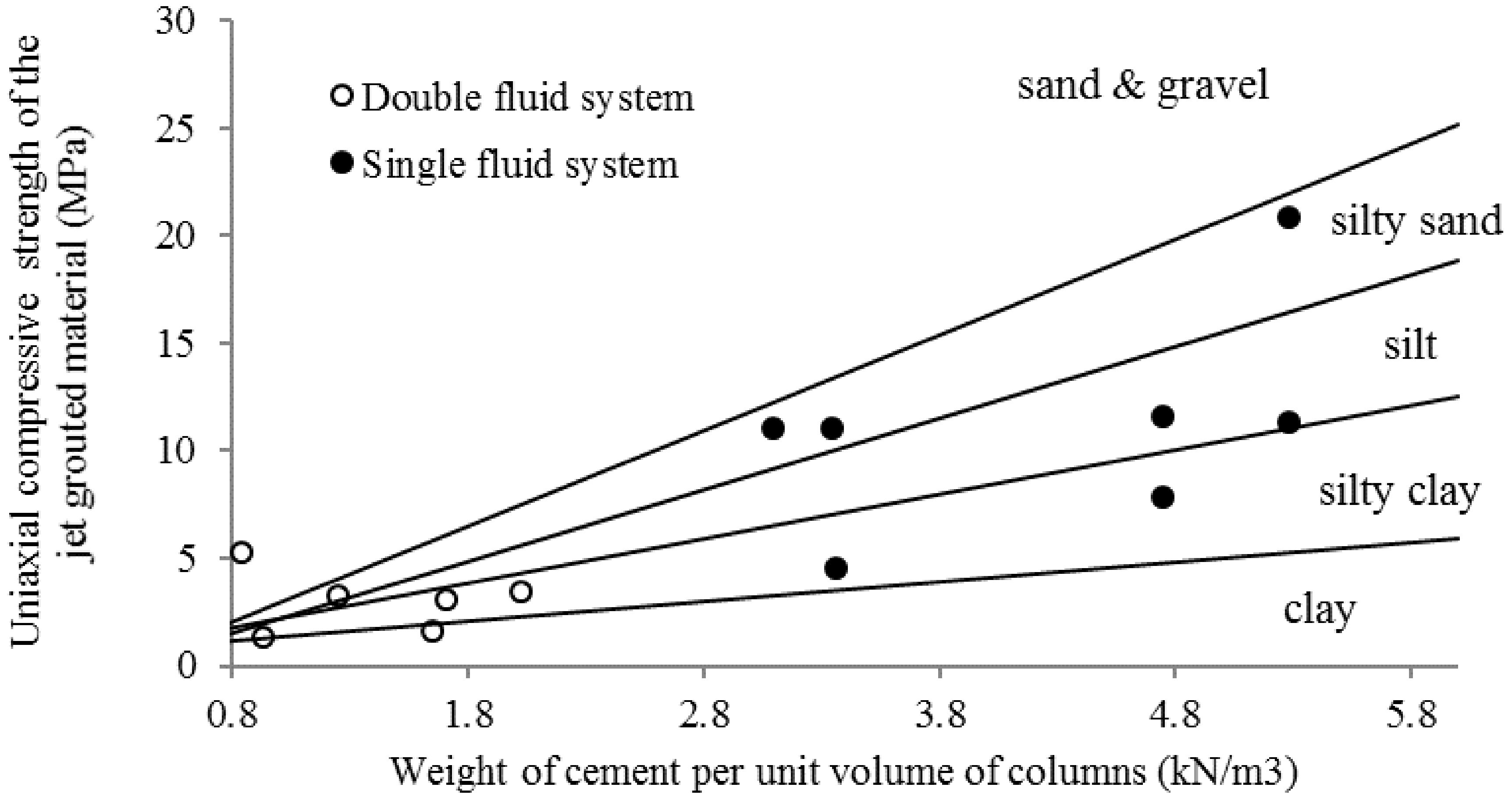
Column #	Nr and diameter [mm] of nozzles	Grout pressure [bar]	Grout flow rate [l/min]	Lifting speed [m/s]	Average diameter [m]	Cemen per uni volum [kg/m³
1S	2x4.0	360	316	0.0083	1.13	474
2S	2x2.8	360	155	0.0083	0.94	337
3S	2x4.0	180	223	0.0083	0.90	528
4S	2x2.8	250	129	0.0083	0.78	407
5S	2x4.0	360	316	0.0083	1.13	475
6S	2x2.8	360	155	0.0083	0.98	310
7S	2x4.0	180	223	0.0083	0.90	528
8S	2x2.8	250	129	0.0083	0.86	335
1D	2x4.0	360	316	0.0083	1.75	198
2D	2x4.0	180	223	0.0083	1.61	165
3D	2x4.0	360	316	0.0083	1.73	203
4D	2x4.0	180	223	0.0083	1.58	171
5D	2x2.8	360	155	0.0083	1.54	125
6D	2x2.8	260	131	0.0083	-	-
7D	2x2.8	360	155	0.0083	1.88	84
8D	2x2.8	250	129	0.0083	1.63	93



Wanik (2017)

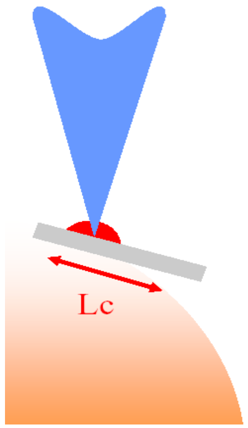
PROPERTIES OF COLUMNS: strength

Single vs double fluid

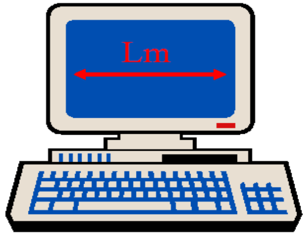


PROPERTIES OF COLUMNS: strength

Scanning Electron Microscope

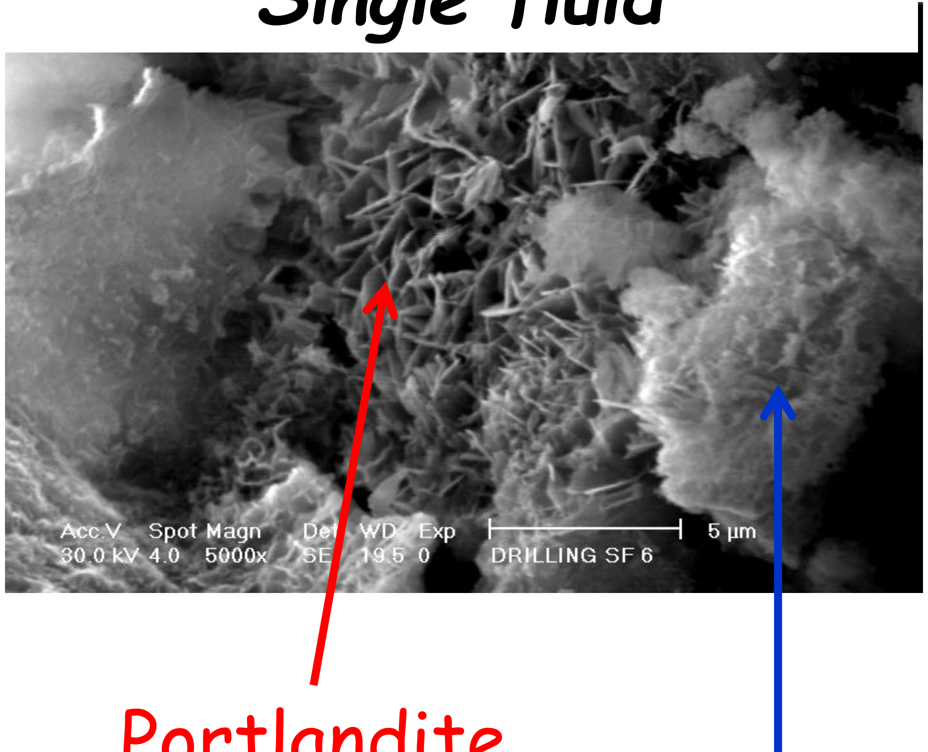


$$M = \frac{Lm}{Lc}$$



Single vs double fluid

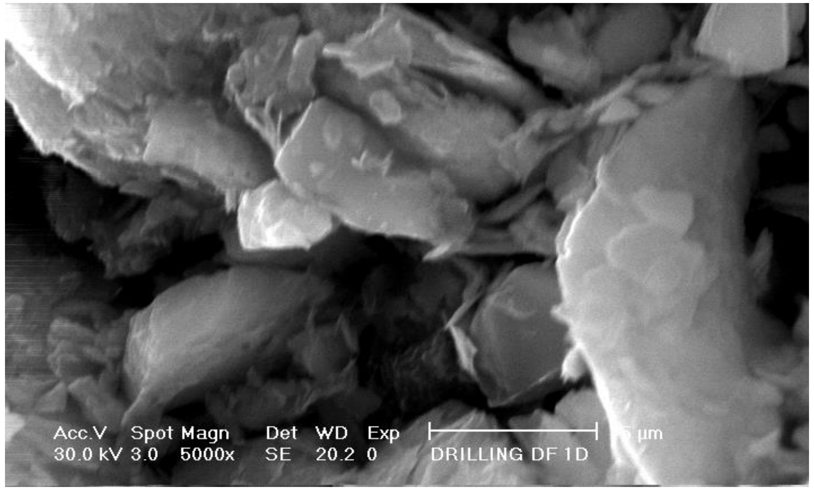
Single fluid



Portlandite
$Ca(OH)_2$

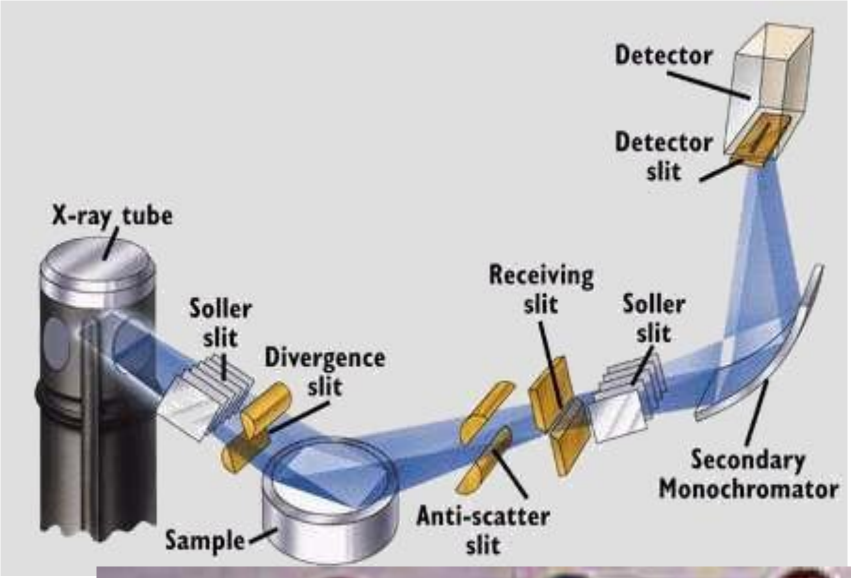
Calcium Silicate Hydrate (CSH)

