DESIGN AND CONTROL CRITERIA OF JET GROUTING TREATMENTS

PARAMÈTRES DE CONCEPTIONET CRITÈRES DE CONTRÔLE DE L'AMÉLIORATION DES SOLS PAR JET GROUTING

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ABSTRACT - A tentative classification of soils in terms of required specific energy has been drawn from the statistical analysis of field trials with direct size assessment of jet grouted elements, enabling to select treatment energy as a function of design size. Analytical balances are then presented, based on estimate of treated soil and spoil compositions, by different approaches aiming to congruence checks, as regards cohesive soils.

RÉSUMÉ – Cette communication propose un classement des sols en fonction de l'énergie spécifique appliquée pour la mise en ouvre des colonnes de jet et de la nature des sols traités. Des résultats de chantiers sont présentés pour corréler les paramétres suivants: éenergie spécifique, diamétre des colonnes, rapports C/E, résistance à la compression. Des graphiques illustrent les relations d'évolution entre ces paramétres.

1. Design criteria

1.1 Introduction

At the design stage there is a lack of reliable methods for predicting the diameter of jet grouted columns, as pointed out by Croce & Flora (2000) in a comprehensive review of current concepts and design rules as regards single-fluid jet grouting.

Various and widely contrasting suggestions have been made about the influence of soil properties (grain size distribution, SPT blow count for cohesionless soils, undrained shear strength for cohesive soil), disregarding the influence of treatment parameters.

On the other hand several empirical correlations with jet parameters have been proposed which don't seem to have a clear physical meaning.

At the preliminary design stage the problem may be faced in a simpler and more reliable way by a quite different approach, based on two energetic parameters:

(a) - applied (treatment) specific energy per unit length of jet grouted columns E_s (MJ/m)

(b) - specific energy E'_s (MJ/m^3) necessary for the treatment of the unit volume of soil, i.e. a single design parameter taking into account both grading and relative density or consistency characteristics of native soil.

When the mean diameter D (m) is known by visual inspection or adequate corings and translated in terms of specific volume of column VC (m^3/m) we obtain the volumetric specific energy, as a function of applied energy:

$$E'_s = E_s/VC \qquad (1)$$

The first part of the paper deals with the statistical analysis of well documented comprehensive field trials and site control data involving a wide range of soils (from gravel and sand up to clayey and peaty soils).

The knowledge of the orders of magnitude of E'_s for various types of soils may enable to restrict the range of treatment energy E_s to be checked in field trials that anyhow are advisable for the final design stage.

As regards our documentation, in most cases the sizes of jet grouted columns have been assessed by visual inspection.

In some cases the interlooking controls by vertical and inclined corings on groups of elements acting as foundation structures enabled to assess the mean specific volume of single elements.

Besides the single fluid system, that is the main and best documented topic, double and triple fluid jet grouting will be discussed as well.

1.2. Treatment specific energy

The applied energy per unit length of column is calculated at the pump by the following formula for single fluid treatment:

$$E_s = \frac{Q \cdot p}{v_t} \quad \text{(MJ/m)} \tag{2}$$

where

Q = grout flow rate (m^3/h)

p = grout pressure (MPa)

v_t = monitor lifting rate i.e. treatment speed (m/h)

The actual variables become two, since the main operational parameter (the specific volume of injected grout) is:

$$VM = \frac{Q}{v_t} \quad (\text{m}^3/\text{m}) \tag{3}$$

and hence:

$$E_S = p \cdot VM \tag{4}$$

Since observational data don't show in general a remarkable systematic influence of pressure (within the current range of 30 to 50 MPa, but mostly around 40 MPa), a further simplification leads to a direct proportionality between applied specific energy and specific grout volume:

$$E_S = 40 \cdot VM \tag{4a}$$

As regards the selection of Q and v_t in order to obtain the design value of VM according to formula (2) fig. 1 shows the correlations for VM values from 0,2 to 1,0 m^3/m, within the advisable range of v_t (between 16 and 24 m/h), corresponding to specific injection times T between 9 and 6 sec for 4 cm lifting steps.

In double and triple systems the linear specific energy of compressed air is given by the formula:

$$E_{sa} = 0{,}35 \cdot Q_a \cdot \left[(10 \cdot p_a)^{0{,}29} - 1 \right] / v_t \tag{5}$$

where:

Q_a = air flow rate (m^3/m)

p_a = air pressure (MPa)

The correlations between E_{sa} and lifting rate v_t (m/h) are shown in fig. 2, considering the combinations of Q_a and Pa values within the current ranges.

Since the practical upper limits of pressure and flow rate are not much higher, the need of a considerable energetic contribution of compressed air may impose a reduction of treatment speed under the current minimum of 18 m/h for single fluid jet grouting (5÷10 m/h).

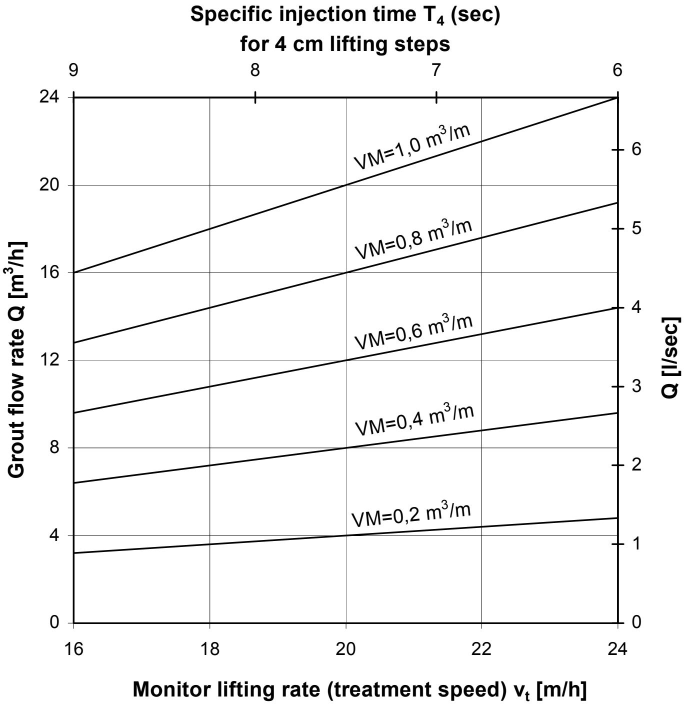


Figure 1. Correlations among treatment speed, grout flow rate and specific grout volume

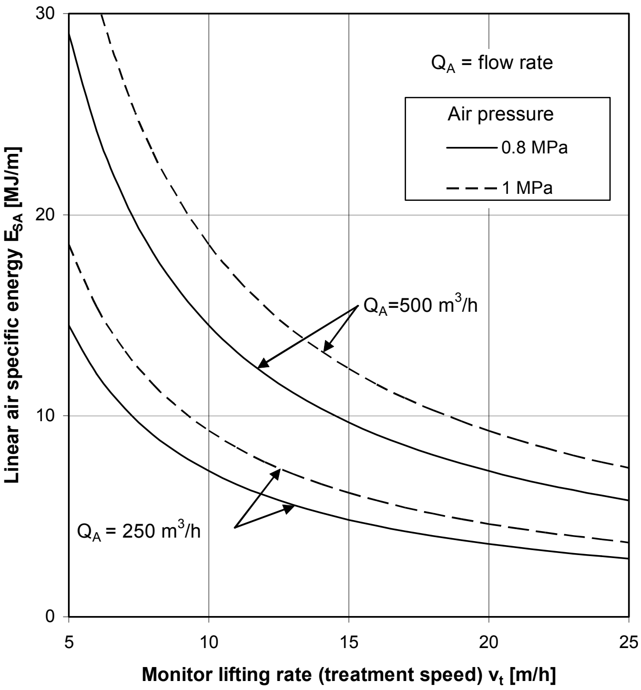


Figure 2. Double fluid jet grouting: influence of pressure, flow rate and treatment speed on specific linear energy of compressed air

In the triple fluid treatments the additional specific energy of water is given by formula (2) inserting the p and Q values of water.

Since specific water volumes range in general between 1 and 2 m^3/m and pressures between 40 and 50 MPa, the energetic contribution may reach the order of 100 MJ/m.

In comparison with single and double jet systems, the cement grout is injected at a much lower pressure (a few MPa in general) so that its energetic contribution is fairly low or even negligible.

1.3. Volumetric specific energy

1.3.1. Case records

Table I presents a summary of case records, as regards the site location, the jet grouting system, the native soil nature and the dimensional assessment mode.

Table I. Summary of case records

CASE No	SITE LOCATION	JET GROUTING SYSTEM			NATIVE SOIL TIPOLOGY	SIZE ASSESSMENT METHOD		FIELD TRIAL COLUMNS	PRODUCTION COLUMNS
		SINGLE	DOUBLE (AIR)	TRIPLE		VISUAL INSPECTION	CORING		
1A	VARALLO POMBIA (NORTH ITALY)	X			GRAVEL IN SILTY SANDY MATRIX	X		X	
1B		X			STIFF SANDY SILT	X		X	
2	CASALMAIOCCO (MILAN)	X	X	X	STIFF SANDY SILT	X		X	
3	S.BENEDETTO DEL TRONTO (CENTRAL ITALY)	X	X	X	MEDIUM LOOSE SILTY SAND	X		X	
4	VESUVIUS TUNNEL (NEAPLES)	X			SILTY SAND WITH SOME GRAVEL (PYROCLASTIC)	X		X	
5	AREZZO (CENTRAL ITALY)	X			MEDIUM STIFF CLAYEY SANDY SILT	X		X	
6	COMO	X	X	X	SOFT PEATY SOIL	X		X	
7	MAZZE' (NORTH ITALY)	X			GRAVEL IN SILTY SANDY MATRIX		X	X	X
8	SINGAPORE	X			SOFT SILTY CLAY	X	X	X	X
9	QUED NIL (ALGERIA)	X			VERY SOFT CLAYEY SILT (VASE)		X	X	X
10	VENICE		X		SOFT CLAYEY SILT		X	X	

Coarse grained soils with gravel or silty sand prevailing are involved in three cases (1A,4,7).

