Jet-Grouting effects on Pyroclastic soils
Effetti della Gettiniezione sui terreni Piroclastici

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Abstract

The effects of jet-grouting on pyroclastic soils are investigated by means of in situ measurements and laboratory tests, performed on both natural and cemented soils. Reported data include treatment parameters, soil properties, columns dimensions and mechanical characteristics of the cemented material. The experimental results are examined in detail, pointing out the influence of soil properties and treatment procedures. The percentages of removed soil and retained mortar are estimated by means of back-calculations, providing new information on the phenomena induced by jet-grouting. The mechanical behaviour of the cemented soil is interpreted with the criteria adopted for soft rocks.

1. Introduction

The use of jet-grouting for soil improvement has greatly increased, in recent years, replacing or modifying several traditional construction procedures of geotechnical engineering. Currently adopted methods can be subdivided in three main groups, depending on the number of fluids injected into the subsoil: namely grout (usually water-cement mortar), air+grout, water+air+grout. The fluids are injected at very high speed through small diameter nozzles placed on a grout pipe, which is rotated at constant rate and is slowly raised towards the surface.

The jet propagates radially, with respect to the treatment axis, inducing a mechanical phenomenon which may include remoulding and/or permeation, with or without partial soil removal. The injected mortar solidifies underground and eventually produces a cemented soil body, which is usually named jet-column. By appropriately arranging several columns in the subsoil, it is possible to solve different geotechnical problems (e.g. increasing bearing capacity and reducing settlements of new or existing foundations, supporting open and underground excavations).

Since the early stages of jet-grouting application [YAHIRO and JOSHIDA, 1973], attention was focused primarily on the development of very powerful and efficient equipment [SHIBAZAKI and OHTA, 1982; MIKI, 1985], with the aim to apply the method to all kinds of soils. Progressive experience has shown, however, that results depend on the combination of treatment procedures and geotechnical characteristics of the subsoil. Documented case histories [CHIARI and CROCE, 1991; CROCE *et al.*, 1994] have pointed out, in particular, that jet-grouting produces good and extensive cementing of coarse-grained soils, while treatment effectiveness is drastically reduced for fine-grained ones.

The experimental data obtained in such cases can provide a first estimate of jet-grouting results for similar employment conditions. Considering however the many possible combinations of soil properties and jet-grouting procedures, it appears that available data are still very limited. In fact, treatment procedures are usually specified on site, for each specific project, by means of trial and error tests. Unfortunately, results of such tests remain frequently unpublished and only few of them are analysed in sufficient detail. Therefore, in spite of the very extensive use of jet-grouting, there is still a relevant degree of uncertainty at the design stage, with particular reference to the diameter of the jet-columns and to the properties of the cemented soil. Such uncertainty could be progressively reduced, by reporting a sufficient number of detailed experimental studies.

The investigation presented herein regards the effects of jet-grouting (single fluid method) on pyroclastic soils. The test site is located near Naples, Italy, at the foothill of mount Vesuvius and belongs to a thick pyroclastic deposit formed by its volcanic activity. In situ measurements and laboratory tests were performed on both natural and cemented soils. Reported data include treatment parameters, soil properties, columns dimensions and mechanical characteristics of the cemented material. The experimental results are examined in detail, pointing out the influence of both soil properties and treatment procedures. The percentages of removed soil and retained mortar are estimated by means of back-analysis, providing valuable information on the phenomena induced by jet-grouting.