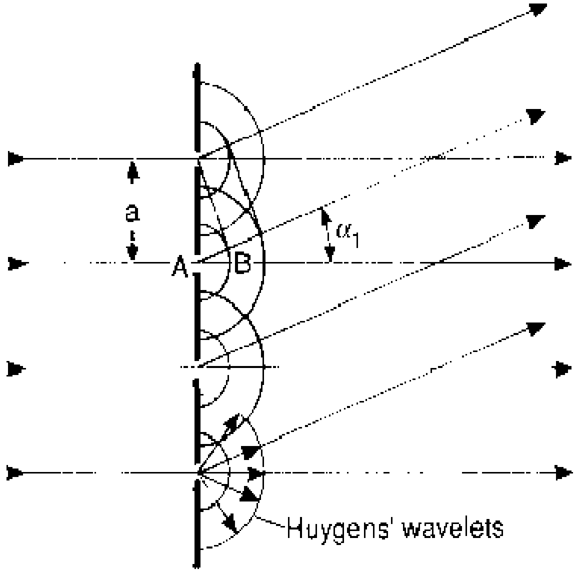
Double fluid



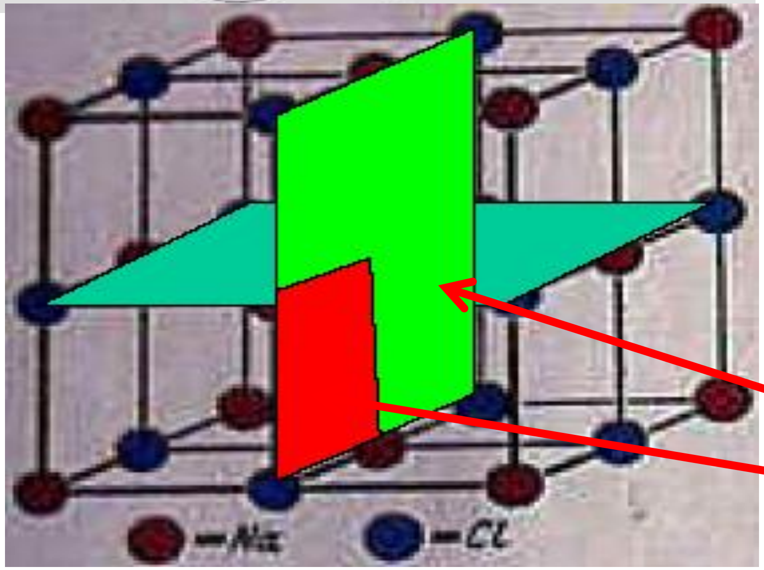
PROPERTIES OF COLUMNS: strength

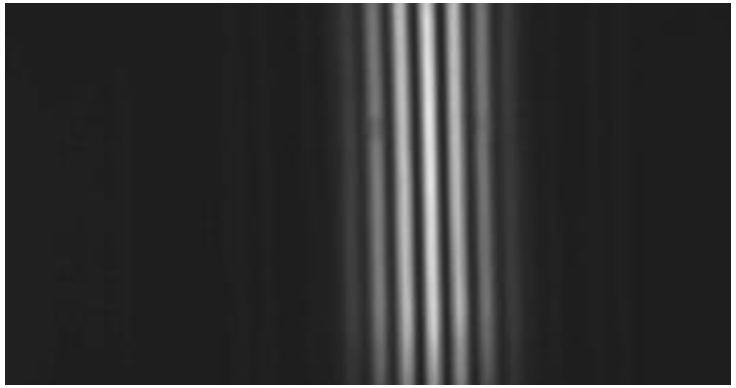
Xray diffraction





Single vs double fluid





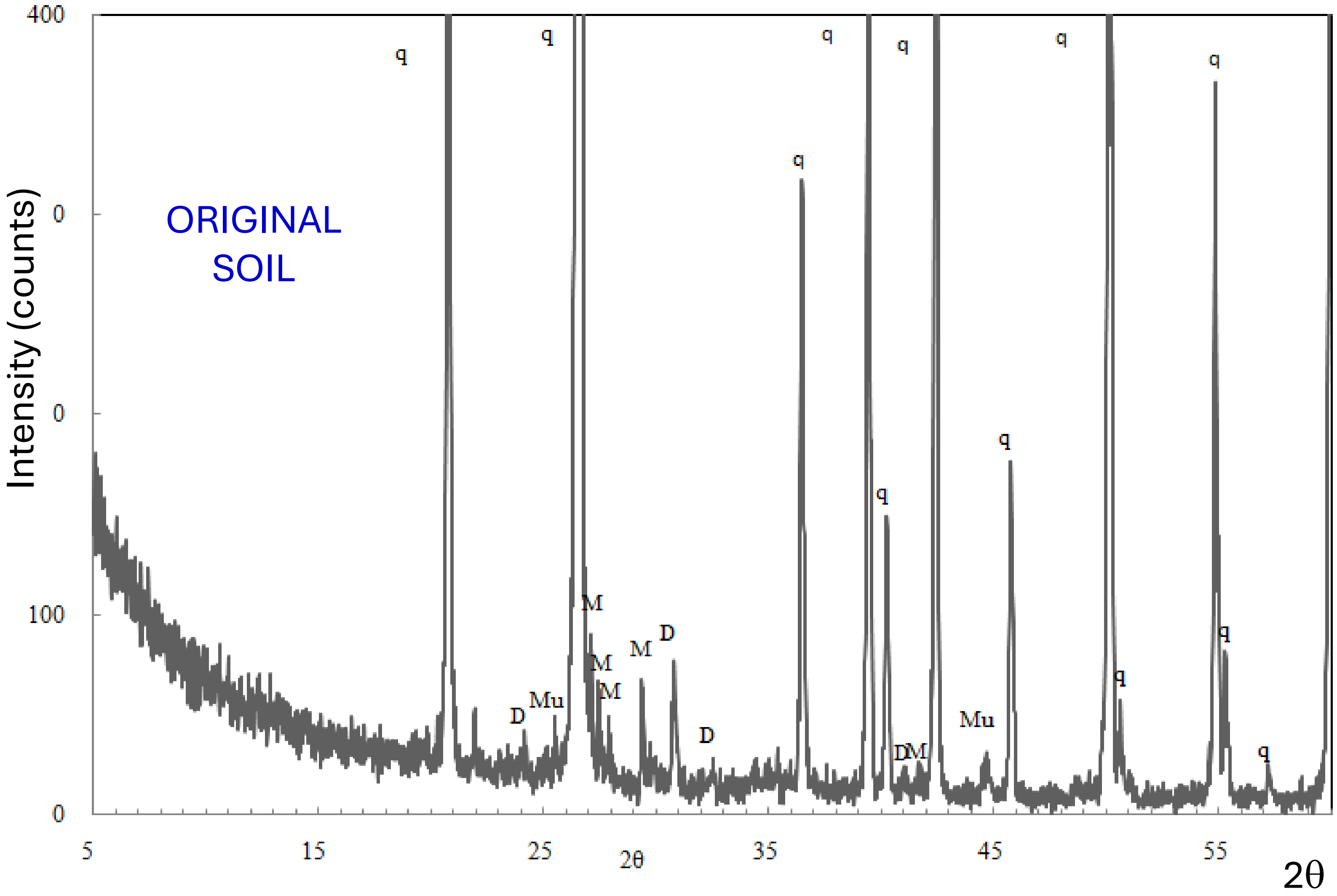
Reticular plane

Miller Index (hkl)

PROPERTIES OF COLUMNS: strength

Xray diffraction

Single vs double fluid



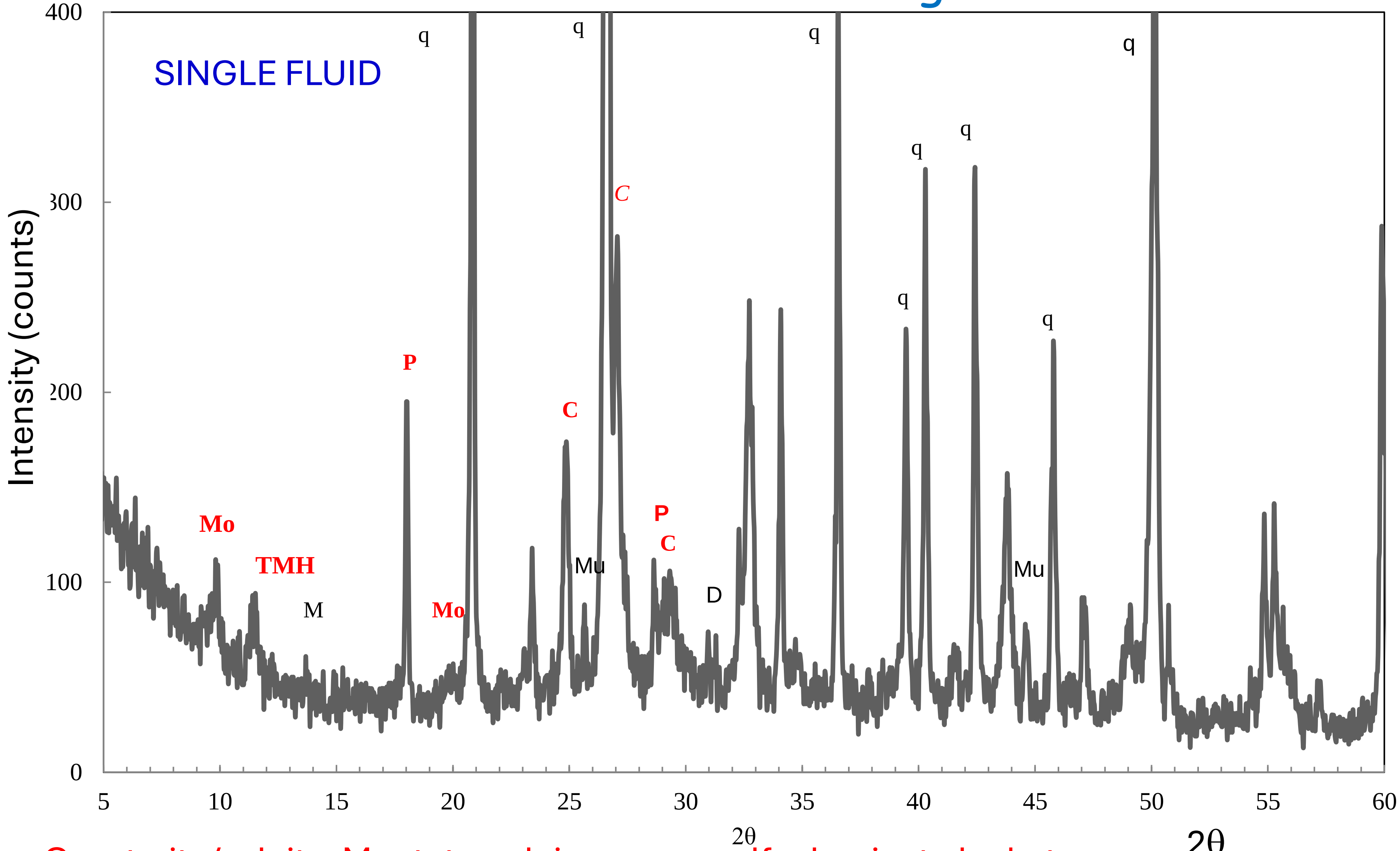
Q= quartz [SiO_2] D= dolomite ferroan [$Ca(Mg, Fe)(CO_3)_2$]

Mu= muscovite [$KAl_3Si_3O_{10}(OH)_2$] M= microclin [$KAlSi_3O_8$]