In case 4 (pyroclastic silty sand with some gravel) the data reported by Croce & Flora (1998) have been considered.

In case 3 the soil consists of medium-loose fine silty sand, while stiff sandy silts have been treated in cases 1B,2,5.

Soft silty-clayey formations have been the object of important soil improvement works for the solution of tunnelling and deep foundation problems in cases 8 and 9.

At last, case 6 relates to soft peaty soil treated to support railway embankments.

The first three case records listed in Table I refer to large scale field trials carried out by Rodio Co. to evaluate the influence of operational systems and parameters in the initial stage of jet grouting practice in Europe (1983-1990).

At Varallo Pombia (1983) the single fluid system has been tested in two different types of soil (1A,1B); The statistical analysis regards 17 and 9 columns respectively, with sizes directly observed up to a depth of about 7 m.

All the three systems have been used in the Casalmaiocco field trial (1986) with visual inspection (up to 3-4 m depth) of 26 columns, 14 of which made by the double fluid system.

In the S. Benedetto case (1990) the three systems have been tested by a total number of 16 columns.

Two elements only were executed by the SF system, since the main purpose of the field trial was the evaluation of more economical treatments with additional fluids and execution times (i.e. costs) closer to those required by the SF system.

In the case 6 (Como) the construction of two railway embankments (along an additional line for international traffic connecting Milan to Basel) on a peaty soil deposit up to 7 m thick, required a foundation improvement program meeting with very strict specifications in terms of environmental protection, speed of execution and early effectiveness (De Paoli et al. 1988,1989).

In this soil (a fibrous peat with a silty clayey matrix) the water content is very high and close to liquid limit (200÷400%) and the organic content is mostly around 50%.

The problem was solved successfully by the triple fluid technique with air/water prejetting in the drilling stage, selected and optimized by exhaustive field testing.

The direct size observation up to 3,5 m depth regards 8 trial columns executed by various procedures:

- single fluid (1)
- double fluid with prejetting (2)
- triple fluid (3 with prejetting and 2 without).

In the cases 8, 9 e 10 involving soft silty-clayey soils (undrained shear strength lower than 0,03 MPa in general) the size of columns has been evaluated by means of continuous corings on blocks of improved soil consenting to check the planned interlocking of elements.

The specific volume of treated soil (and hence the mean equivalent diameter) is given by the total covered area divided by the number of columns.

If the continuity of the treatment is ascertained, the resulting mean diameter is a conservative value for design, since the potential size may be greater.

An important application of single fluid system for block treatments of soft cohesive soils from ground surface to solve tunnelling problems, has been carried out on Lot 106 of the Singapore Mass Transit System (Mongilardi & Tornaghi, 1986 ; Lunardi et al. 1986).

In four tunnel sections with a total length of about 400 m, 9.400 m^3 of soil have been treated by more than 10.000 columns; ground movements, recorded daily by a close network of datum points, were kept within the safe limits.

Case 9 regards the deep foundations of the abutments and two piers of a bridge on the river Nil (Oued Nil) along a road between Constantine and Jijel in Algeria.

Soil conditions, characterized by the presence of a very soft silty-clayey formation ("vase" in the local french terminology) 15 to 25 m thick (Fruguglietti et al. 1989) were such to require foundations 40 to 50 m deep, reaching a sandy bearing substratum.

The selected solution was soil improvement by single fluid jet grouting; as a whole about 820 columns have been realized with a total length 0f 33.000 m for the treatment of about 10.000 m^3 of soil.

Strict inclinometric controls on trial and production columns recorded deviations of less than 0,25% from the vertical axis, at 50 m depth.

The reconstruction of La Fenice Theatre in Venice involved complex and delicate foundation problems (Balossi Restelli et al. 2003).

Safety against piping and excessive seepage from the bottom of deeper underwater excavations was obtained creating horizontal cutoffs by means of double fluid treatments.

In order to optimize the operational parameters, a field trial has been carried out; three terns of columns have been executed, with centers forming equilateral triangles with the same geometry (0,8 m c/c) according to design, and variable linear specific energy.

Later, three control corings were performed, as follows:

- vertical in the center of one column
- vertical in the tern center
- inclined 20% to the vertical, crossing a couple of columns.

Core recovery and laboratory test data on undisturbed samples led to select the intermediate value of E_S (20MJ/m).

The specific volume of treated soil to introduce in formula (1) (para. 1,0) is:

$$VC = 0{,}8^2 \cdot \sin 60° = 0{,}554 m^3 / m \qquad (6)$$

corresponding to a mean diameter D = 0,84 m.

The same procedure for size evaluation has been adopted in cases 7,8,9.

1.3.2. Single fluid system

The most exhaustive information about the influence of pressure on treatment specific energy E_s has been obtained in the Varallo Pombia field trial (case 1A), where 17 columns have been executed at 3 different pressures (30-40-50 MPa).

In fig. 3 the specific volume of treated soil VC (according to mean measured diameters of exposed columns) are plotted against the specific volume of injected cement grout.

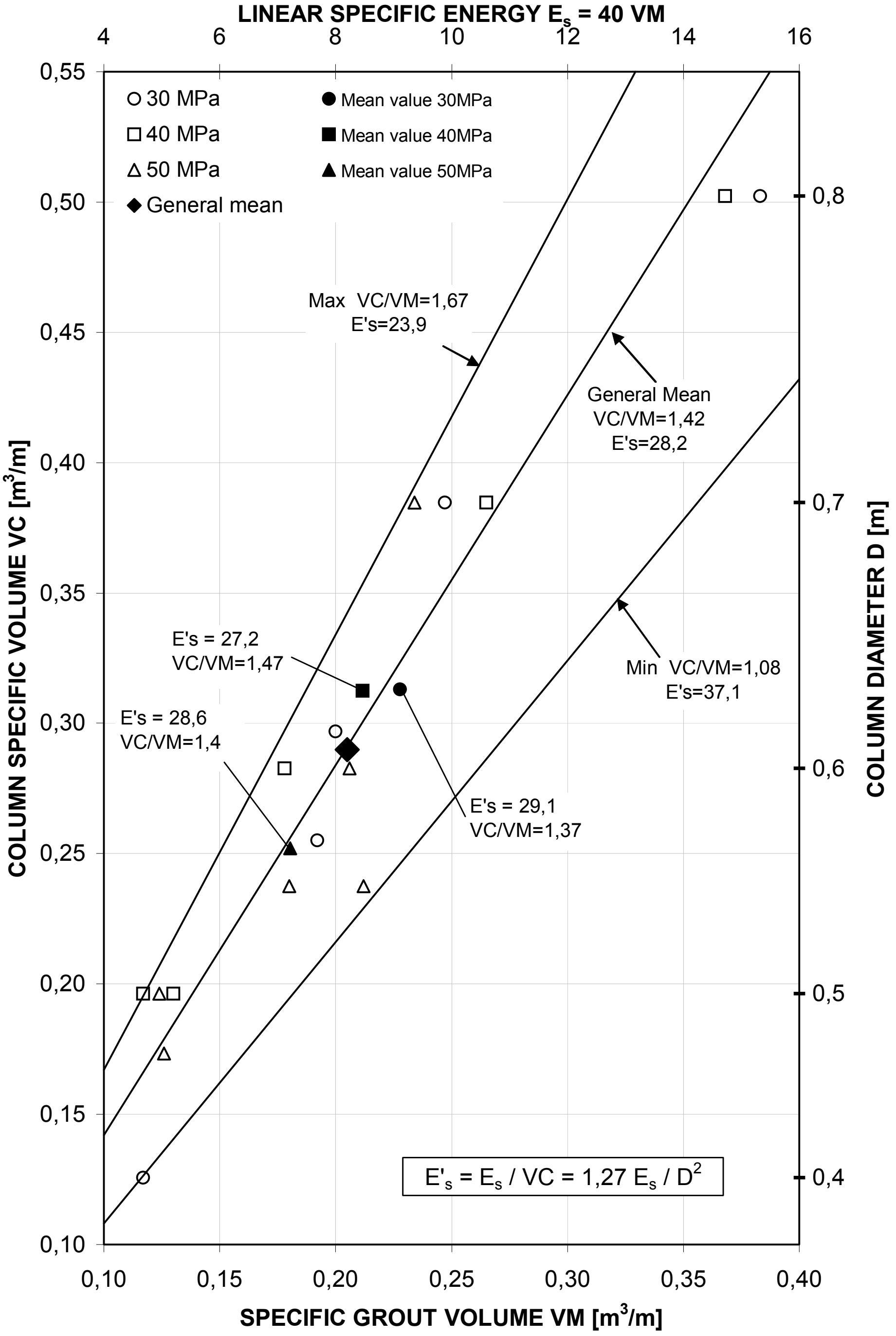


Figure 3. Evaluation of volumetric specific energy
(Case 1A: Varallo Pombia field trial)

We may remark that the mean VC/VM values are practically identical, with a general average of 1,42, corresponding to a volumetric specific energy E'_s = 28,2 MJ/m^3 with E_s = 40.VM, according to the formula (4a) proposed in para. 1.1.

The only case where pressure seems to have a significant influence is the Casalmaiocco field trial, where the two extreme pressures of 30 and 50 MPa have been used on a smaller number of columns (7 in all).