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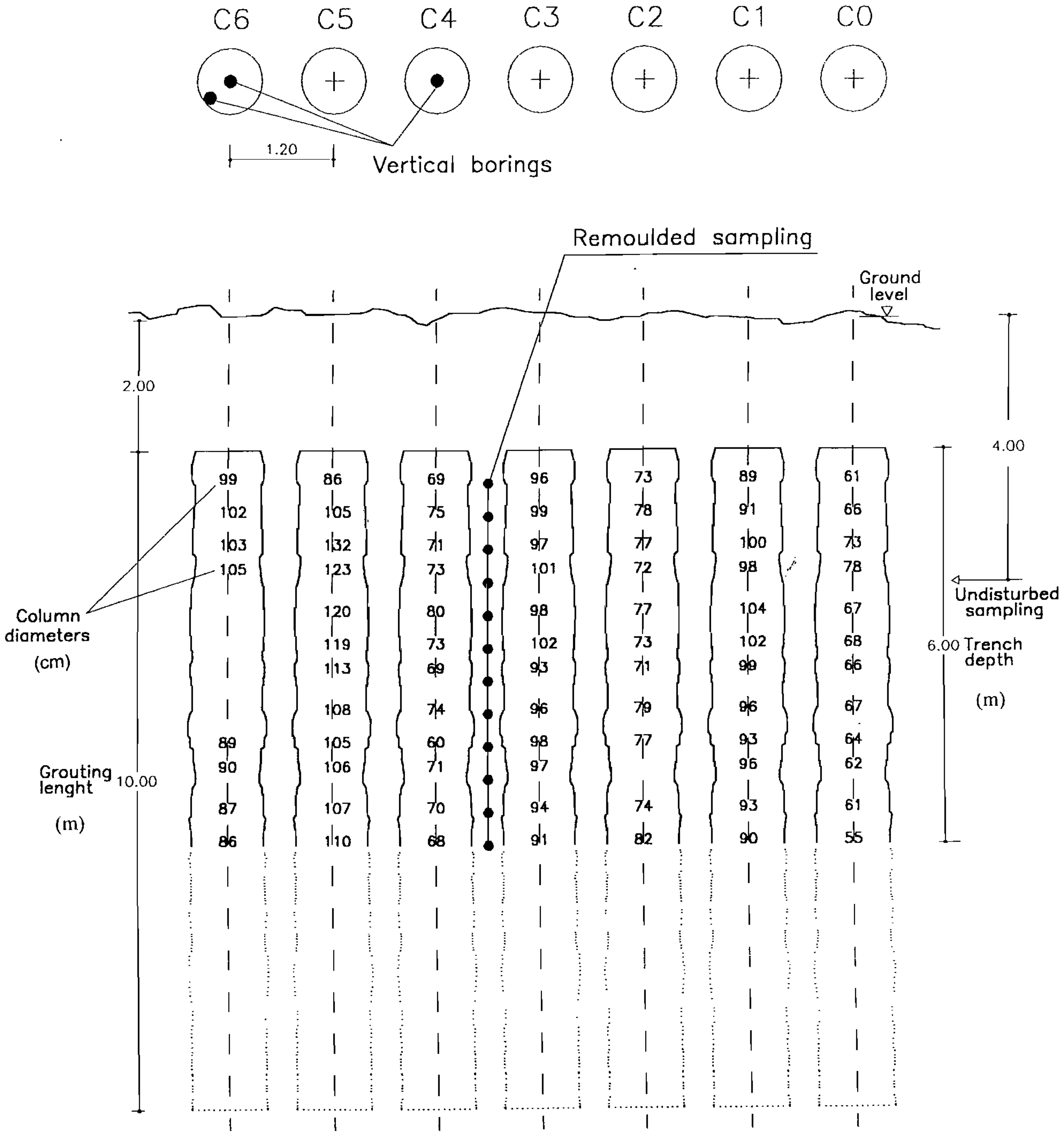

Fig. 1 – Sketch of jet-grouting treatments and in situ investigations.

2. Soil treatments

Seven vertical jet-grouting treatments were performed, by single fluid injection. The treatment axes were positioned in a single row, at 1.20 m centres; the drilling depth was 12 m and the grouting length was 10 m, starting from the bottom (Fig. 1). All treatment parameters were continuously recorded, during drilling and injection.

Grout mix (water-cement mortar with weight ratio $r_m = 1$), grout pressure ($p = 45$ MPa) and lifting step ($\Delta z = 40$ mm) were kept constant for all columns, while the other parameters were changed, from one column to the other, in order to determine their influence (Tab. I).

The grout flow rate (Q) was kept relatively law (1.38×10^{-3} m^3/s) for the first trial column (C_0) and it was then substantially raised for the others ($Q = 2.35 \div 2.50 \times 10^{-3}$m^3/s). Four treatments were made with a single nozzle (diameter $d_{noz.} = 3.8$ mm) and the remaining with two nozzles ($d_{noz.} = 2.0 \div 2.6$ mm). The injection time per lifting step (Δt) varied

Tab. I – Treatment parameters and average column diameters.