PROPERTIES OF COLUMNS: strength

Xray diffraction

Single vs double fluid



2θ

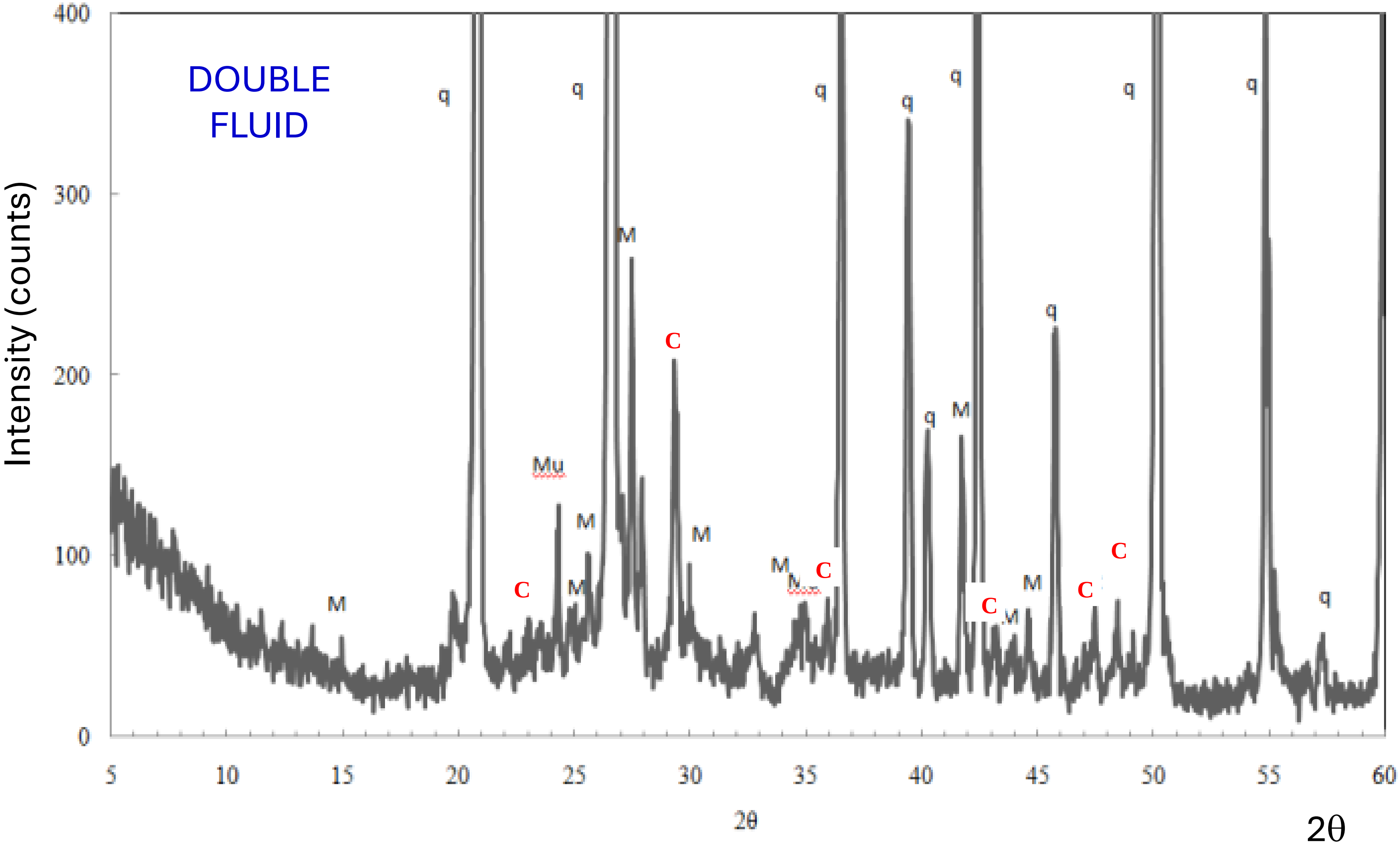
C=vaterite/calcite; Mo=tetracalcium monosulfoaluminate hydrate;

P=portlandite TMH=tetracalcium monocarboaluminate hydrate

PROPERTIES OF COLUMNS: strength

Xray diffraction

Single vs double fluid



C=vaterite/calcite; Mo=tetracalcium monosulfoaluminate hydrate; TMH=tetracalcium monocarboaluminate hydrate

PROPERTIES OF COLUMNS: strength

Thermogravimetric analysis

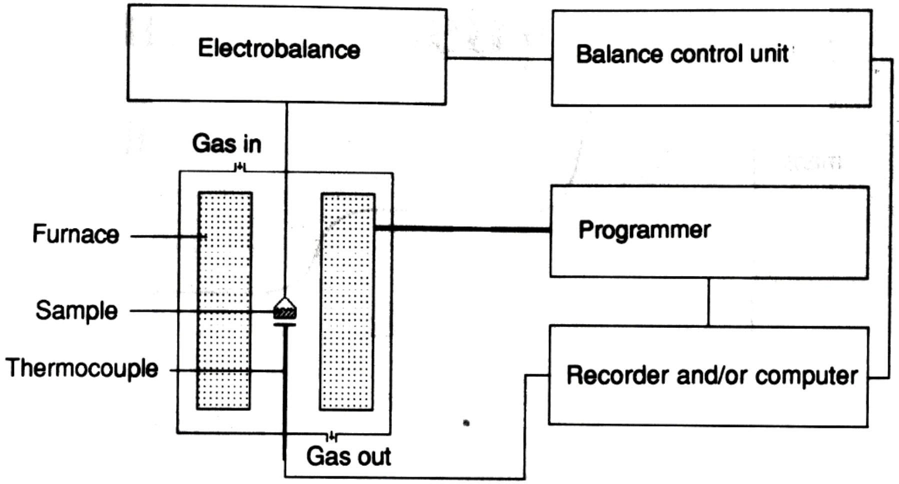
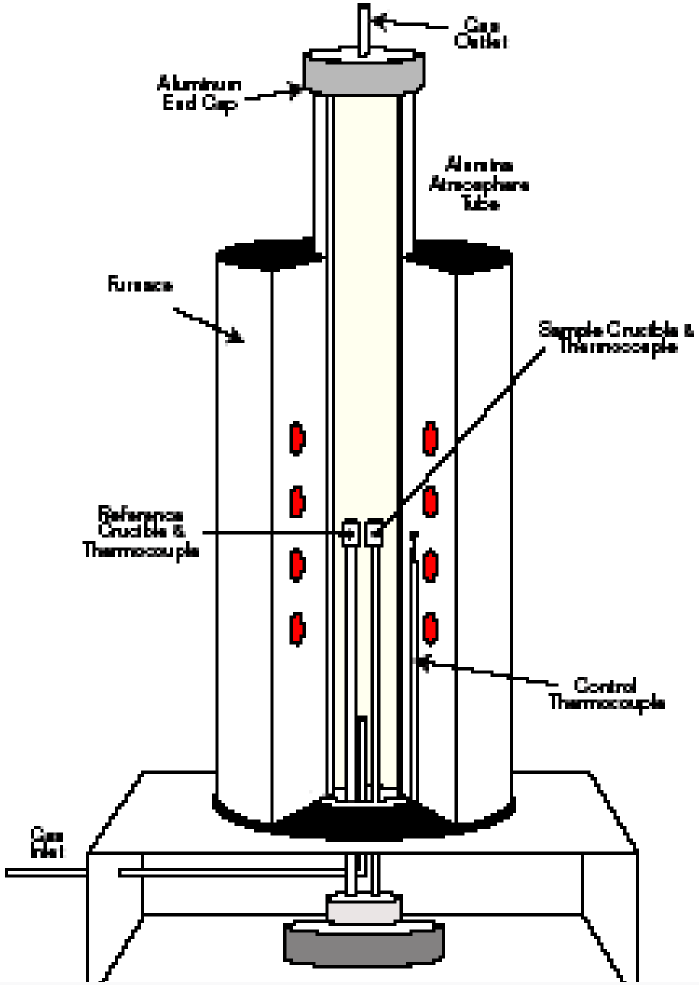


Figure 2.2 Schematic diagram of thermobalance system.