As shown in fig. 4 the higher pressure involves an increase of VC/VM ratio and a consequent decrease of E'_s if formula (4a) is used as in the Varallo P. case.

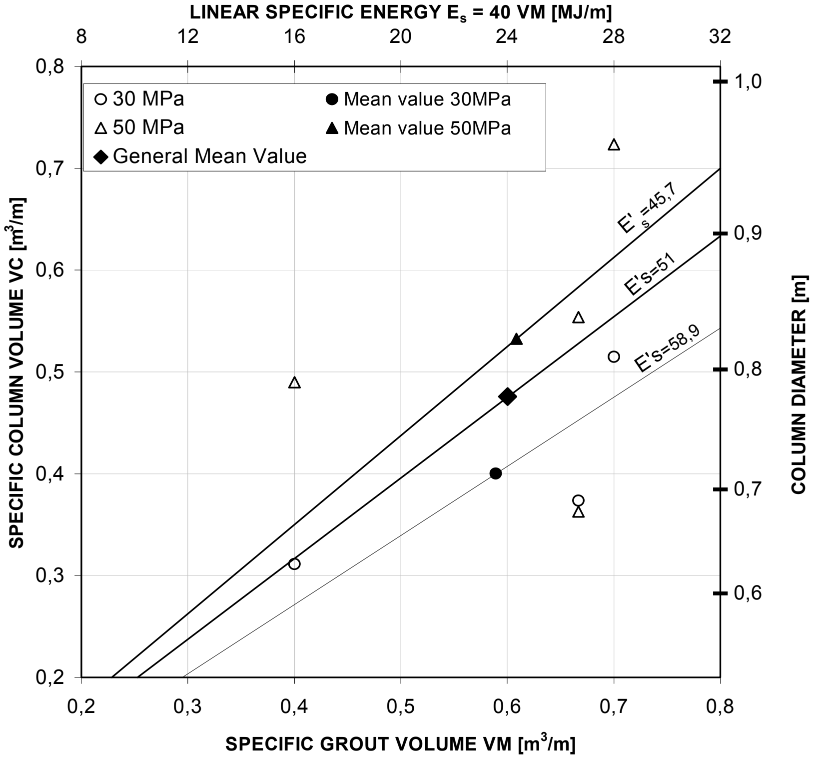
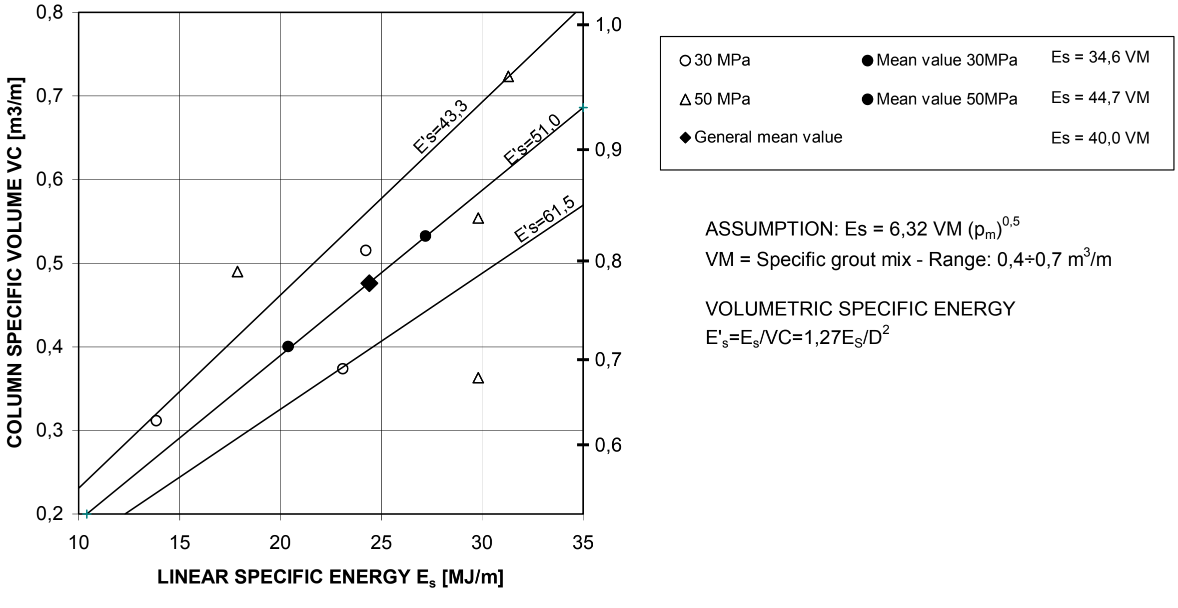


Figure 4. Evaluation of volumetric specific energy (Case 2: Casalmaiocco field trial)
Assumption (a) – see table II



ASSUMPTION: $E_s = 6{,}32\ VM\ (p_m)^{0,5}$
VM = Specific grout mix - Range: 0,4÷0,7 m^3/m

VOLUMETRIC SPECIFIC ENERGY
$E'_s = E_s/VC = 1{,}27 E_S/D^2$

Figure 5. Evaluation of volumetric specific energy (Case 2: Casalmaiocco field trial)
Assumption (c) – see table II

On the contrary the assumption of E_s increasing with p, expressed by correlation (4) leads to a greater mean value of volumetric specific energy E'_s with higher pressure.

The same value of E'_s with both pressures is obtained by the following expression of treatment energy:

$$E_S = 6{,}32 \cdot VM \cdot \sqrt{p} \tag{7}$$

as shown in fig. 5

The results obtained by the three alternative assumptions are summarized in Table II

Table II. Casalmaiocco field trial

Single fluid system. Alternative assumptions on the influence of pressure for the evaluation of specific energy parameters (Case 2: Casalmaiocco field trial, single fluid system)

ASSUMPTION		P [MPa]	E'_s [MJ/m^3]	
				MEAN
a)	E_s= 40VM	30	58,9	50,5
		50	45,7	
b)	E_s= p VM	30	44,2	52,6
		50	57,1	
c)	E_s= 6,32 VM $(p)^{0,5}$	30	51,0	51,0
		30	51,1	

Anyway the general mean value of E'_s is about 50 MJ/m^3 with all the assumptions.

The complete data of all the ten reviewed case histories (plots of VC versus E_s and resulting E'_s ranges) are represented in fig. 6, subdivided in two groups.

The upper graph refers to the four cases where the lowest values of volumetric specific energy have been found out (about 20 to 30 MJ/m^3).

In the other 6 cases the range of E'_s is between 30 and about 70 MJ/m^3 (medium-high energy required).

Table III. Single fluid jet grouting. Summary of energetic parameters and columns sizes

CASE RECORD No		NUMB. OF COLUMNS	E_s [MJ/m]		D [m]		E'_s [MJ/m^3]		NATIVE SOIL TIPOLOGY	
			RANGE	MEAN	RANGE	MEAN	RANGE	MEAN		
3	S.BENEDETTO	2		8		0,69		21,4	MEDIUM LOOSE SILTY SAND	A
6	COMO	1		8,4		0,7		22	SOFT PEATY SOIL	
1A	VARALLO	17	4,7÷15,3	8,2	0,40÷0,80	0,61	23,7÷37,3	28,2	GRAVEL IN SILTY SANDY MATRIX	
4	NEAPLES	6	9,7÷25	17,1	0,66÷0,95	0,84	27,1÷35,7	30,7	SILTY SAND WITH SOME GRAVEL (PYROCLASTIC)	
8	SINGAPORE			10		0,63		32	SOFT SILTY CLAYEY SOILS (C_U<0,03 Mpa) MED.-HIGH PLASTICITY	B
9	OUED NIL			12		0,64		37		
7	MAZZE'		12÷20	16	0,60÷0,80	0,7	39,8÷42,5	41,1	GRAVEL IN SILTY SANDY MEDIUM STIFF MATRIX	
2	CASALMAIOCCO	7	13,9÷31,3	24,3	0,63÷0,96	0,78	36,5÷61,5	51	STIFF SANDY (CLAYEY) SILTS (LOW-MEDIUM PLASTICITY) C_U>0,05 Mpa	C
5	AREZZO	2		16		0,63		51,3		
1B	VARALLO	9	4,7÷8,5	6,6	0,30÷0,45	0,39	39,5÷75,3	56,5		

The following main data are listed in the summary of Table III:

- number of columns with directly measured size
- ranges and mean values of treatment specific energy, diameter and resulting values of volumetric specific energy.

The case records are listed in increasing order of E'_s and subdivided in three groups, with a brief description of involved soils.

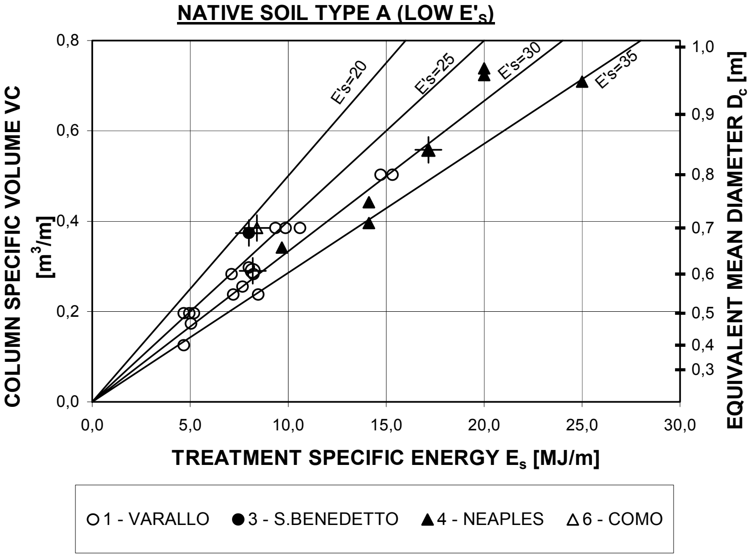
In group (A) (E'_s = 20-30 MJ/m^3) we have a medium-loose silty sand (case 2), gravel and silty sand, with the coarser granular fraction prevailing in case 1A, and silty sand prevailing in case 6; a quite different type of soil (soft fibrous peat with a silty-clayey matrix) is included as well in this group.