Column	r_m	p *(Mpa)*	Δz *(mm)*	Q *(10^{-3} m^3/s)*	*Noz.* *#*	$d_{noz.}$ *(mm)*	Δt *(s)*	*Rot.* *#*	ϖ *(rad/s)*	v *(mm/s)*	V_j *(m^3/m)*	$d_{av.}$ *(m)*
C_0	1.00	45	40	1.38	2	2.0	7	1.75	1.57	5.71	0.242	0.66
C_1	1.00	45	40	2.50	1	3.8	8	1.00	0.79	5.00	0.500	0.96
C_2	1.00	45	40	2.35	2	2.6	6	1.50	1.57	6.67	0.353	0.75
C_3	1.00	45	40	2.50	1	3.8	8	1.50	1.18	5.00	0.500	0.97
C_4	1.00	45	40	2.35	2	2.6	6	1.00	1.05	6.67	0.353	0.71
C_5	1.00	45	40	2.50	1	3.8	10	1.00	0.63	4.00	0.625	1.11
C_6	1.00	45	40	2.50	1	3.8	10	1.50	0.94	4.00	0.625	0.95

r_m = water/cement ratio of mortar; p = grout pressure; Δz = lifting step; Q = grout flow rate; Noz. = number of nozzles; d_{noz} = diameter of nozzles; Δt = injection time per lifting step; Rot. = number of rotations per lifting step; ϖ = average rotational speed; v = average lifting speed; V_j = injected volume of mortar per unit length of treatment; $d_{av.}$ = average diameter of jet-column.

from 6 to 10 seconds. The number of rotations per step was either 1 or 1,5 with the exception of the first trial column (Rot. = 1.75).

As a consequence, the average rotational speed (ϖ) ranged between 0.63 and 1.57 rad/s and the average lifting speed (v) ranged between 4.00 and 6.67 mm/s. Finally, the grout volume injected per unit length of treatment ($V_j = Q/v$) ranged between 0.242 and 0.625 m^3/m.

3. Investigations

An 8 m deep trench was excavated, one month after treatment completion, allowing direct observation of the columns surface, for 6 m length (Fig. 1). Diameter measurements were taken for each column, every 0.5 m depth, and soil samples were recovered, at corresponding heights, for geotechnical identification.

Undisturbed sampling was very difficult, because of the soil granular nature. However, two undisturbed samples were taken from a finer grained layer, located at 2 m depth with respect to the columns top, by pushing thin wall samplers into the trench side. Two oedometer compression tests and one drained triaxial compression test were performed on specimens trimmed from these samples.

The properties of the jet-column material (cemented soil) were investigated by means of several laboratory tests, carried out at the laboratory of the Department of Geotechnical Enginering of the University of Napoli Federico II on samples recovered from the surface, by making three vertical borings with continuous rotary sampling. In particular, one boring was drilled along the axis of column C4 and two borings were drilled in column C6, respectively along the treatment axis and on a vertical axis located 0.3 m out of centre. The R.Q.D. index ranged between 86 and 100 %.

In order to minimize the disturbance of the cemented soil, laboratory testing was carried out on specimens of the same diameter of the drilled samples ($d = 82 \div 82.5$ mm) with length $L = 162 \div 163$ mm. The testing program included 27 unconfined compression tests (16 on specimens taken from column C4 and 11 on specimens taken from column C6) and 6 triaxial compression tests (3 specimens for each column).

In the unconfined compression tests, the axial and radial displacements were measured with local dial gauges. In particular, three gauges were employed for the vertical displacements, and two for the horizontal ones. The vertical load was measured by means of a load cell, placed directly on the specimen top.

Triaxial tests were carried out in a cell designed to allow high confining pressures (up to 9 Mpa). In particular, confining pressures $\sigma_3 = 0.5 \div 1.5 \div 3.0$ Mpa were adopted. However, load and displacement measurements were taken outside the cell. As a consequence, Young moduli calculated from the triaxial tests are affected by some errors due to apparatus compliance, bedding and tilting. All tests were carried out with a strain rate of $1.33 \div 1.50 \times 10^{-6}$ min^{-1}.