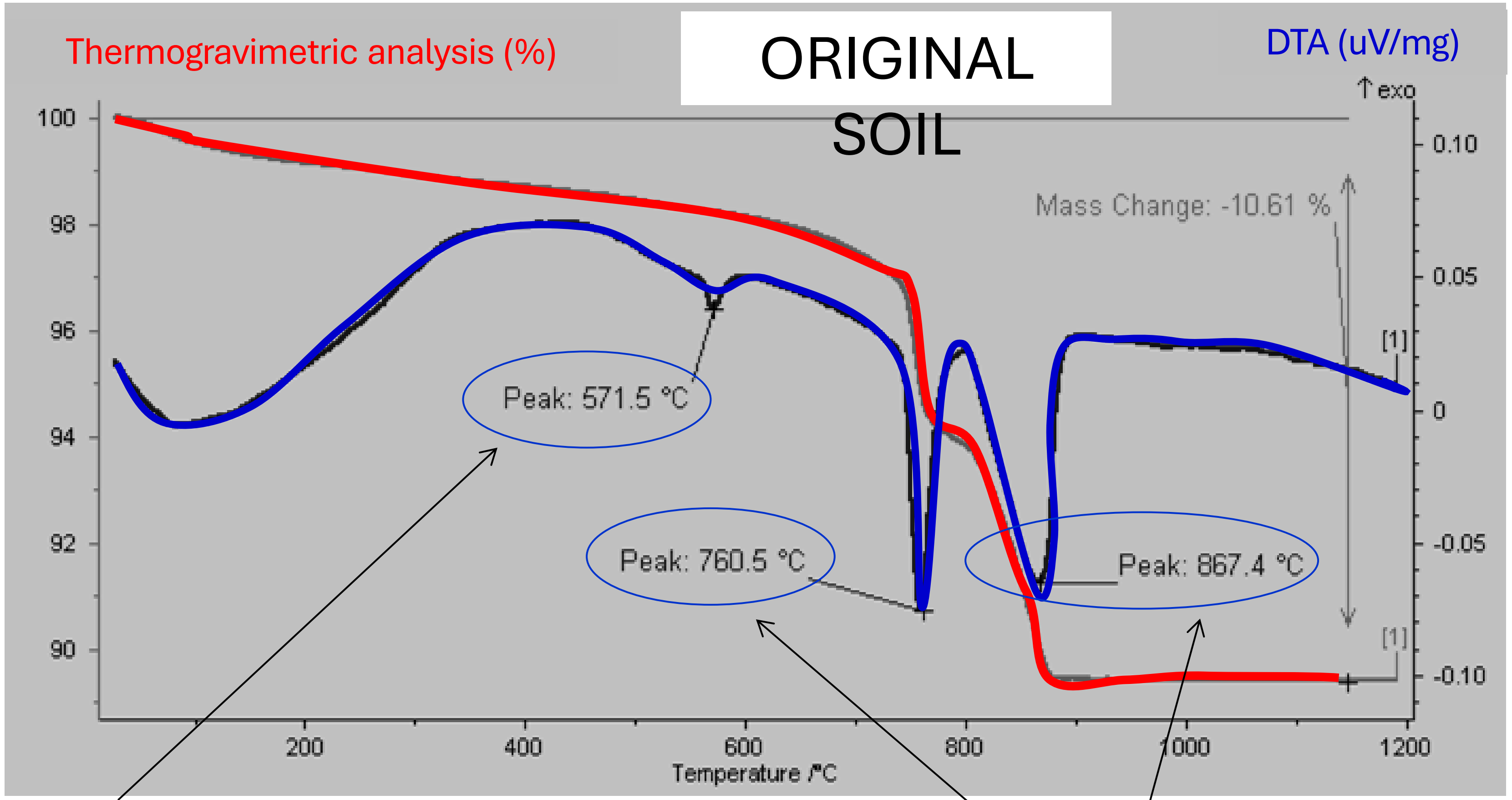
Differential thermal analysis



PROPERTIES OF COLUMNS: strength

Thermogravimetric analysis
Differential thermal analysis

Single vs double fluid



polymorphic transformation of quartz

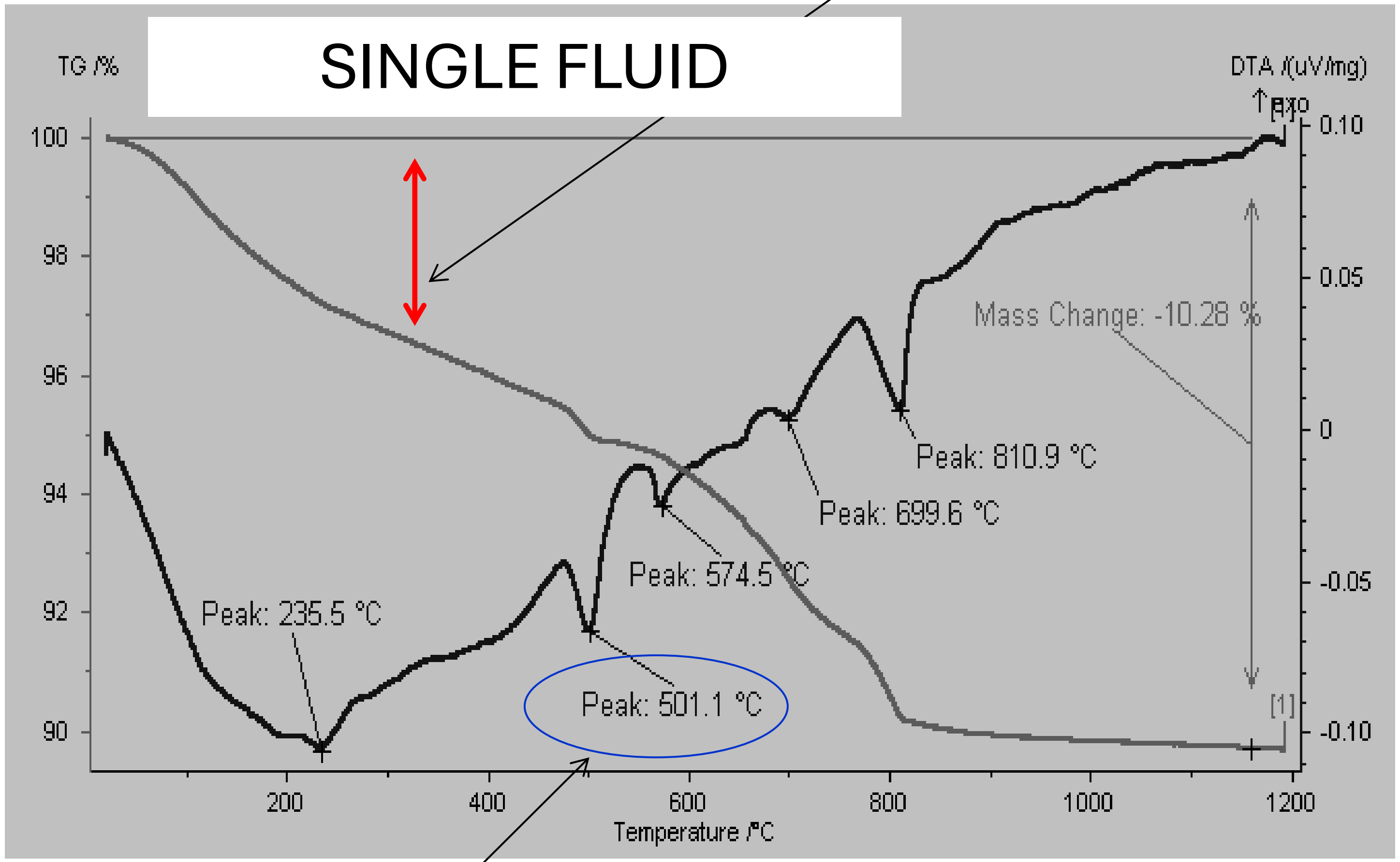
decomposition of dolomite

PROPERTIES OF COLUMNS: strength

Thermogravimetric analysis
Differential thermal analysis

Single vs double fluid

partial dehydration of Calcium Silicate Hydrate

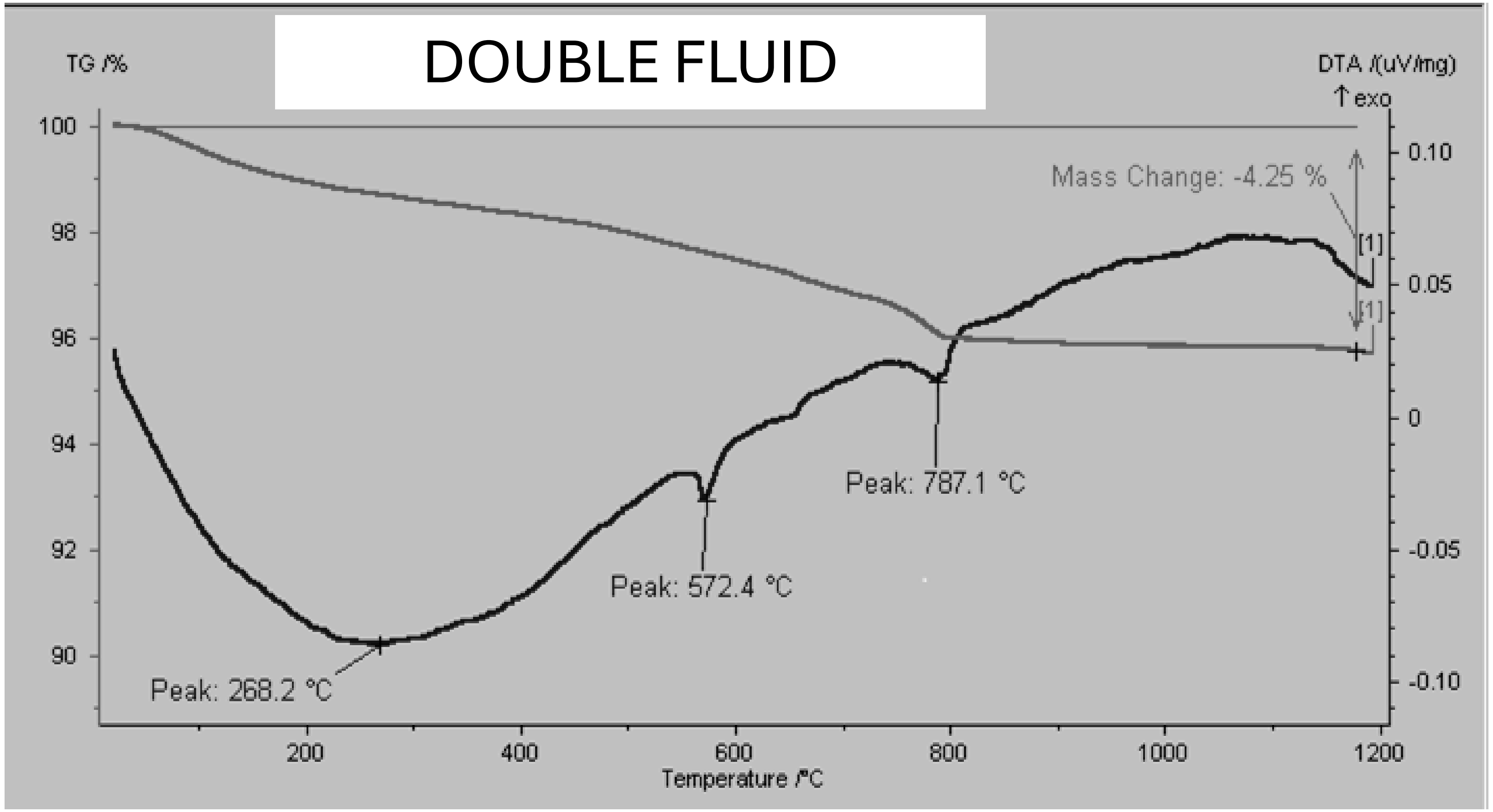


decomposition of portlandite Ca(OH)

PROPERTIES OF COLUMNS: strength

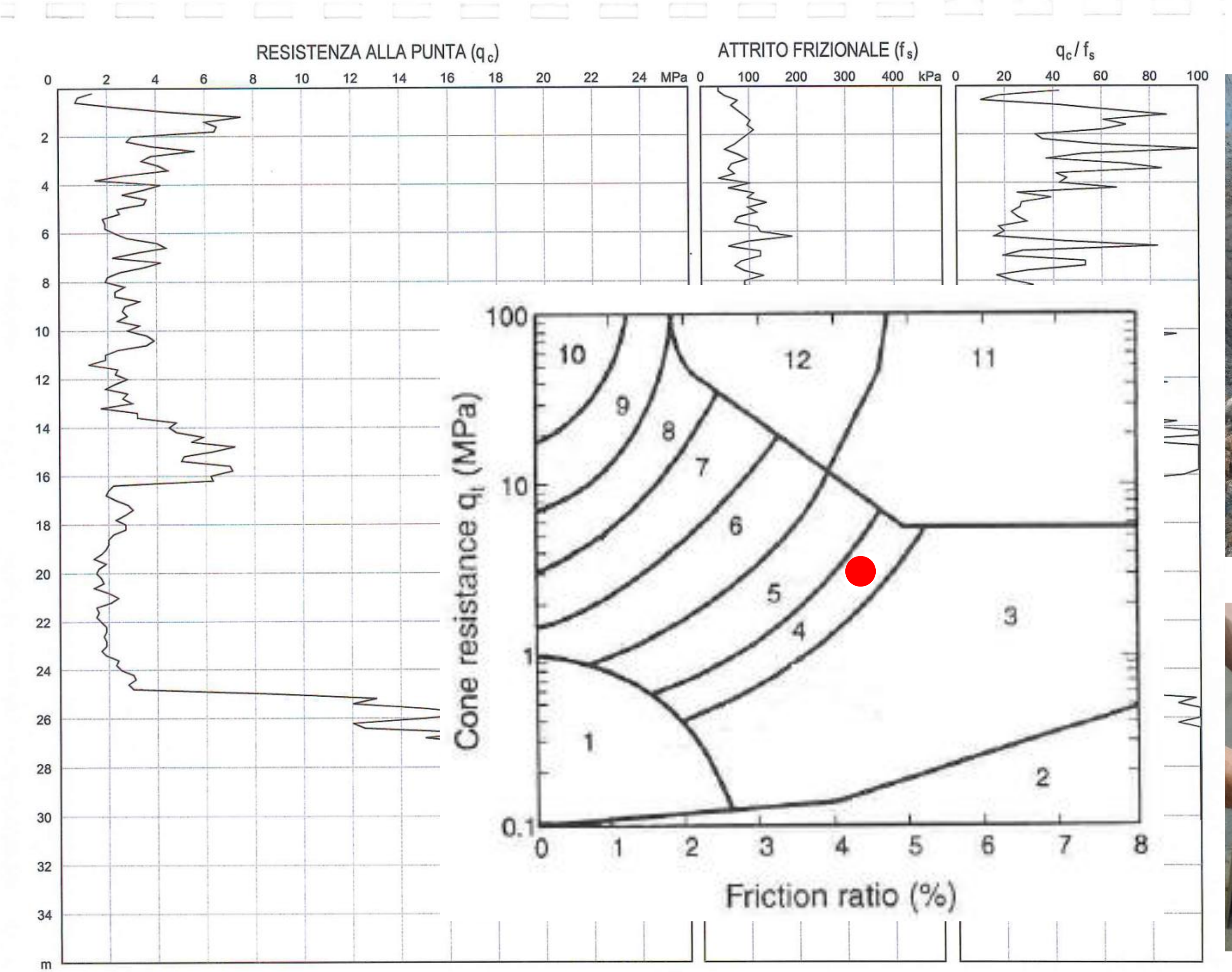
Thermogravimetric analysis
Differential thermal analysis

Single vs double fluid



PROPERTIES OF COLUMNS: strength

Single vs double fluid

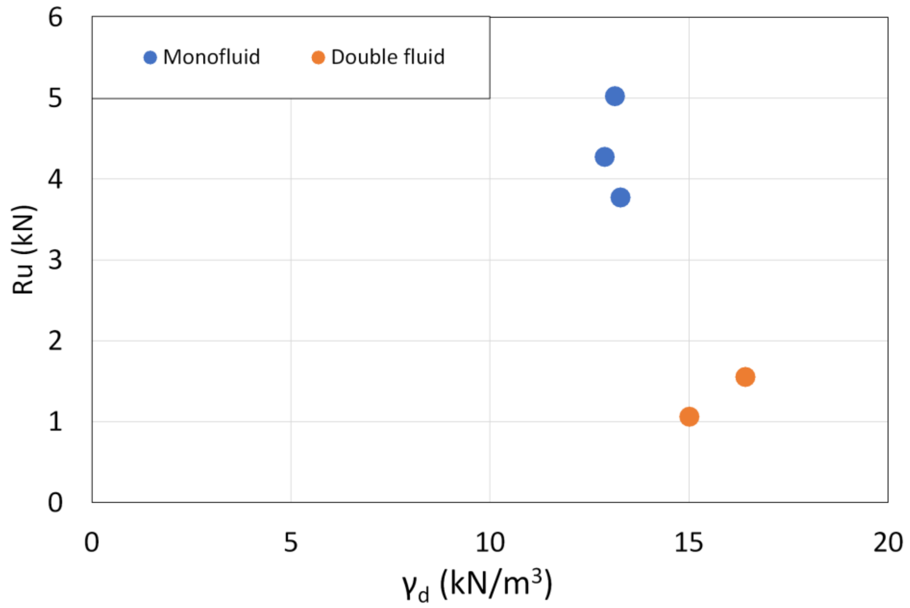


Clayey soils
(Moglia, Italy)

PROPERTIES OF COLUMNS: strength

Technology	ID	cement per unit of volume (kg/m³)	v (m/s)
Monofluid	M#1-1	545	1054.65
	M#1-2		960.97
	M#2-1		1014.83
	M#2-2		1221.65
Bifluid	B#1-2	501	489.83
	B#1-3		370.05
	B#2-2		342.50
	B#2-3		/