The intermediate group (B) (E'_s = 30+45 MJ/m^3) is represented by a soil similar to that of case 1A (Varallo P.), but with a finer and stiffer silty-sandy matrix (case 7).

The two cases of silty-clayey soils characterized by medium-high plasticity and low consistency (c_u lower than 0,03 MPa in general) are included as well in this group (cases 8-9).

Single E'_s up to 75 and mean values up to nearly 60 MJ/m^3 (group C) have been found in three cases (1B,2,5) on stiff sandy and sandy-clayey silts of low-medium plasticity (c_u > 0,05 MPa).

The wider scattering of data in the field trials of Casalmaiocco and Varallo Pombia (1B) means that on these types of soils we are at the practical limit of a convenient and effective use of the single fluid system.



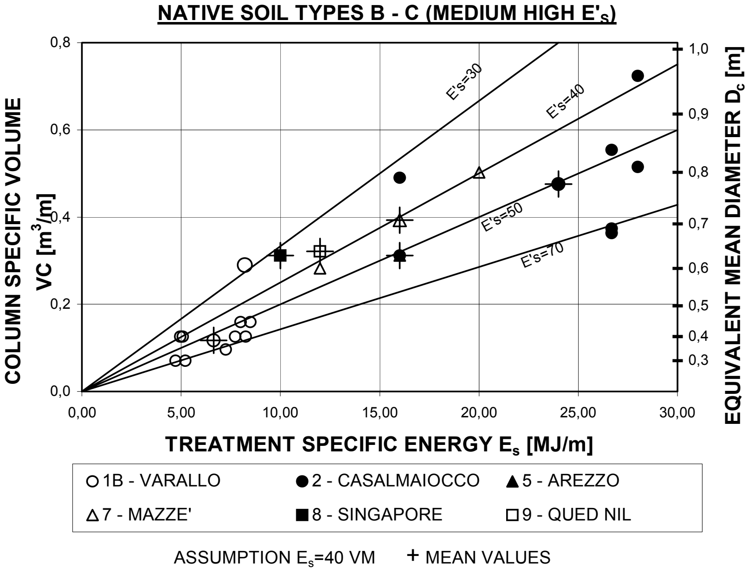
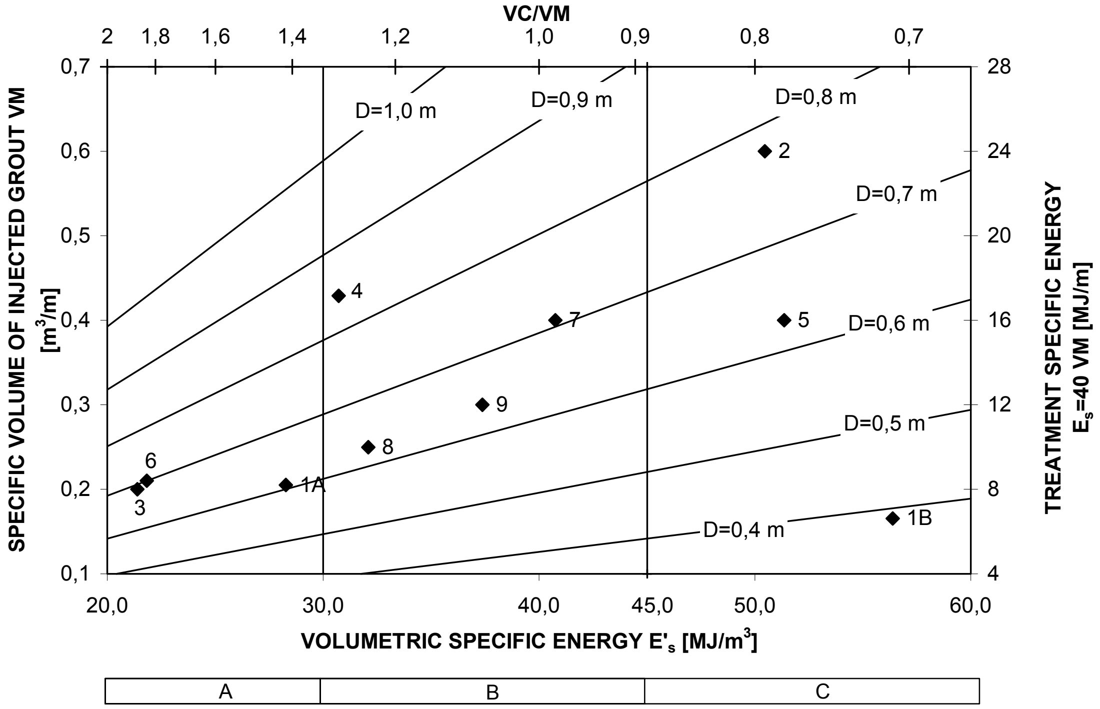


Figure 6. Single fluid system. Summing up of case records.
Volumetric specific energy resulting from treatment specific energy and assessed size of columns

The diagram of fig. 7, where the mean data of case records are plotted, enables the selection of treatment energy E_s as a function of the required diameter, according to the soil energetic parameter E'_s.



FOR SOIL TYPOLOGY OF GROUPS A, B, C SEE TABLE III

Figure 7. Single fluid system. Summing up of mean data.
Diameter of columns as a function of the ratio of linear to volumetric specific energy

1.3.3. Double fluid system

The experimental data of 4 case records are shown in the upper graph of fig. 8 (specific volume of jet grouted soil as a function of treatment specific energy) and summarized numerically in Table IV (ranges and mean values of diameter and energetic parameters).

The greater number of columns (14) has been tested in the Casalmaiocco trial field (case 2).

With treatment energy ranging between about 15 and 80 MJ/m, diameters of about 1,2 up to 2,2 m have been obtained.

The resulting volumetric energy is within about 10 and 30 MJ/m^3; the mean value (18,7) is nearly one third of that found in the same site for the single fluid system (51).

In the S. Benedetto trial field (case 3) diameters of 1,4-1,6 m have been measured, recording a volumetric specific energy of 15,6 MJ/m^3 on an average, i.e. not much lower in comparison with the Casalmaiocco case (18,7) and much closer to the mean value recorded by the single fluid system (21,4).

Since the two types of soil represent the extreme cases of low and high E'_s related to the single fluid system, an explanation may be as follow:

- the additional fluid (air) does not modify sensibly the required specific energy when fairly low in the single fluid system
- in this case the advantage is the possibility to reduce the amount of cement, diameters being equal, or to obtain greater sizes limiting the specific grout volume
- as remarked at the end of the preceding paragraph, E'_s values higher than 40-50 MJ/m^3 are beyond the practical limit for a convenient use of the single fluid system; an important energetic contribution of air (20-40%), as in the Casalmaiocco case, reduces greatly the required specific energy per unit soil volume, making similar two soils so different when treated by cement grout only.

In the Como site (case 6) the treatment of a fibrous peaty soil has been carried out after air-water prejetting.

The calculated E'_s value is about 19 MJ/m^3 on an average, that is actually the same as in case 2, and not much different in comparison with the single fluid mean (22); as we shall see about the triple fluid system, a higher energy would be necessary without prejetting.

No direct comparison with other systems is possible in the Venice case, since the double fluid jet only has been applied.

In similar soil conditions (cases 8,9) mean E'_s values of 32-37 MJ/m^3 had been estimated for single fluid jet; consequently the volumetric specific energy related to the double fluid in the Venice case (35) is likely to be similar as for a single fluid treatment.