4. Original soil properties

It was already mentioned that the test site is located at the foothill of Mount Vesuvius and belongs to a thick pyroclastic deposit formed by its volcanic activity. Detailed analyses of the famous eruption which buried Pompei and Herculaneum in 79 A.D. [RIPPA, 1996] have shown that grain size distribution and deposit thickness of these materials strongly depend on the relevant depositional mechanisms (i.e. fall, surge or flow).

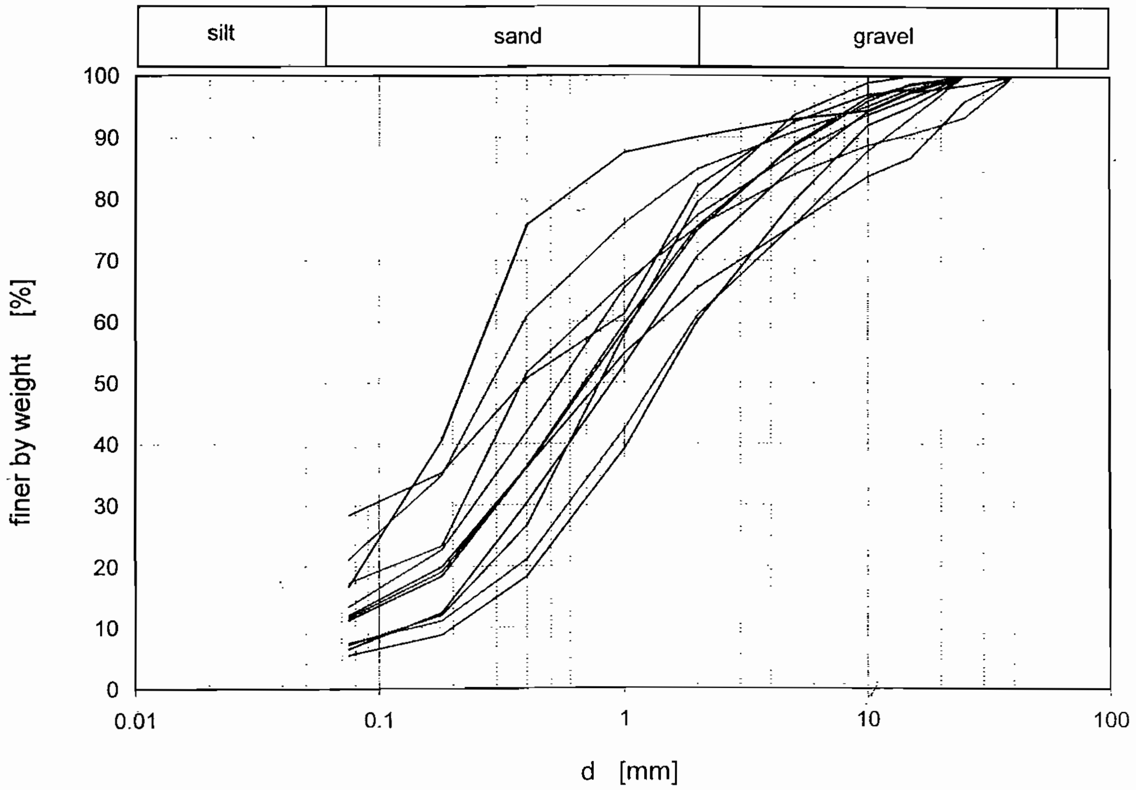

Fig. 2a – Grain size distribution curves of the natural soils.

The investigation was performed in an area where the upper 30 meters of soil have mainly been formed by flow. Such deposits are characterised by massive structure and are usually made of well graded soils, ranging from gravel to silt. Physical and structural properties are random with depth.

Observation of the trench walls pointed out that the soil is made of sandy-silty ashes, with some large blocks known as "bombs". From the granulometric standpoint, the soil ranges from silty sand to gravelly sand (Fig. 2a). The percentages of silt, sand and gravel are plotted versus depth (Fig. 2b), together with the elevation of two layers with the highest percentage of bombs.