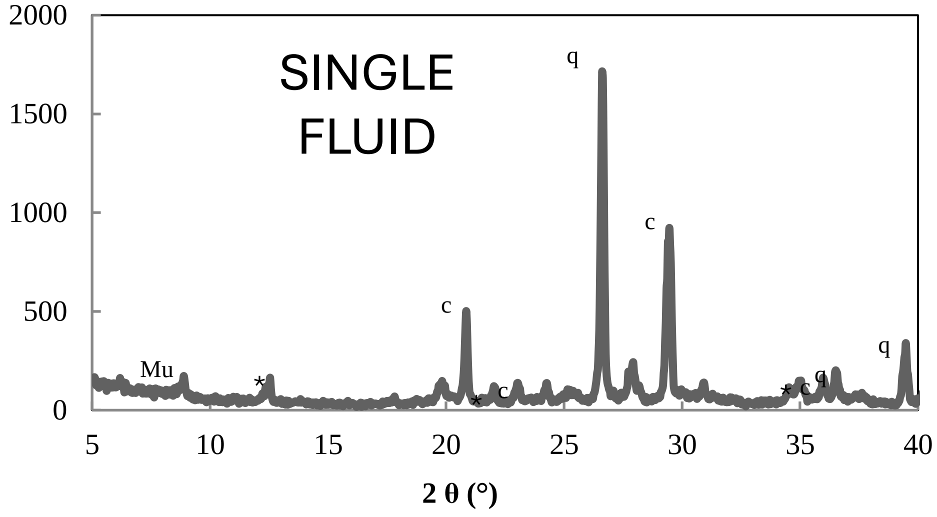
Single vs double fluid

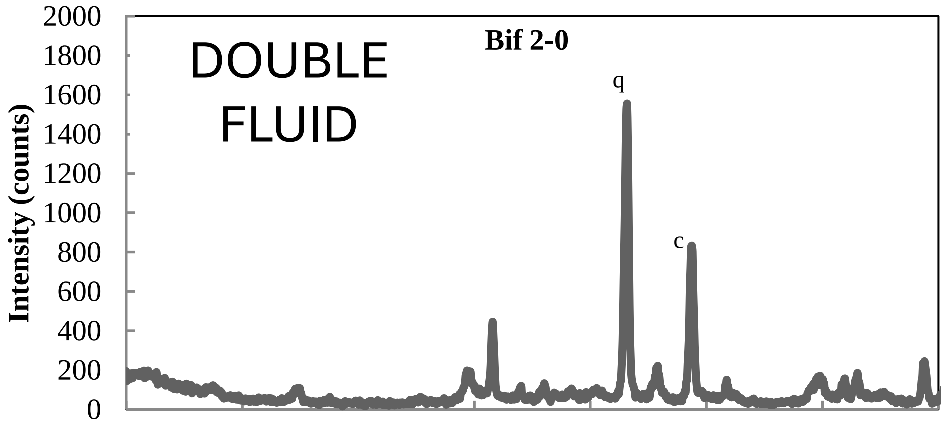


PROPERTIES OF COLUMNS: strength

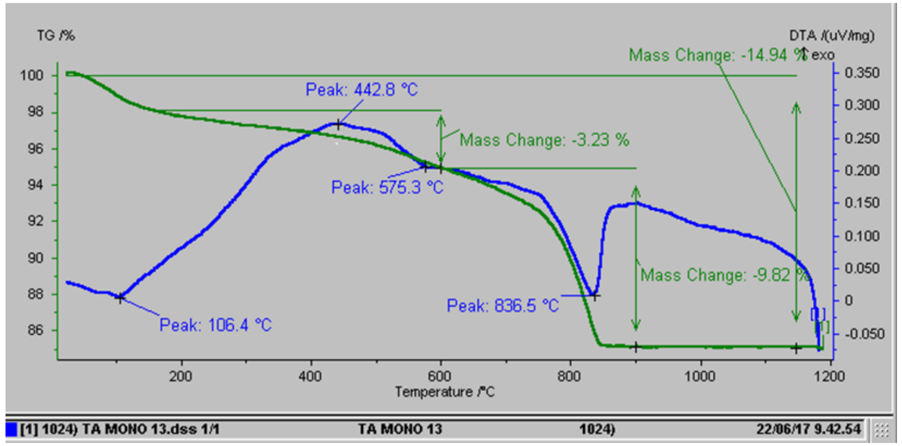
Single vs double fluid

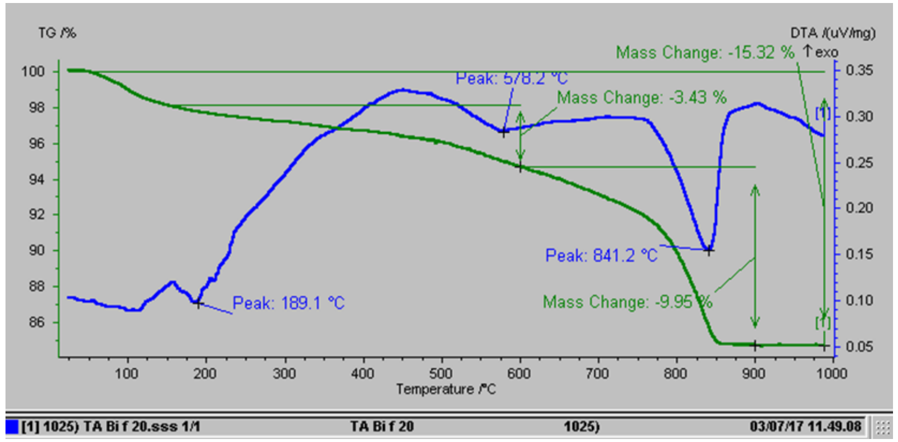
X ray diffraction





Thermogravimetric analysis
Differential thermal analysis





PROPERTIES OF COLUMNS: strength

Single vs double fluid

SINGLE FLUID

DOUBLE FLUID

Phenophthalein test (violet is due to the presence of calcium hydroxide/portlandite)

PROPERTIES OF COLUMNS: strength

SINGLE FLUID

Single vs double fluid

After 24 hours of air exposure

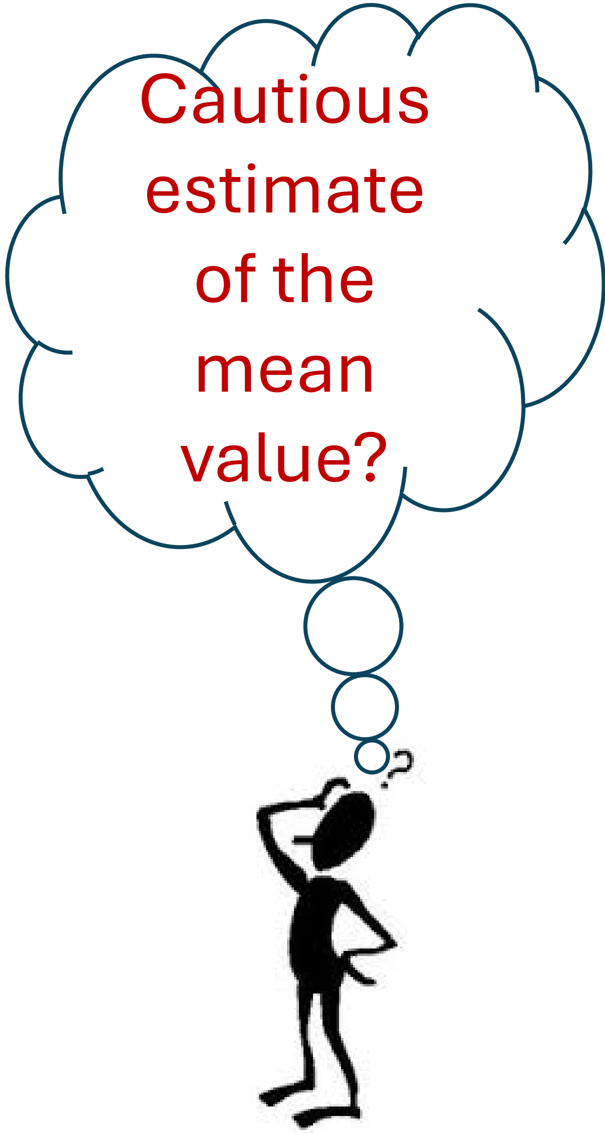
PROPERTIES OF COLUMNS: strength

EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

FINAL DRAFT
prEN 1997-1

English version

Eurocode 7: Geotechnical design - Part 1: General rules



Par.2.4.3 Ground properties

(5) When establishing values of geotechnical parameters, the following should be considered:

....

the variation of the geotechnical parameters that are relevant to the design;

....

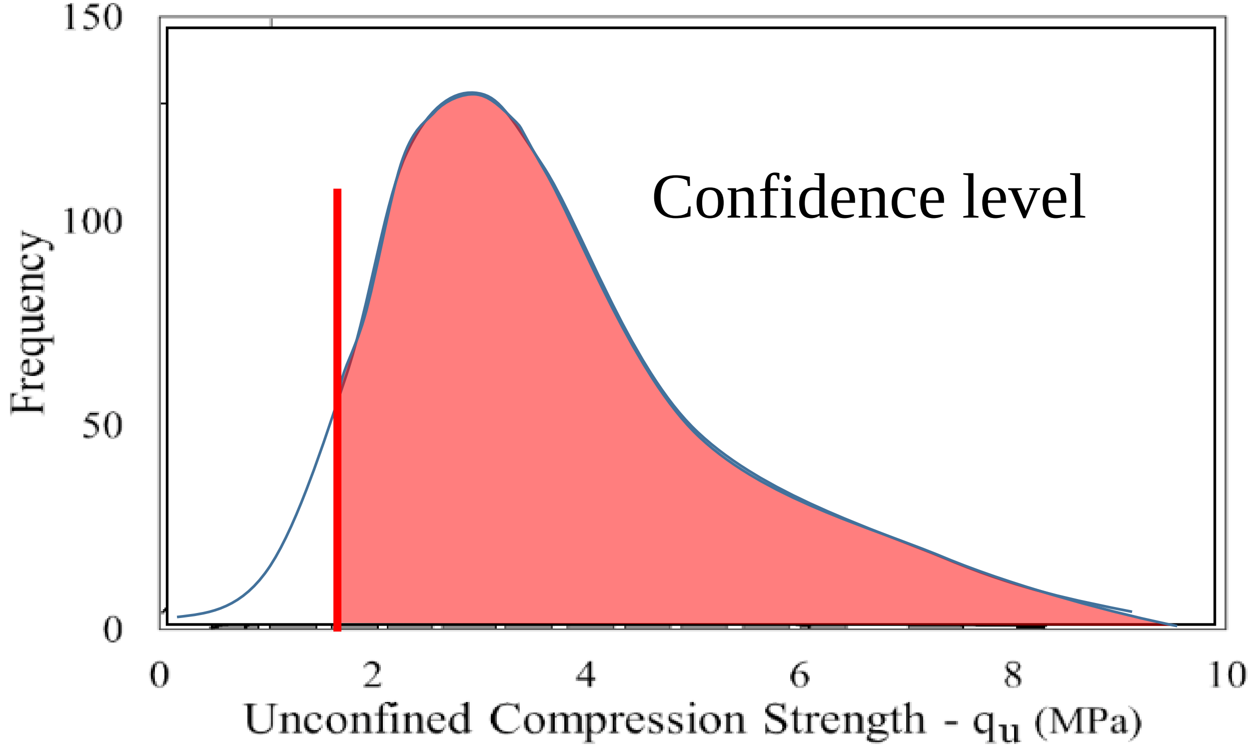
Par.2.4.5 Characteristic values of the geotechnical parameters

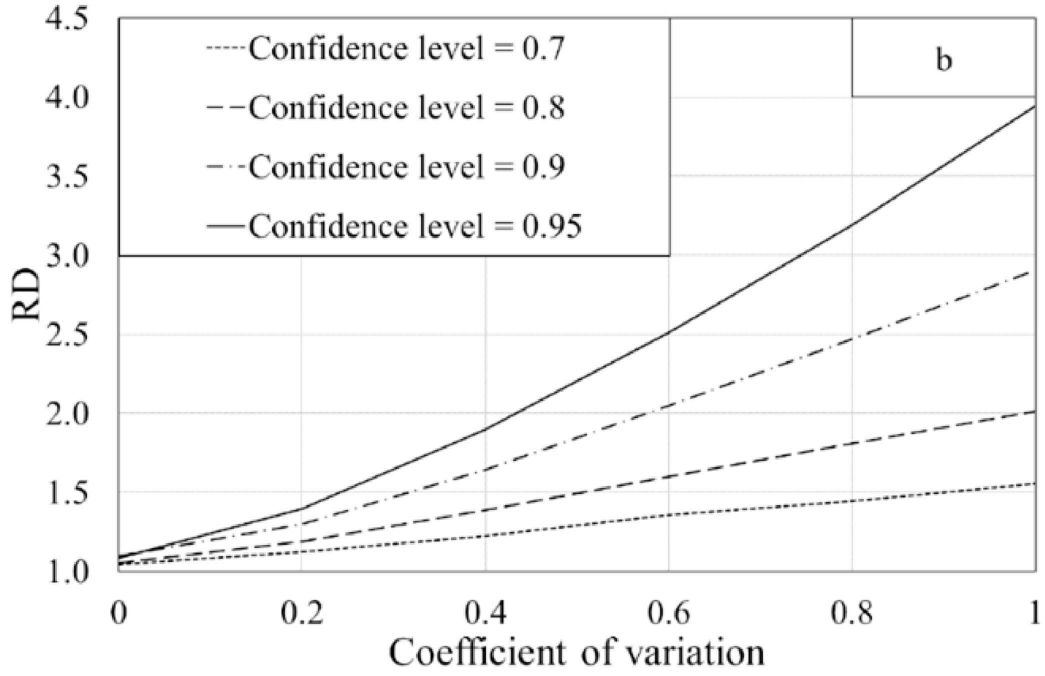
....