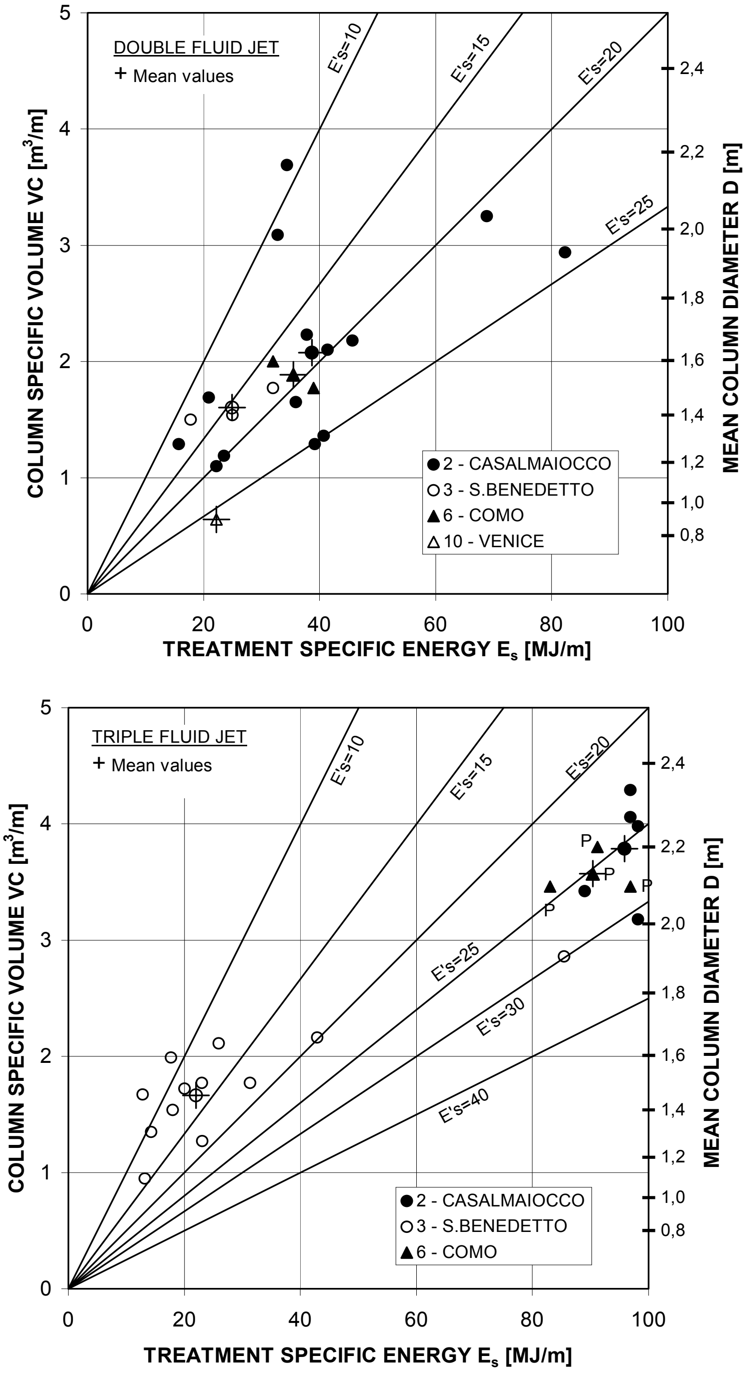


Figure 8. Double and triple fluid jet grouting: summing up of case records.
Volumetric specific energy resulting from the correlation between treatment specific energy and assessed size of jet columns

Table IV. Double and triple fluid jet grouting.
Summary of energetic parameters and column sizes

	CASE RECORD		NUMB. OF COLUMNS	E_s [MJ/m]		D [m]		E'_s [MJ/m^3]		REMARKS
				RANGE	MEAN	RANGE	MEAN	RANGE	MEAN	
DOUBLE FLUID JET	2	CASALMAIOCCO	14	15,7÷82,3	38,7	1,18÷2,17	1,63	9,3÷30,4	18,7	
	3	S.BENEDETTO	3	17,8÷32	24,9	1,38÷1,50	1,43	11,9÷18,1	15,6	
	6	COMO	2	32÷39	35,5	1,50÷1,60	1,55	16÷22	18,9	WITH AIR-WATER PREJETTING
	10	VENICE			20		0,85		35,3	
TRIPLE FLUID JET	2	CASALMAIOCCO	5	89÷98,2	95,8	2,01÷2,34	2,2	22,6÷30,9	25,3	
	3	S.BENEDETTO	11	12,8÷42,9	22	1,1÷1,66	1,4	7,7÷19,9	13,3	
	6	COMO	2		76,7		1,5		43,4	
			3	83÷96,9	90,4	2,10÷2,20	2,13	24÷28	25,3	WITH AIR-WATER PREJETTING

1.3.4. Triple fluid system

The experimental data of the same case records as above (except Venice) are shown in the lower graph of fig. 8 and summarized numerically in Table IV.

The greater number of columns (11) has been tested in the S. Benedetto trial field (case 3).

With treatment energy between 18 and 32 MJ/m, a range of diameters from 1,1 up to nearly 1,7 m has been ascertained.

The resulting volumetric energy is within about 8 and 20 MJ/m^3; the mean value (13,3) is of the same order as estimated for the double fluid treatment (15,4).

In the Casalmaiocco trial field, higher specific energy has been used (about 90-100 MJ/m) obtaining 2-2,3 m diameters; on an average the volumetric specific energy (25 MJ/m^3) is somewhat greater with respect to the double fluid jet, but still remarkably smaller than estimated for the single fluid system.

Identical mean E'_s values characterize the quite different soils of Casalmaiocco and Como (the latter with prejetting); without prejetting the peaty soil required a much greater specific energy (43 against 25 MJ/m^3).

1.3.5. Closing remarks on multifluid systems

In the diagram of fig. 9 (such as in fig. 7 for single fluid jet) the mean data of double and triple fluid treatments are plotted in terms of E_s as a function of E'_s and the ranges of diameters:

$$D = 1{,}13 \cdot \sqrt{E_S / E'_S} \tag{8}$$

are represented.

We may remark briefly:

- the energetic parameter E'_s is fairly similar for both double and triple systems
- the influence of soil conditions is smaller than for single fluid jet grouting
- in fact the mean E'_s values are within 13 and 25 MJ/m^3, against a range of 21 to 51 in the same set of case records, with a few exceptions in the cases of Como and Venice, where a less exhaustive documentation is available for comparison.

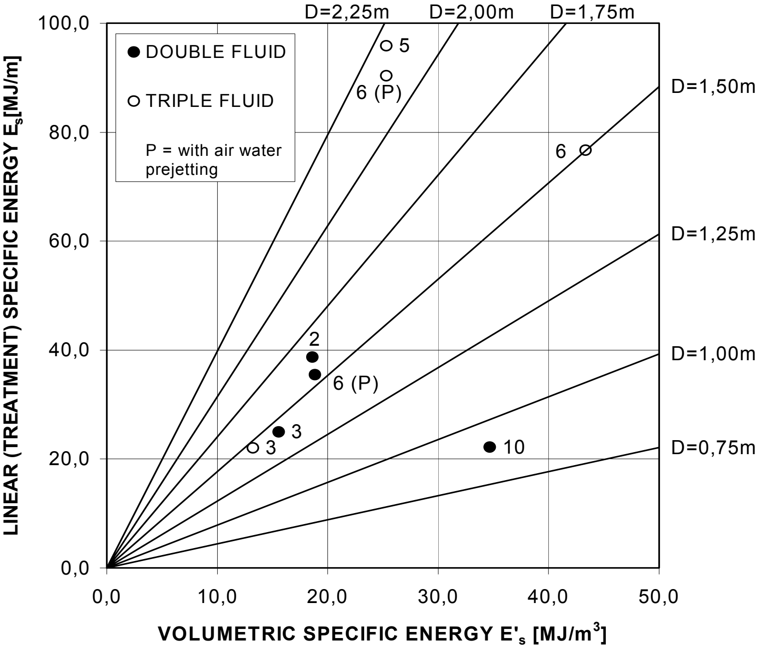


Figure 9. Double and triple fluid system. Summing up of size of jet grouted columns resulting from the correlation between linear and volumetric specific energy (mean values)

2. CONTROL CRITERIA

2.1. Introduction

In order to check the design assumptions, whenever visual inspection is not possible, or not sufficiently deep, information about the cross-sectional dimensions would require a network of continuous corings, properly distributed and inclined.

The costs related to deep dimensional controls strengthen the need of analytical approaches exploiting preliminary information and the results of quantitative and qualitative controls on jet grouted soil columns and ejected material (spoil return).

Coring of jet columns and simple laboratory tests on cured samples (to evaluate volumetric and mechanical properties) should be an usual practice, with modes and frequency planned according to the importance and delicacy of the problems.

The quantification of spoil is necessary, particularly during the treatment of fine grained soils where the flow rate of spoil must be sufficiently high (with respect to that of injected grout) to avoid excessive lateral soil displacements and surface lifting.

This control, even if discontinuous, should be frequent enough to enable timely operational adjustments and the evaluation of reliable quantitative data on an average.

As regards the input data for final analytical balances, the qualitative control of spoil samples (by the same laboratory testing procedure used for treated soil samples), generally neglected , is the only additional requirement outside current recommended practice.

The estimate of composition of treated soil and spoil is the first step of data processing for statistical balances aimed to improve the understanding of soil modifications, leading to useful information such as:

- the specific volume of treated soil, i.e. the mean diameter of columns
- the specific volume of native soil involved by the treatment (range of jet action)
- the possible displacement of surrounding soil if the former is greater.

Moreover it is worth remarking that the above estimates may be related to any depth interval, according to soil profile, when volumetric characteristics of native soil are known.

The above evaluations are simpler and more reliable just where they are more useful and when undisturbed sampling of native soil is easier, that is for the improvement of soft cohesive soils, where the following assumptions may be made:

- full saturation of samples
- no significant drainage occurred during the treatment.

Consequently single fluid system only will be dealt with.

2.2. Composition of jet grouted soil and spoil

The evaluation of composition (in terms of cement, dry soil and water contents) may be made by various analytical procedures according to available experimental data, besides bulk density and evaporable water content.

Three types of approach are presented and discussed:

(a) - based on direct determination of cement content by standard chemical analysis

(b) - based on the correlation between u.c. strength and cement /(total water) ratio C/W, according to statistical records, or better to preliminary tests on slurries with variable C/W ratio

(c) - based on the (hydration water)/cement ratio W_h/C according to statistical assumptions or to preliminary tests on samples with known C and W contents; the hydration water results from the difference ($W-W_e$) between total and evaporated water (by standard oven-drying).

The availability of data enabling to try different approaches and adjustments for congruence, leads to more reliable results as a basis for further evaluations.

2.2.1 Procedure (a)

The determination of cement content C in the unit volume of samples (according to the standard method used for concrete quality control) is based on soluble silica content to be evaluated: on the samples with cement and dry soil as solid components and on single components.

The dry soil content is

$$S = p' - q' \cdot C \quad (\mathrm{t/m^3}) \tag{9}$$

where:

$$p' = \frac{\gamma - 1}{1 - 1/G_S} \tag{10}$$

$$q' = \frac{1 - 1/G_C}{1 - 1/G_S} \tag{11}$$

γ (t/m^3) = bulk density

G_s, G_c (t/m^3) = specific gravity of soil and cement.