Further information was gained from an extensive investigation carried out in a large area surrounding the test site. These results were obtained from laboratory tests performed on the few undisturbed samples successfully recovered from the many borings drilled. Void ratios and dry unit weights are plotted versus depth (Fig. 3), showing a large data scatter which is consistent with the depositional features of the deposit. The results of several drained triaxial tests indicate a mean value of peak friction angle $\phi' = 35.4°$, with a standard deviation of 4.1°, and a mean value of cohesion $c' = 54.6$ kPa, with a standard deviation of 42.8 kPa. This data scatter confirms the dishomogeneity of the flow deposit. Oedometric compression tests give values of the compression index Cc ranging from 0.198 to 0.248. It is finally pointed out that the ground water table is very deep, with degrees of saturation S at the treatment depths ranging from 0.83 to 0.98.

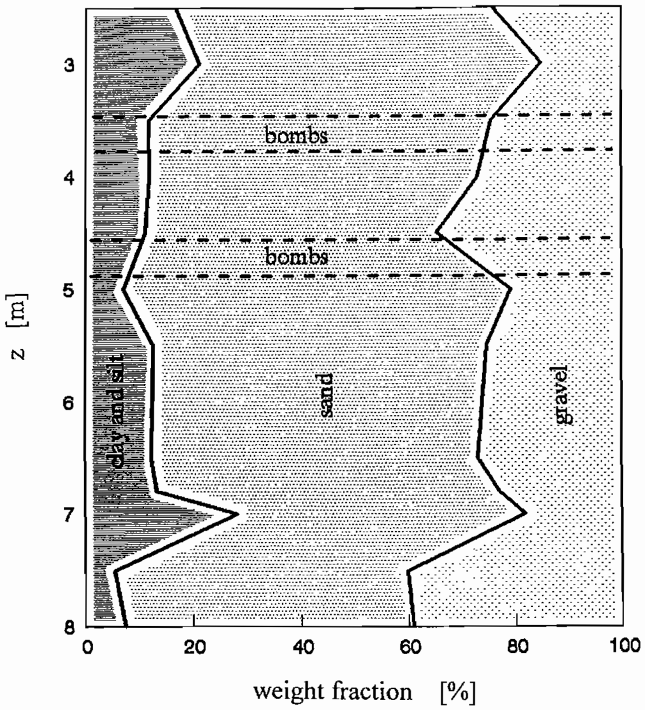

Fig. 2b – Granulometric fractions of the natural soil versus depth from ground level.