(7) The zone of ground governing the behaviour of a geotechnical structure at a limit state is usually much larger than a test sample or the zone of ground affected in an in situ test. Consequently the value of the governing parameter is often the mean of a range of values covering a large surface or volume of the ground. The characteristic value should be a cautious estimate of this mean value.

....

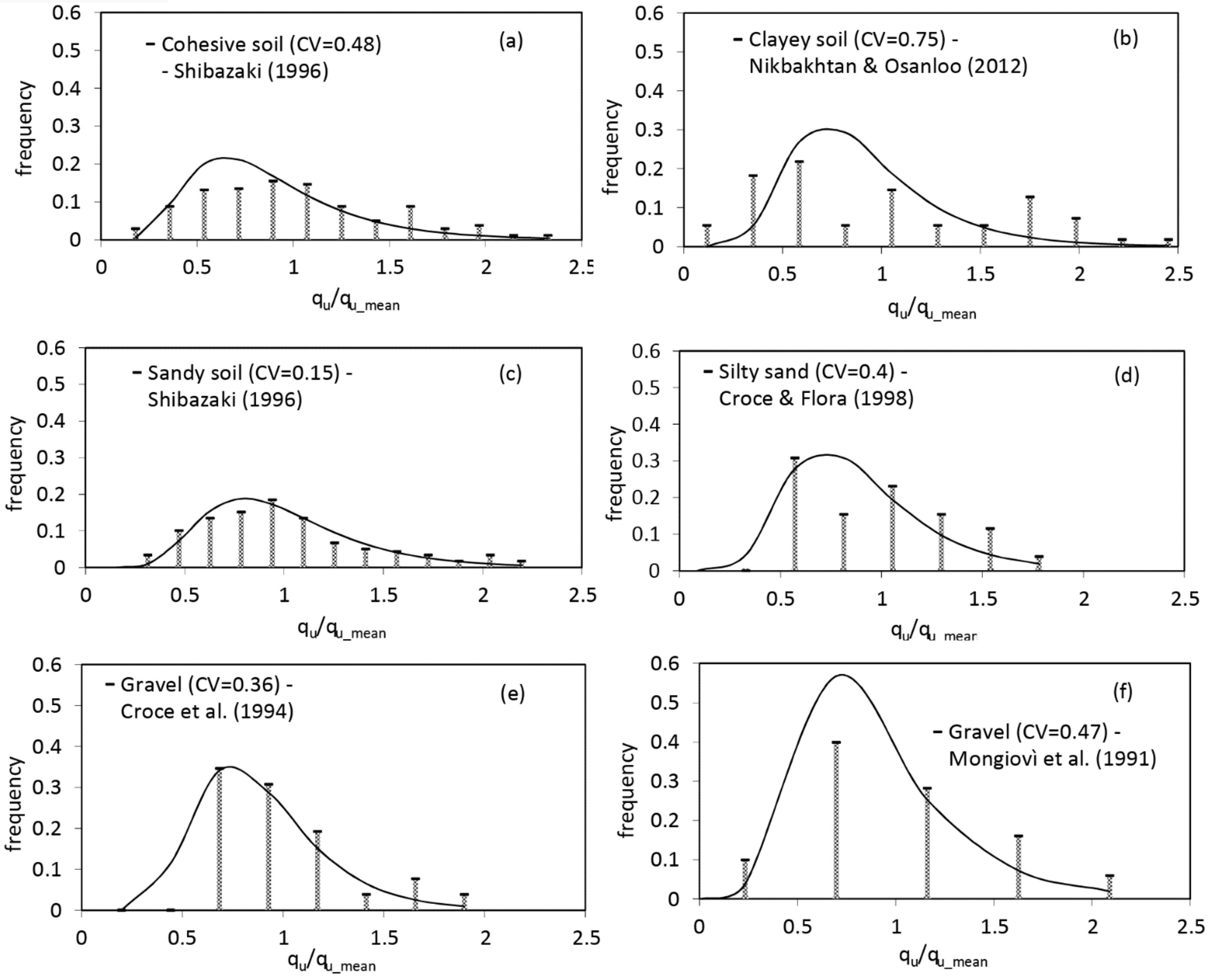
PROPERTIES OF COLUMNS: strength





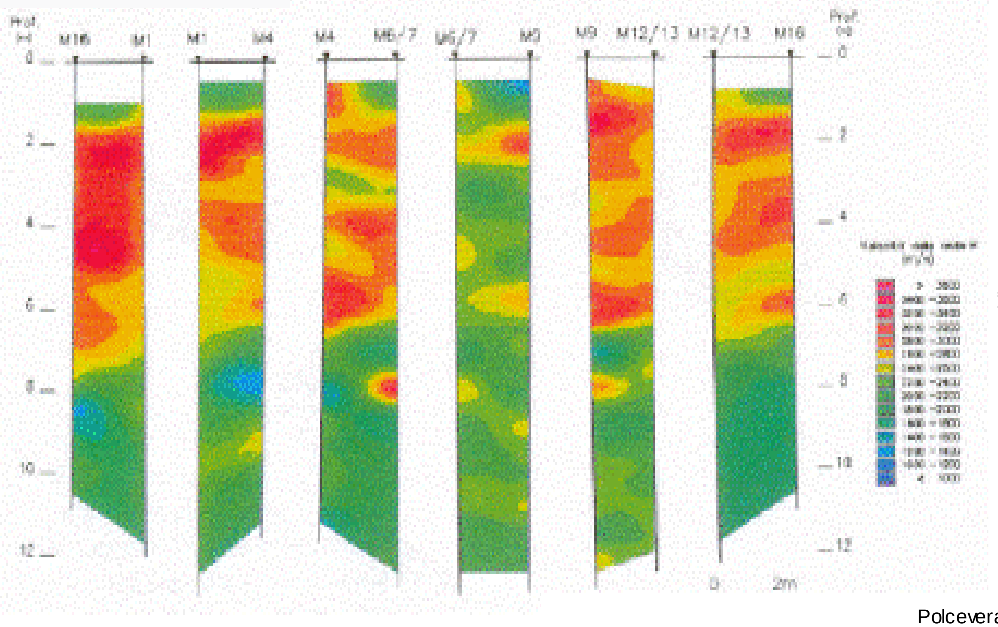
$$q_{uck} = \frac{\overline{q_u}}{RD}$$

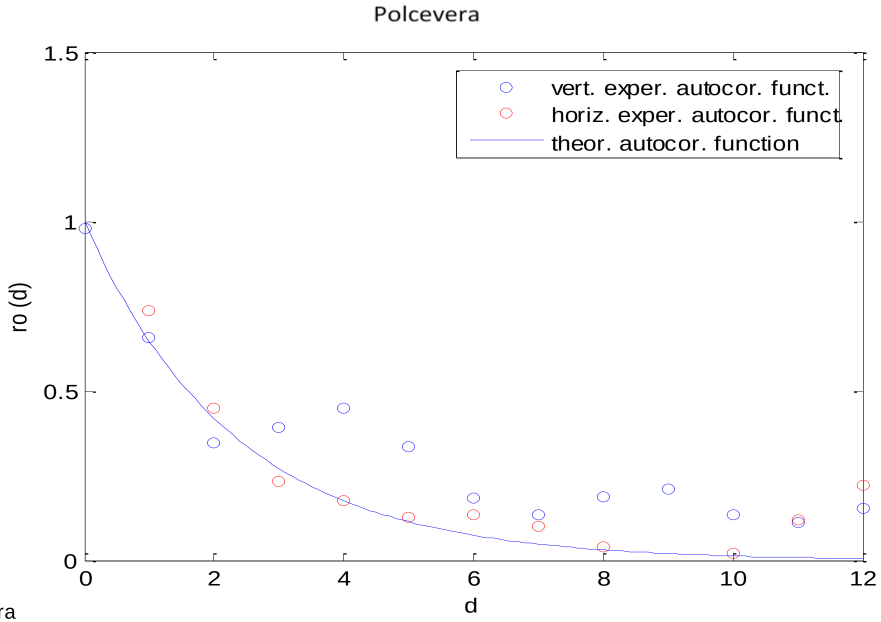
PROPERTIES OF COLUMNS: strength

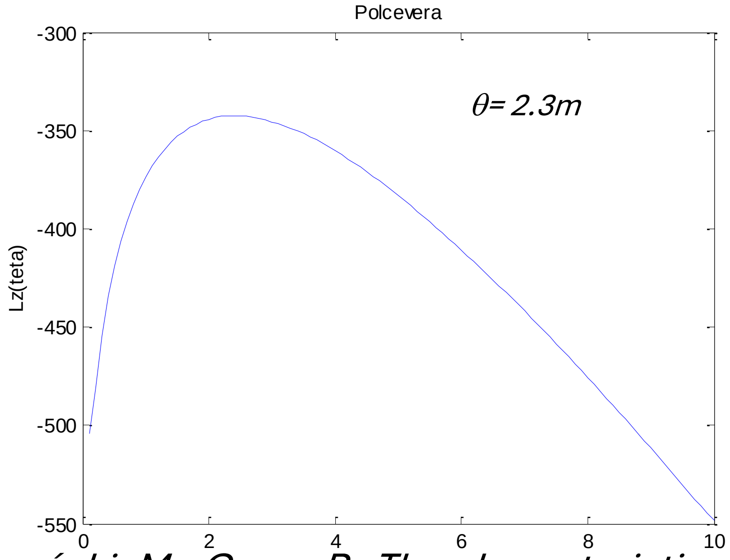


Croce P, Flora A., Modoni G., 2014, Jet Grouting: technology, design and control, Taylor &