This procedure is the most reliable, since it doesn't require statistical assumptions or preliminary calibration tests, but unfortunately it is by far the most expensive one when executed accurately on a sufficiently representative number of samples.

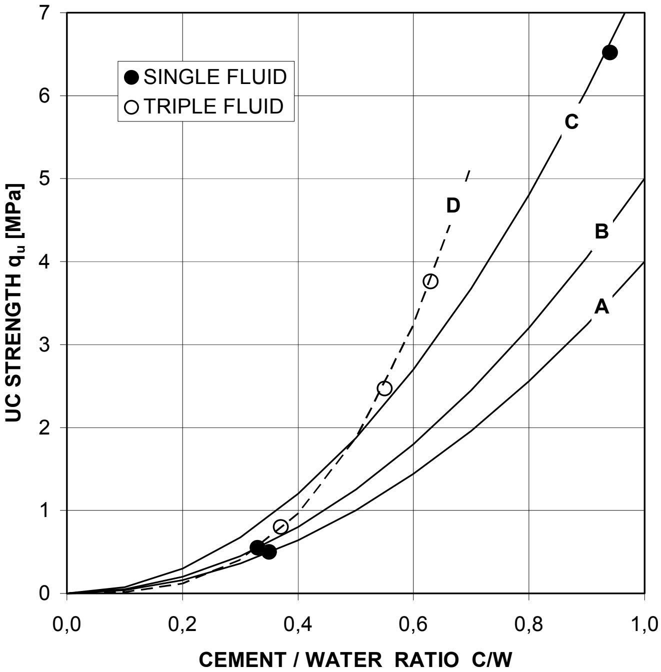
Nevertheless a few direct determinations of cement content are advisable to check the results of the following indirect methods.

2.2.2. Procedure (b)

The most frequently used approach (see some of the papers quoted in the references) is based on the correlation between unconfined compression strength q_u and the cement/water ratio C/W according to the general formula:

$$q_u = q_{u0} \cdot \left(C/W\right)^n \tag{12}$$

For any soil-grout couple and curing age, the strength index q_{uo} and the exponent n may be evaluated by means of preliminary tests on mixes with variable total C/W ratio.



CASE	NATIVE SOIL	J.G. SYSTEM	GROUT C/W	TREATED SOIL (MEAN VALUES)					
				γ [t/m^3]	C/W	C $^{(§)}$ [t/m^3]	q_u [Mpa]	q_{u0} [Mpa]	n
A	SOFT SILTY PEATY CLAY	SF	0,6	1,41	0,35	0,268	0,5	4	2
B	MEDIUM SOFT CLAYEY SILT	SF	0,5	1,6	0,33	0,216	0,55	5	2
C	SOFT CLAYEY SILT	SF	1,25	1,72	0,94	0,596	6,52	7,5	2
D	PEATY SOIL	TF WITH PREJETT.	1,4	1,34	0,37	0,297	0,8	15	3
				1,45	0,55	0,296	2,47		
				1,45	0,63	0,460	3,76		

(§) C = CEMENT CONTENT

Figure 10. UC strength as a function of cement/water ratio (typical cases)

From a statistical analysis of experimental data we may infer on an average: n=2, so that C/W may be estimated as follows:

$$\left(C/W\right) = \sqrt{q_u / q_{u0}} \tag{13}$$

The strength index q_{uo} depends on various factors such as:

- type of cement
- physical characteristics of soil (mineralogy, grain size distribution, plasticity, possible organic content) and water in abnormal cases
- curing age.

In general for inorganic fine grained soils, normal Portland cement and ages between 1 and 2 months the strength index may range between 4 and 8 MPa.

The graph and table of fig. 10 show the results obtained in three cases (A,B,C) of single fluid treatments in soft silty-clayey soils and in the Como case, where the triple fluid system with prejetting was used for the improvement of a peaty soil (see par. 1.3.1.).

As regards the single fluid treatments we remark:

- the lowest q_{uo} and q_u values have been recorded in cases A-B, where similar soils have been treated with a grout poor in cement (C/W = 0,5-0,6)

- in case C, the higher strength index is likely due to a concurrence of factors as the soil mineralogy and the finer grain size of cement; the higher stregth is related also to the greater C/W ratio of the grout (1,25) and hence of the treated soil.

In the triple fluid case a very wide scattering of strength data were obtained, due to the variable distribution of fibrous peat and clayey soil and consequent variable effects of prejetting and jet grouting.

The data shown in fig. 10 are the averages of 3 ranges of strength (from 0,80 to 3,76 MPa), and corresponding C/W (from 0,37 to 0,63) well fitting in a curve defined by: $n = 3$ and $q_{u0} = 15$ MPa

The dry soil/total water ratio is given by:

$$S/W = p - q \cdot (C/W) \tag{14}$$

Where

$$p = \frac{\gamma - 1}{1 - \gamma / G_S} \tag{15}$$

$$q = \frac{1 - \gamma / G_C}{1 - \gamma / G_S} \tag{16}$$

When the specific gravity values have been selected, p and q depend on bulk density only.

When bulk density is known, a linear correlation enables to determine S/W as a function of C/W, as shown in the example of fig. 11, and hence the composition in terms of C,S,W contents, by simple proportions.

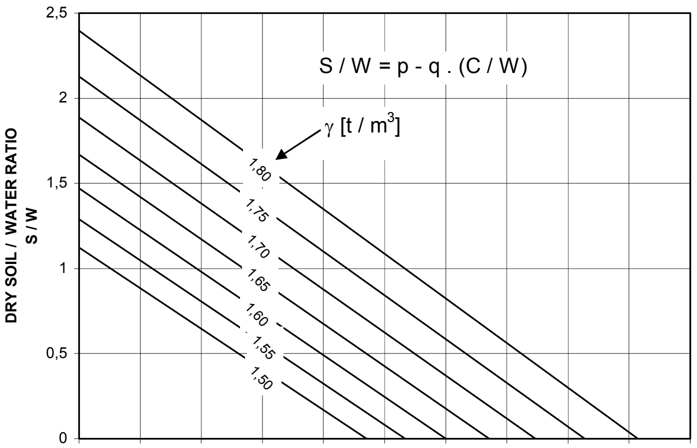


Figure 11. Dry soil / water ratio as a function of bulk density and cement / water ratio

The plots of fig. 12 represent the cement and water contents as a function of bulk density and cement/water ratio.

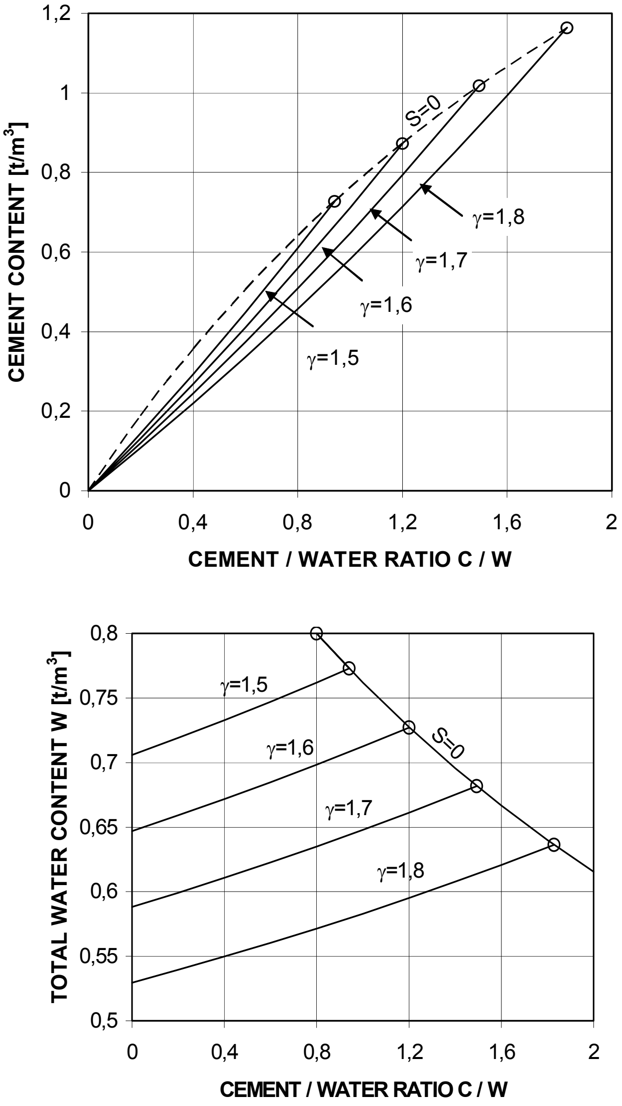


Figure. 12 Cement and total water content as a function of cement / water ratio and bulk density (G_c = 3,2 t/m^3 – G_s = 2,7 t/m^3)

2.2.3 Procedure (c)

This procedure is based on the preliminary determination or on a statistical estimate of the ratio:

$$\beta = W_h / C$$

of hydration (non evaporable) water to cement, that may be expressed as a function of C/W and of the following conventional laboratory data:

- specific gravity of cement (G_c) and soil (G_s)
- bulk density γ
- evaporable water content W_e