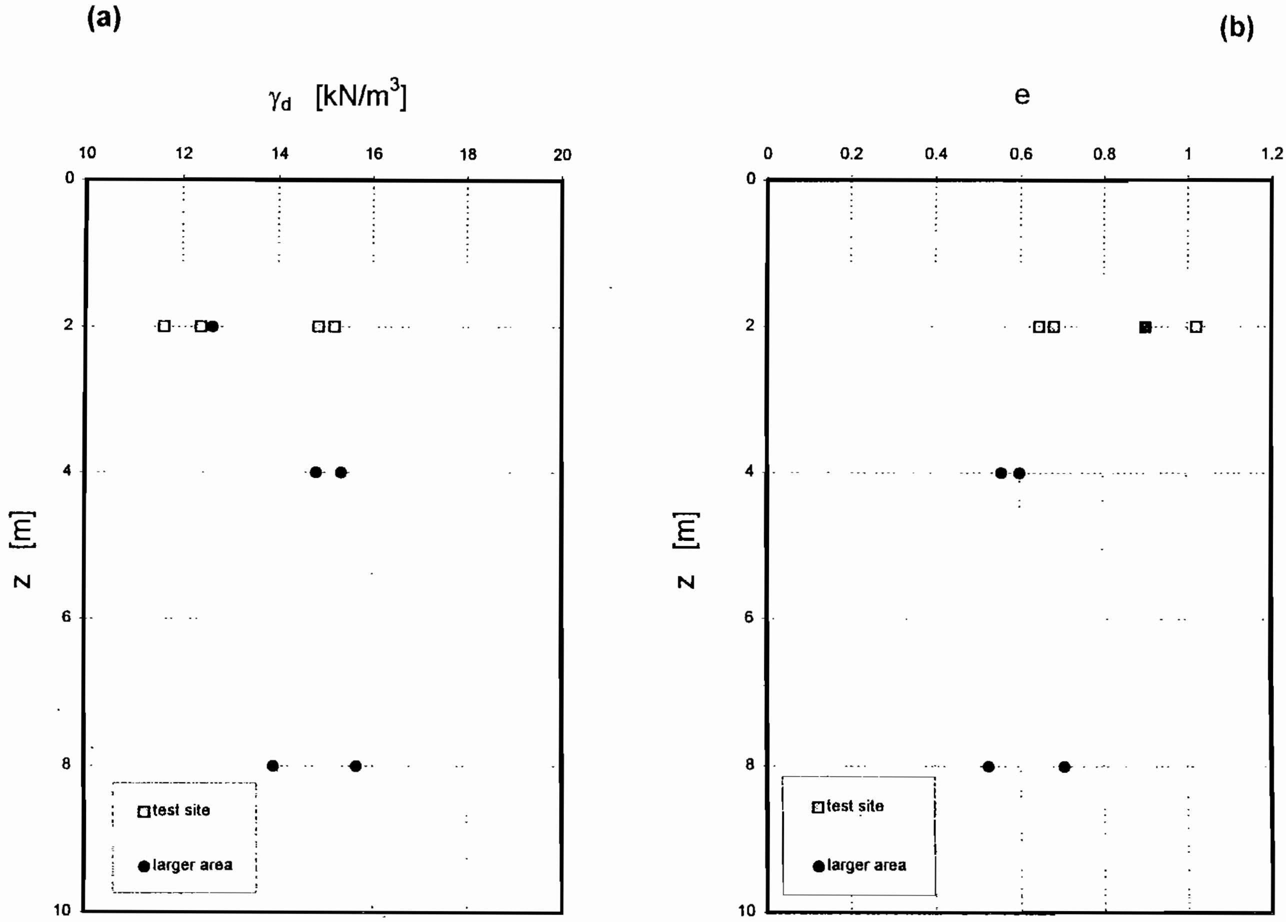

Fig. 3 – Original soil properties: (a) dry unit weight and (b) void ratio versus depth.

5. Columns dimensions

The diameter (d) of the jet-columns was measured every 0.5 m of depth (Fig. 4a). The measurements were taken directly from the observation trench, along the plane connecting the treatment axes.

For a first group of columns (C0, C2, C4), the diameter varies from 0.55 to 0.80 m while, for a second group (C1, C3, C6), it ranges between 0.87 and 1.05 m.

The diameter of column C5 is the largest one, reaching the maximum value of 1.32 m, but this result is probably due to an accident during perforation. In fact, treatment recordings show that the water pressure was substantially raised, during the drilling phase. This anomaly can only derive from the involuntary closure of the tip valve. As a consequence, the perforation water was expelled at high speed through the radial nozzle, determining partial soil remoulding before the subsequent grouting phase. It follows that this involuntary pre-treatment had a positive effect; it could be usefully employed, if necessary, in similar conditions. However, since the treatment of column C5 is different from the others, the relevant data will not be considered in the following analyses.

The influence of treatment parameters (Tab. I) can be examined by comparing each of them with the column average diameters (d_{av}). The best correlation is obtained between d_{av} and the square root of the injected grout volume V_j (Fig. 5). This finding is hardly surprising, since it is equivalent to a linear correlation between jet-column and injected grout volumes.

Since $V_j = Q/v$, it follows that there is a combined influence of grout flow rate (Q) and average lifting speed (v). The other parameters did not show any meaningful effect.

For the sake of data interpretation, measured diameters are also plotted in non dimensional form (Fig. 4b) dividing them by the respective column average diameters (d_{av}.). In this way, the trend of diameter variation with depth can easily be detected. In fact, the data scatter is reduced and it appears that all the columns become smaller, proceeding from top to bottom.