PROPERTIES OF COLUMNS: strength

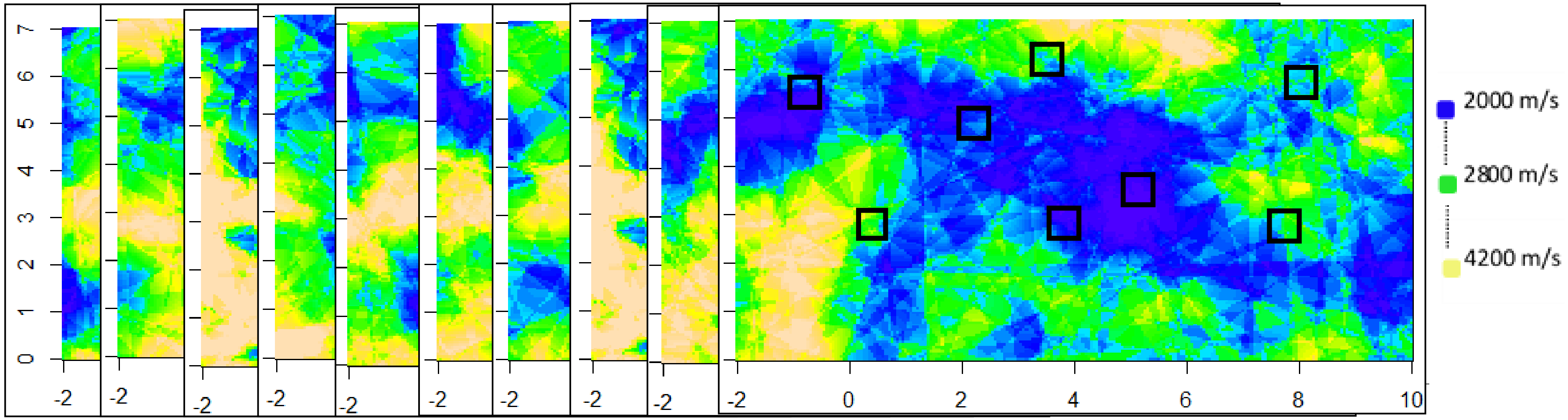


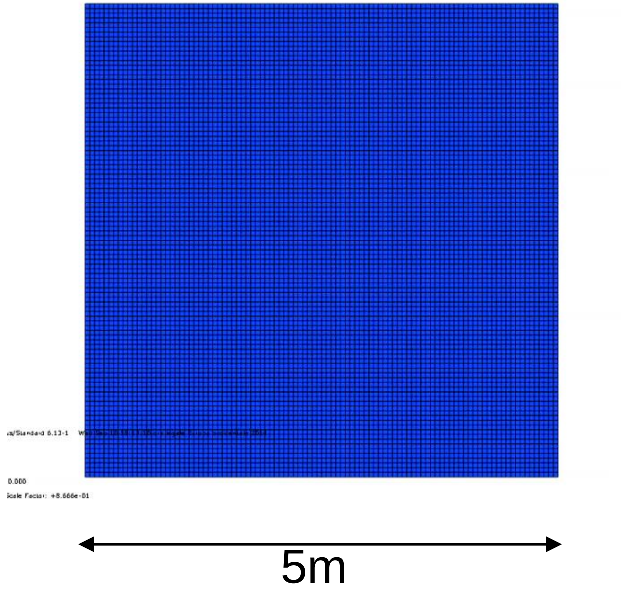


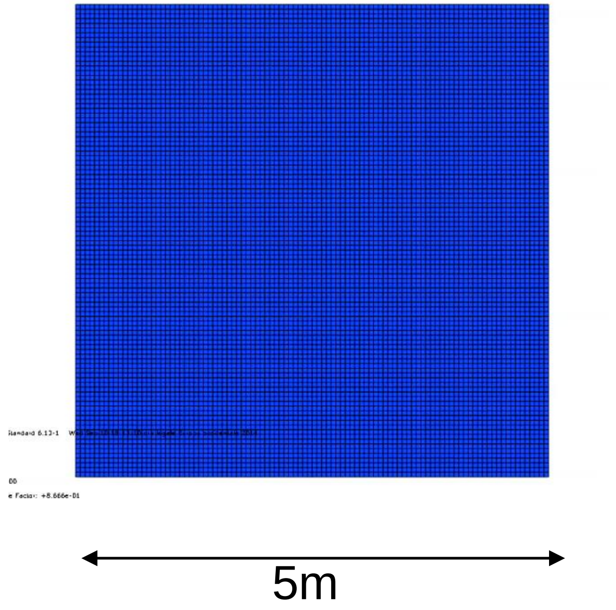


Toraldo C., Modoni G., Ochmański, M., Croce P., The characteristic strength of jet grouted material.