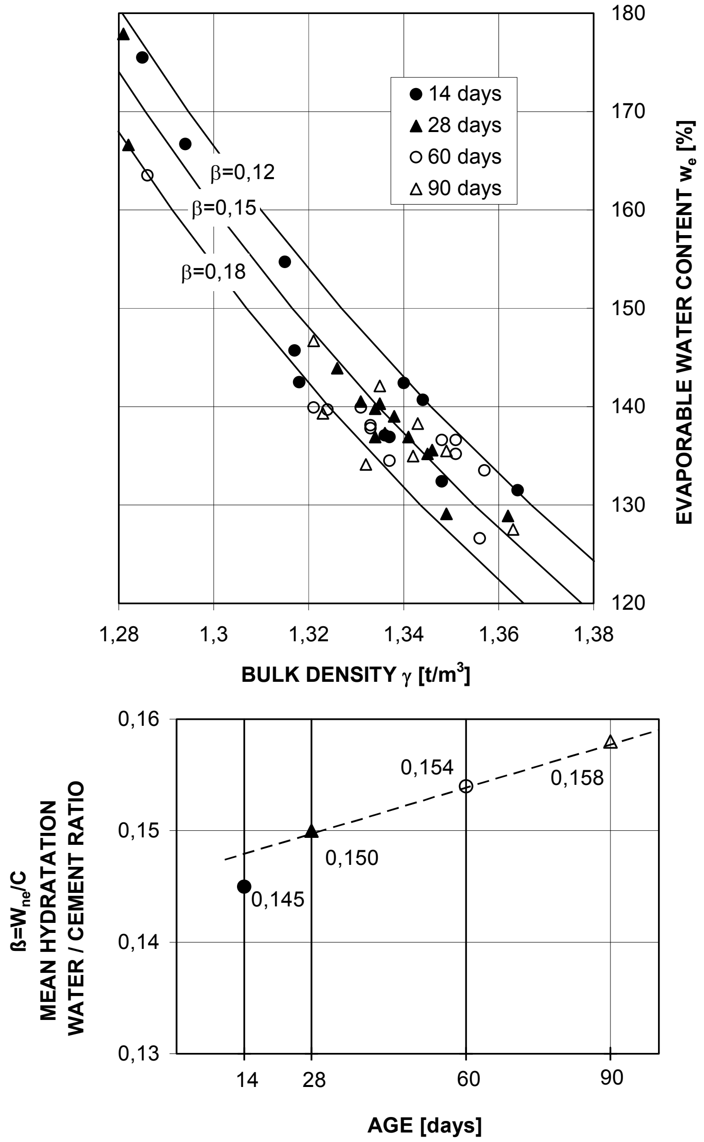


Figure 13. Direct determination of hydration water / cement ratio β on cement-bentonite mixes

by the following data processing:

$$\beta = \frac{W}{C} - \frac{W_e}{C} \tag{17}$$

$$\beta = \gamma \cdot \frac{C/W}{C/W + S/W + 1} \tag{18}$$

$$\beta = \frac{1}{C/W} - \frac{W_e \cdot (1 - S/W + C/W)}{\gamma} \tag{19}$$

$$S/C = \frac{S/W}{C/W} = \frac{p}{C/W} - q \tag{20}$$

$$\beta = F1 + F2 \cdot C/W \tag{21}$$

$$F1 = W_e \cdot \frac{(q-1)}{\gamma} \tag{22}$$

$$F2 = 1 - \frac{W_e \cdot (1 - 1/G_t)}{(1 - \gamma/G_t)} \tag{23}$$

$$C/W = \frac{F2}{\beta - F1} \tag{24}$$

The (hydration water) / (cement) ratio β may range between 0,1 and 0,2 as stated in specifications for concrete quality control and confirmed by an exhaustive documentation on cement-soil mixes, with a trend to increase with time.

Fig. 13 shows the results of a research on cement-bentonite mixes tested after 14-28-60-90 days.

The upper graph presents a plot of evaporable water content against bulk density, with resulting β values in a range between 0,12 and 0,18.

On an average, a slight increase with time is observed; a general mean of 0,15 might be assumed in this case.

2.3. Congruence checks

Two different approaches at least are required in order to find a congruence, if possible, or to select the most reliable one, according to circumstances, such as quantity and scattering of data, testing accuracy and availability of preliminary calibrations as regards procedures (b) and (c).

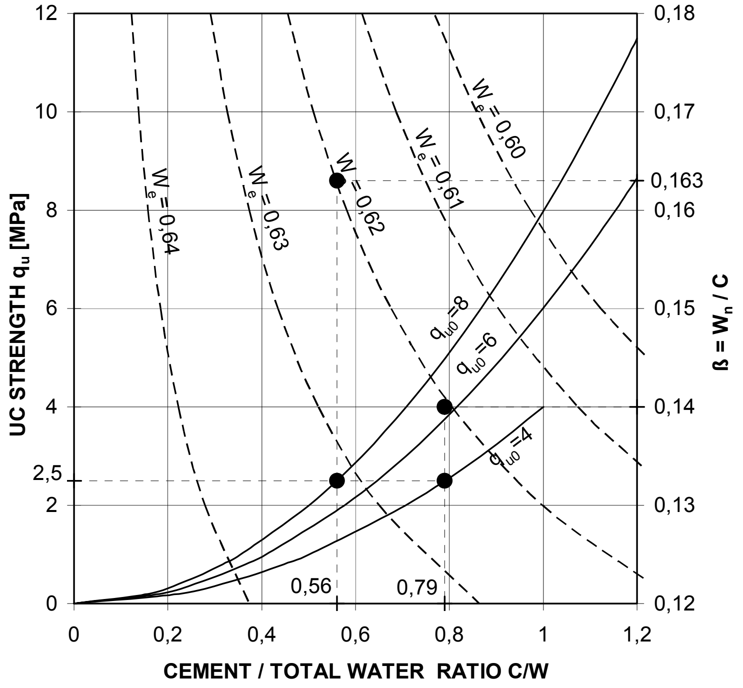


Figure 14. Example of congruence check for the estimate of cement / water ratio

In the example of fig. 14 we have considered a sample with ascertained volumetric characteristics (γ,G_c,G_s,W_e) and compressive strength q_u.

Two families of reference curves are shown representing as a function of C/W:

- compressive strength for values of strength index q_{uo} between 4 and 8 MPa (range of widest statistical variability)
- hydration water/cement ratio β for evaporable water contents W_e between 0,60 and 0,64.

We may remark:

- relying on the experimental value of W_e (0,62) the C/W ratio should be selected between 0,56 and 0,79 according to q_{u0}; anyhow the correspondent β range (0,14÷0,163) is quite normal;
- hence the final selection of C/W would be made easier by a reduction (based on experience in similar cases) of the probable q_{uo} range
- relying on the strength index, the range of W_e values compatible with β smaller than 0,2 (statistical limit) is very narrow.
- consequently oven drying data must be very accurate and, above all, obtained on undisturbed fully saturated samples;
- otherwise the discussed procedure for composition estimate is not valid, since leading to an overestimate of total water content with respect to cement and consequently of the β ratio; β values remarkably higher than 0,2 may be the evidence of unsaturated conditions
- if the only anomaly may be supposed to be a loss of water by evaporation after the sample recovery, with negligible volume change, a correction can be made by the estimate of the water loss and recalculation of the original and final compositions.

2.4. Exploitation of composition data

2.4.1. Estimate of column size

When the specific volumes of injected grout (VM) and ejected spoil (VSP) are known, the compositions calculated with reference to unit volume may be related as well to the unit length of column.

The cement content C'_c(t/m) is the difference between the injected amount C'_i and that contained in the spoil (C'_{sp}).

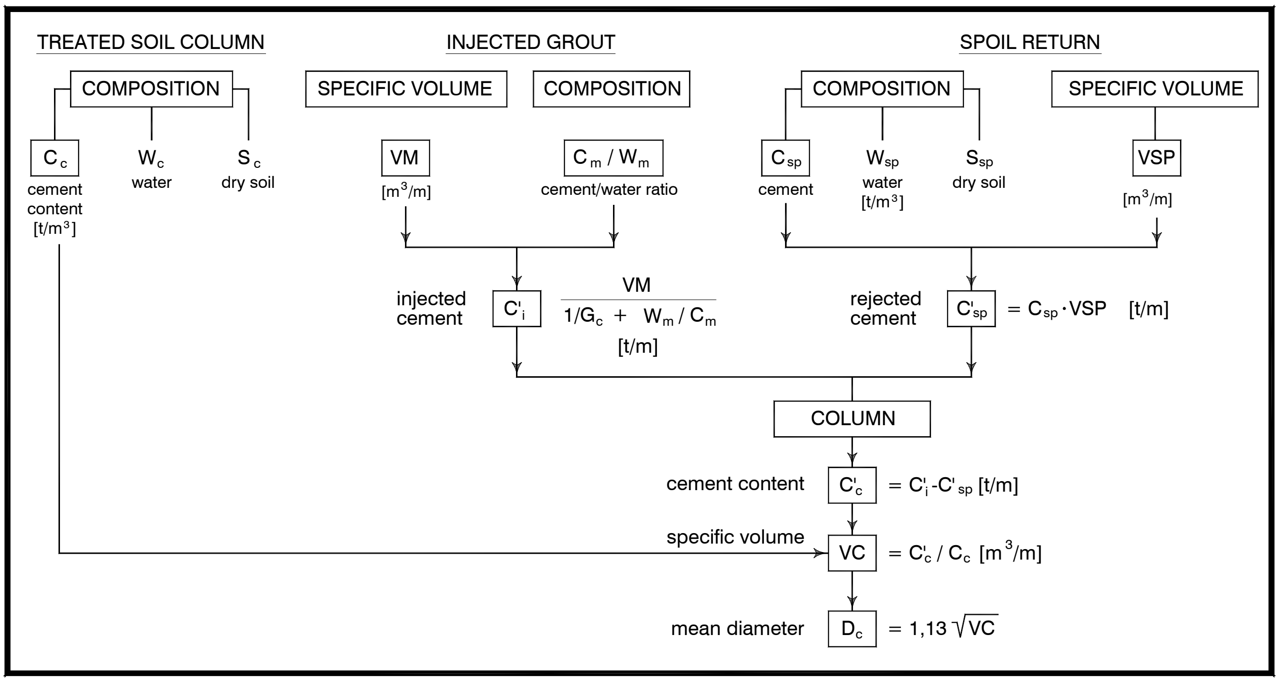


Figure 15. Exploitation scheme of operational and experimental control rate for the indirect estimate of jet grouted columns size (Tornaghi 1989)

Since the ratio of C'_c to the weight per unit volume C_c corresponds to the specific volume of treated soil VC, we may draw the *mean diameter* D_c of the column, as shown in the scheme of fig. 15.