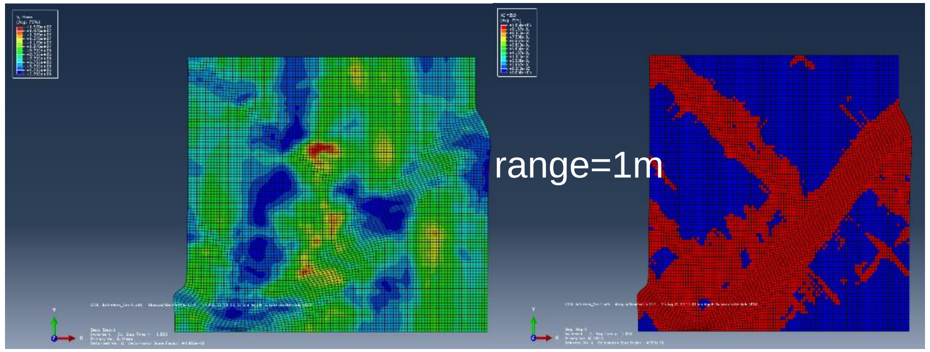
PROPERTIES OF COLUMNS: strength

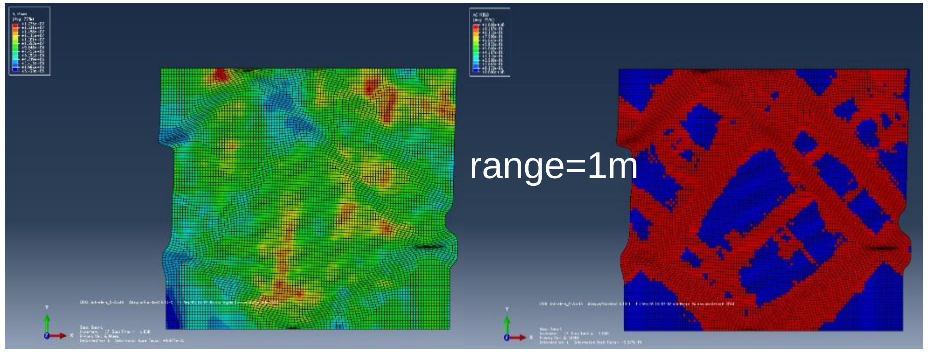


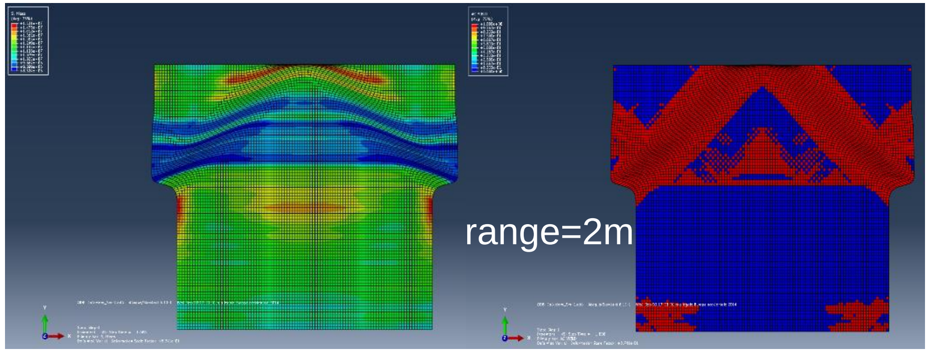


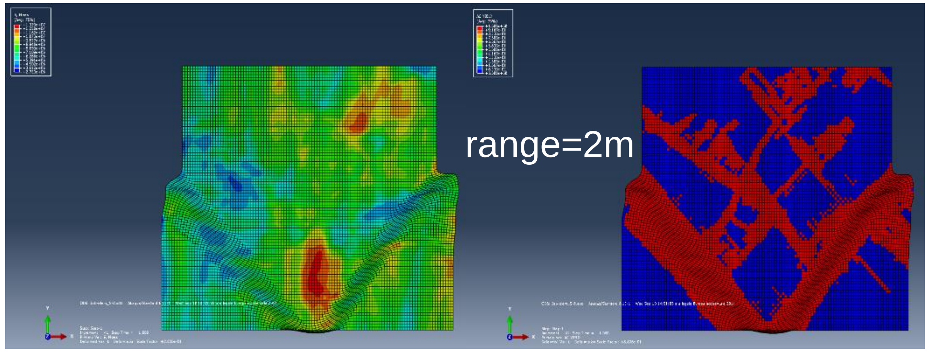


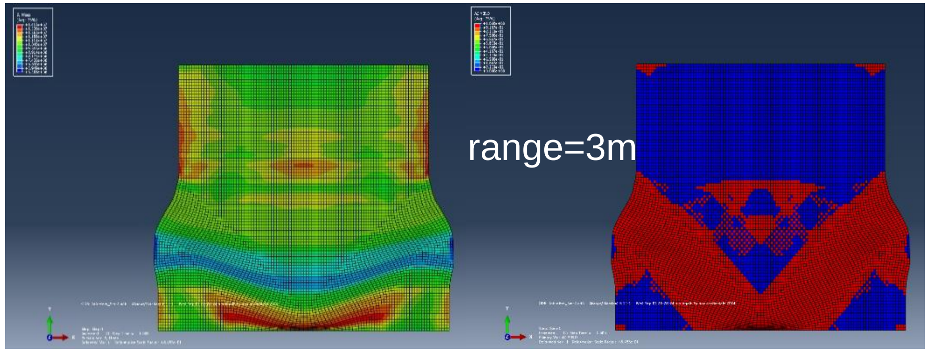
PROPERTIES OF COLUMNS: strength

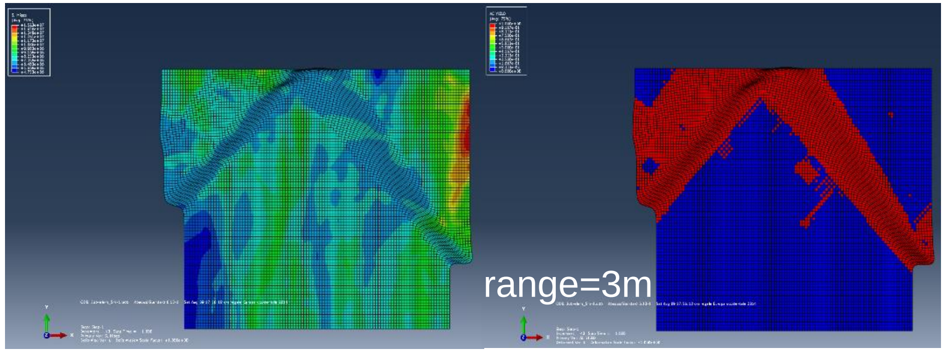




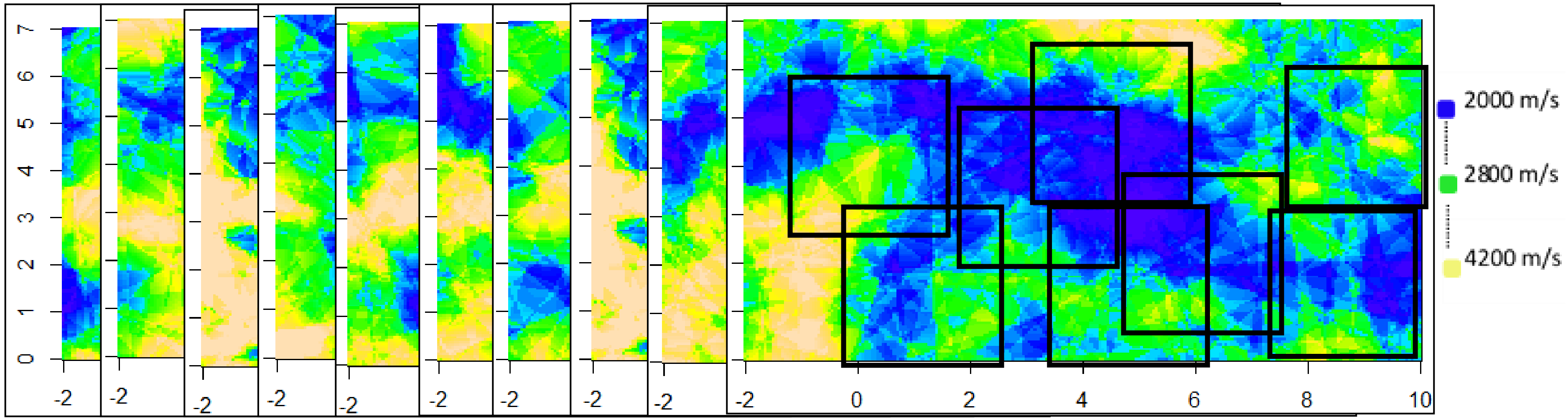


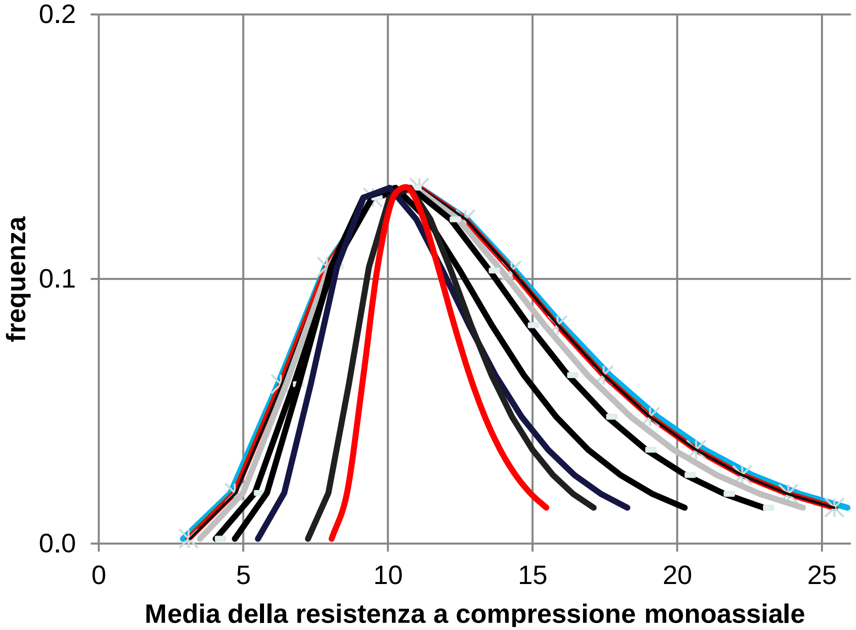






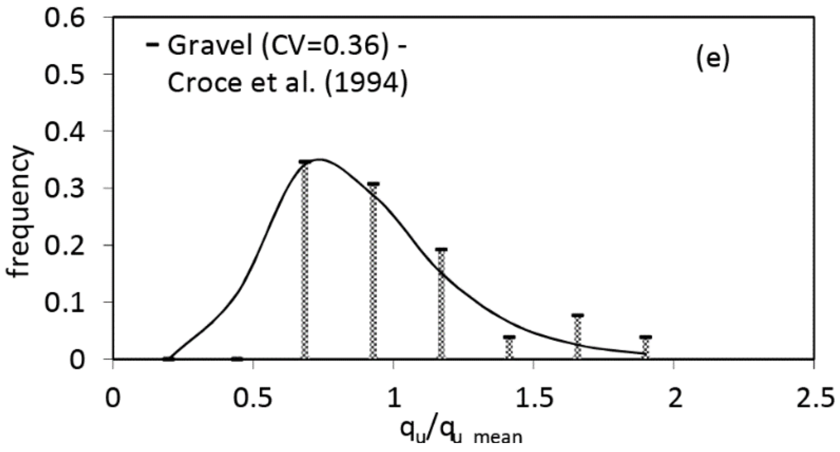
PROPERTIES OF COLUMNS: strength

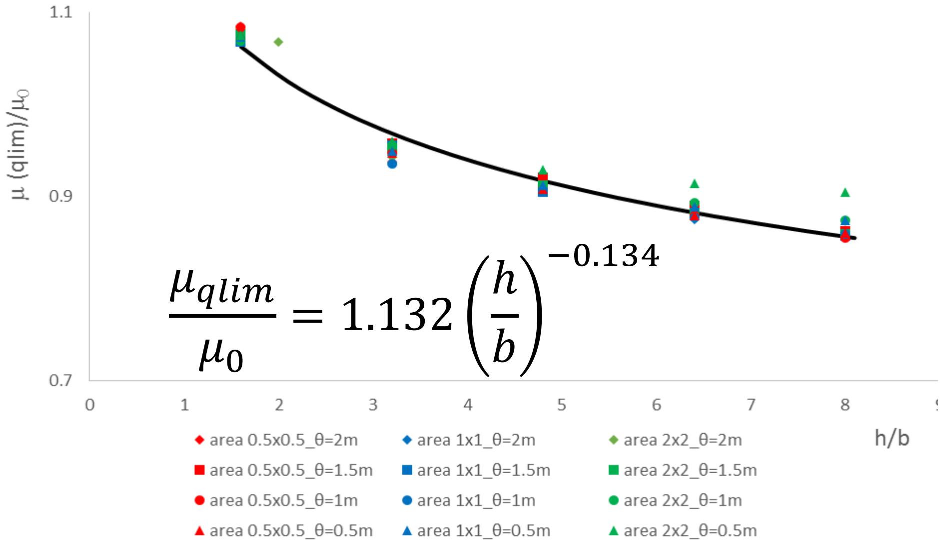




d [m]	Media [Mpa]	Dev.st.[Mpa]
0.1	12.6	5.5
0.2	12.6	5.4
0.3	12.6	5.2
0.5	12.6	5.0
1.0	12.7	4.8
2.0	12.7	4.1
3.0	12.1	3.3
4.0	12.1	2.7
5.0	12.1	2.0
6.0	12.1	1.6

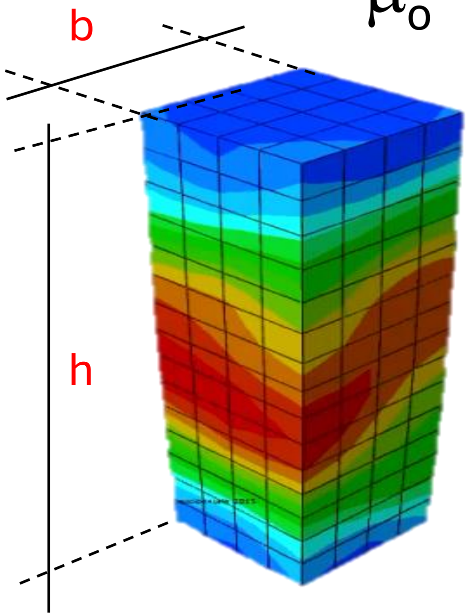
PROPERTIES OF COLUMNS: strength

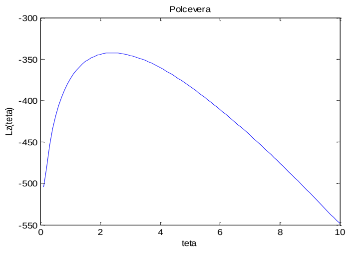


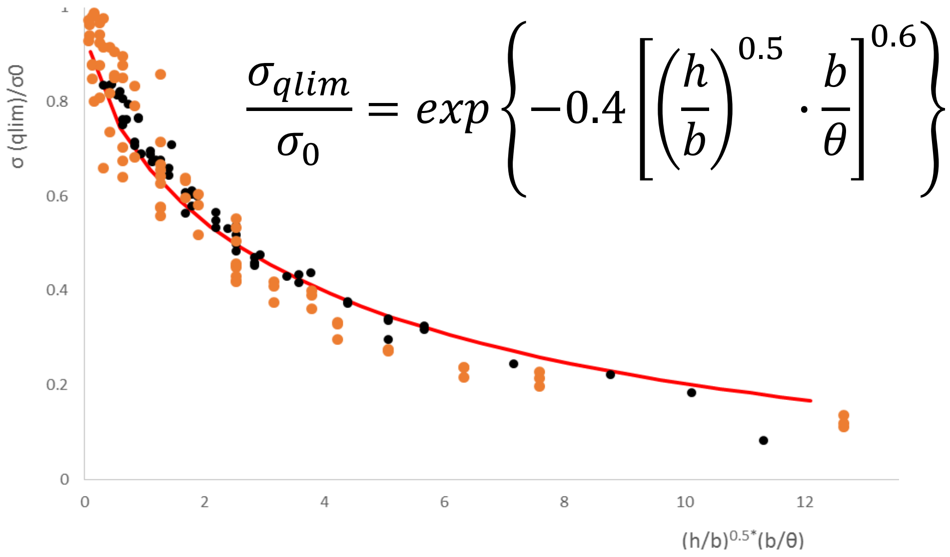


$$\frac{\mu_{qlim}}{\mu_0} = 1.132\left(\frac{h}{b}\right)^{-0.134}$$

μ_o - σ_o







$$\frac{\sigma_{qlim}}{\sigma_0} = exp\left\{-0.4\left[\left(\frac{h}{b}\right)^{0.5}\cdot\frac{b}{\theta}\right]^{0.6}\right\}$$

Bibliography

1. *Croce, P., Modoni, G. (2007). Design of Jet Grouting Cut-offs. Ground Improvement – Proceedings of the Institution of Civil Engineers Ground Improvement 11(1):11-1.*
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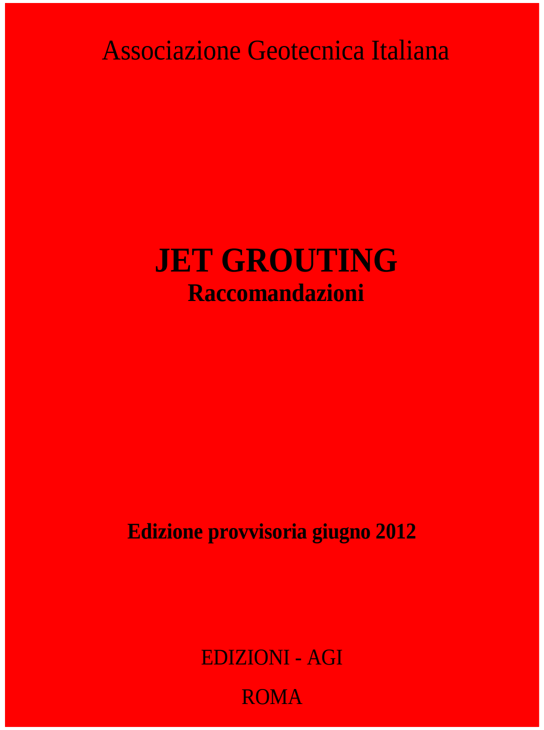

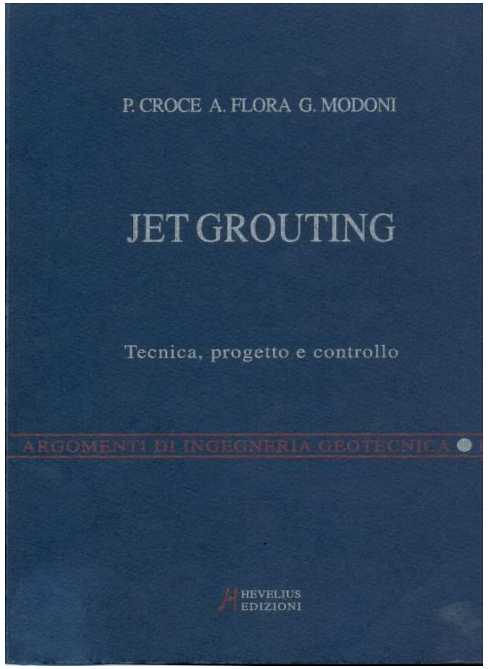

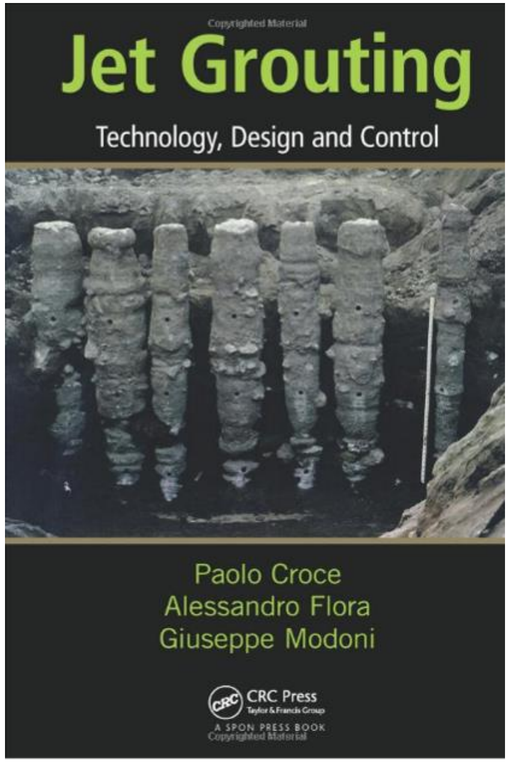

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