Two numerical examples of data processing are given in table V, relating to important sites where single fluid jet grouting has been applied widely.

Table V. Examples of data exploitation according to the procedures summarized in fig. 15

CASE RECORD	SINGAPORE	OUED NIL (ALGERIA)	CASE RECORD	SINGAPORE	OUED NIL (ALGERIA)
VM [m^3/m]	0,250	0,300	C_{sp} [t/m^3]	0,175	0,713
C_m/W_m	0,600	1,200	W_{sp} [t/m^3]	0,642	0,657
C'_i	0,125	0,262	S_{sp} [t/m^3]	0,797	0,336
q_{u0} [MPa]	7,000	7,500	VSP [m^3/m]	0,225	0,075
q_u [MPa]	1,090	7,800	VSP/VM	0,900	0,250
C_c/W_c	0,390	1,020	C'_{sp} [t/m]	0,039	0,053
C_c [t/m^3]	0,276	0,648	C'_C [t/m]	0,086	0,209
W_c [t/m^3]	0,699	0,634	VC [m^3/m]	0,312	0,322
S_c [t/m^3]	0,556	0,458	VC/VM	1,250	1,070
$q_{u\ sp}$ [MPa]	5,200	8,800	MEAN DIAMETER D_C [m]	0,630	0,640
C_{sp}/W_{sp}	0,270	1,090			

The resulting similar diameters (in spite of very different imput data, as regards cement content in the grout, in the spoil and in the column, and spoil return with respect to injected grout volume) are in very good agreement with design target and direct controls.

2.4.2. Estimate of jet range of action

The dry weight of involved soil per unit column length is the sum of the contents S'_c in the column and S'_{sp} in the spoil:

$$S'_C = S_C \cdot VC \qquad S'_{sp} = S_{sp} \cdot VSP \qquad \text{(t/m)} \tag{25}$$

where VC and VSP are the specific volumes of column and spoil per unit length.

Hence the total dry soil weight involved by the treatment is:

$$S'_A = S'_C + S'_{sp} \tag{26}$$

If the dry density of native soil γ_d is known (t/m^3) the volume of native soil within the jet range of action is:

$$V_S = \frac{S'_A}{\gamma_d} \qquad (\text{m}^3/\text{m}) \tag{27}$$

corresponding to a diameter of action:

$$D_A = 1{,}13\sqrt{V_A} \qquad (\text{m}) \tag{28}$$

When the column diameter D_c is fairly greater than D_A, a lateral soil displacement is likely, and it may be approximately quantified in terms of specific volume:

$$\Delta V = VC - V_A \qquad (\text{m}^3/\text{m}) \tag{29}$$

Considering as an example the Singapore case (Table V) this approach leads to the following results, assuming $\gamma_d = 1{,}265$:

$$S'_c = 0{,}1735 \qquad S'_{sp} = 0{,}1795 \qquad S'_A = 0{,}353$$

$$V_A = 0{,}279\ m^3/m \qquad D_A = 0{,}597\ m \qquad \Delta V = 0{,}033\ m^3/m$$

$$VC / V_A = 1{,}12 \qquad D_c / D_A = 1{,}06$$

This analytical balance confirms the negligible magnitude of observed upheaval , due to the high amount of spoil with respect to injected grout (VSP/VM = 0,9 on an average), whereas in the Oued Nil site the low VSP/VM ratio (0,25) involved significant soil displacements (allowable in this case and enhancing the column size).

2.4.3. Volumetric grout content

Still on the assumption of saturated fine grained soil with a low permeability and therefore in undrained conditions, it is allowable to assume that both cement grout and native soil preserve their composition in the column and in the spoil as well.

Hence the composition may be expressed in terms of volumetric contents of the two components.

The specific volume of grout is:

$$V_m = C/G_C + C/\alpha_m \tag{30}$$

where

C, G_C = content and specific gravity of cement

α_m = cement/water ratio of the grout.

In the Singapore case (Table V) we obtain:

- in the column: $V_{mc} = 0{,}276/3{,}2 + 0{,}276/0{,}6 = 0{,}546 = 54{,}6\%$
- in the spoil : $V_{msp} = 0{,}175/3{,}2 + 0{,}175/0{,}6 = 0{,}346 = 34{,}6\%$

From the Oued Nil case we draw remarkably higher values (74% in the treated soil and 82% in the spoil), but this is an abnormal case with lacking spoil return in a cohesive soil.

2.4.4. Congruence check

With the above assumptions of unchanged compositions, the water content of the soil component must be the same in the column and in the spoil, and in fairly good agreement with preliminary soil investigation data.

Still considering the Singapore site we have

- in the column: $W_{sc} = 0{,}699 - 0{,}276/0{,}6 = 0{,}239$
  $W_{sc} / S_c = 0{,}239/0{,}556 = 43\%$
- in the spoil : $W_{ssp} = 0{,}642 - 0{,}175/0{,}6 = 0{,}348$
  $W_{ssp} / S_{sp} = 0{,}348/0{,}797 = 43{,}7\%$

The congruence condition is well satisfied and moreover the resulting water content of native soil is consistent with mean actual values.

3. Conclusions

The proposed approach to the estimate of size of jet grouted elements has the advantage to take into account both soil conditions and operating parameters, expressed in terms of energetic parameters:

(a) - treatment linear specific energy, as a function of two operative parameters only: specific volume per unit length and pressure of injected fluids

(b) - volumetric specific energy, related to native soil and jet grouting system (single fluid or multifluid).

The statistical analysis of field trials data with direct size assessment, involving a wide range of soils and operating parameters, leads to a tentative classification of soils by a single parameter (b).

At the preliminary design stage, the treatment energy may be selected according to required column size and volumetric specific energy.

Assuming the mean value of pressure (40 MPa) within the current range, the conventional yield index VC/VM (specific volume ratio of treated soil to injected grout) may be simply correlated to volumetric specific energy E'_s [MJ/m^3]:

$$VC / VM = 40 / E'_s \qquad (31)$$

In the second part of the paper, the interesting topic of soft cohesive soils treated by the single fluid system is discussed with examples of case records chasing the widespread doubts about the effectiveness of jet grouting in fine grained soils.

As regards the input data for comprehensive analytical balances of treatment effects, the qualitative control of spoil samples (by the same testing procedure used for treated soil samples), often neglected, and a more frequent quantitative control of spoil return are the additional requirements outside current practice.

The estimate of composition of treated soil and spoil is the first step of data processing for evaluations leading to useful information such as:

- the specific volume of treated soil, that is the mean diameter of the jet columns
- the specific volume of native soil involved by the treatment (range of jet action)
- the possible displacement of surrounding soil, if the former is greater
- volumetric grout contents in the treated soil and in the spoil.

Different approaches have been used for congruence checks.

4. References

Balossi Restelli A. (1995) Il miglioramento dei terreni e delle rocce. Controlli sulla validità degli interventi. *XIX Convegno nazionale di Geotecnica, Pavia, Italy, pp. 447-463*

Balossi Restelli A., Tornaghi R, Pettinaroli A, Rovetto E. (2003) Reconstruction of La Fenice Theatre in Venice - Foundation problems. *XIII ECSMGE, Prague sept. 2003, Vol. 2 pp.29-34*

Croce P., Flora A. (1998) Jet grouting effects on pyroclastic soils. *Rivista Italiana di Geotecnica 2/98,5-14*

Croce P., Flora A. (2000) Analysis of single-fluid jet grouting. *Géotechnique 50 No 6 739-748*

De Paoli B., Tornaghi R., Bruce D.A. (1989) Jet grout stabilization of peaty soils under a railway embankment in Italy. *ASCE Conference on Foudation Engineering, Evanston, Illinois, 25-29 june*

Fruguglietti A., Roberti R., Tornaghi R. (1989) Fondazioni a pozzo di un ponte realizzate mediante consolidamento del terreno. *XVII Convegno di Geotecnica, Taormina, 26-28 aprile, Vol. I pp. 217-229*

Lunardi P., Mongilardi E., Tornaghi R. (1986) Il preconsolidamento mediante jet-grouting nella realizzazione di opere in sotterraneo. *Congr. Int: Grandi Opere Sotterranee, Firenze, vol. II, pp. 601-612*

Mongilardi E., Tornaghi R. (1986) Construction of large underground openings and use of grouts. *Int. Conf. Deep Foundations, Beijing (China), vol. II*

Tornaghi R. (1989) Trattamento colonnare dei terreni mediante gettiniezione (jet grouting). *XVII Convegno Nazionale di Geotecnica, Taormina 26-28 aprile, pp. 193-203*

Tornaghi R. (1993) Controlli e bilanci analitici dei trattamenti colonnari mediante jet grouting. *Rivista Italiana di Geotecnica 3/93, Vol II pp. 217-234*

Tornaghi R., Bosco B:, De Paoli B. (1988) Application of developed grouting procedures for tunnelling in the Milan urban area. *5th International Symposium Tunnelling 88, Londra, 18-21 aprile*

Tornaghi R., Perelli Cippo A. (1985) Soil improvement by jet grouting for the solution of tunnelling problems. *Proc. Tunnelling 85, Brighton, pp. 265-275*