This trend cannot be due to the influence of treatment parameters, which are kept constant for each column, and should then be related to the origi-

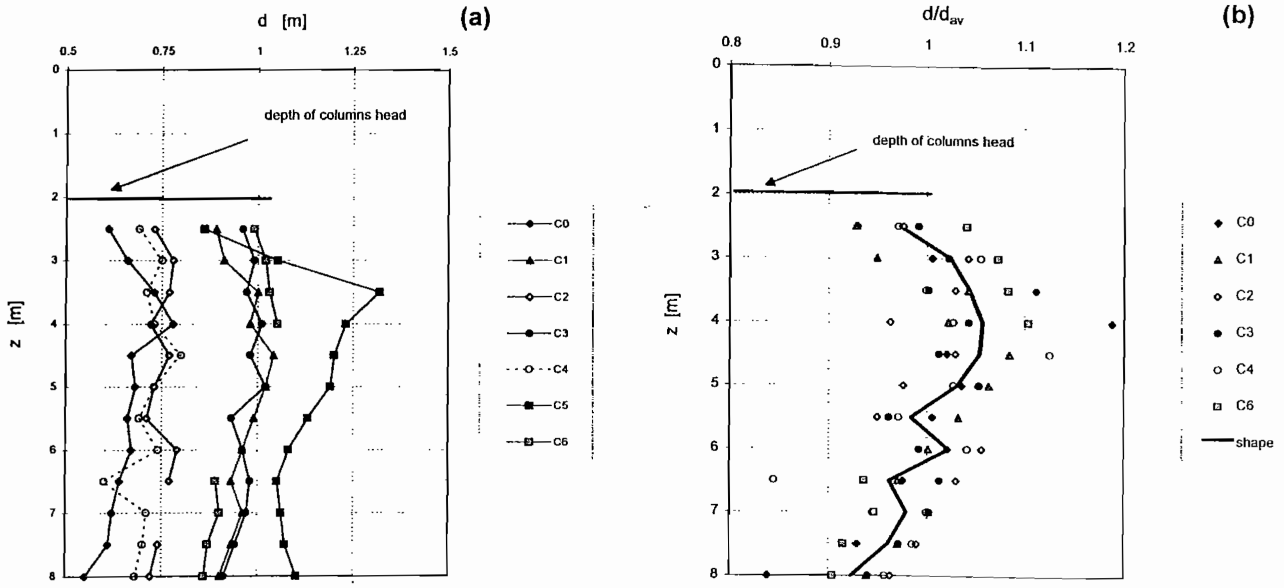

Fig. 4 – (a) diameter d of jet-columns; (b) columns shape d/d_{av}.

nal soil properties. In particular, since treatment extension is related to soil permeation and/or remoulding, the relevant soil properties are permeability and shear strength.

Permeability should in turn be primarily related to soil grains dimensions. However, comparison of column diameters with granulometric distributions do not show meaningful correlations. It can then be argued that the jet action has mainly determined soil remoulding.

The latter effect decreases with increasing shear strength and, therefore, the detected trend of diameter reduction with depth can be attributed to a corresponding shear strength increment. In fact, since the cohesion is generally small, the soil shear strength depends mainly on the effective stress level which increases with depth.

Local abrupt diameter reductions can be explained by the occurrence of thin layers of naturally cemented soil, while the presence of 'bombs' had no measurable influence.

6. Back calculation of removed soil and retained mortar

The available experimental data can also give valuable information for the analysis of the jet-grouting mechanism. It is possible, in particular, to estimate the percentage of soil removed by jet-induced erosion and the percentage of mortar retained by the subsoil.

For this purpose, the jet-grouting effects are subdivided in two phases: the first one concerns the mechanical phenomena related to the jet action (soil remoulding and/or permeation), while the second one consists in the cementing process due to the solidification of the retained mortar. Three subsequent stages should then be considered:

1) original soil composed by grains, water and air;
2) grouted soil (just after treatment) made of soil grains, fluid mortar, water and air;
3) cemented soil (after mortar solidification) made of soil grains, hydrated cement, water and air.

The solution is obtained by applying the continuity condition to a column element of unit length, for each of the above mentioned stages. For the present case, the following simplifying assumptions have been made:

- in stage 2, the mortar fills all the pores (i.e. the soil is fully saturated by fluid mortar);
- in stage 3, the cement particles are fully hydrated;
- the soil grains do not react with mortar.

It follows that the column diameter (d) is related to the injected grout volume per unit length (V_j), the initial soil porosity (n), the percentage of mortar retained by the subsoil ($\alpha=V_m/V_j$) and the percentage of soil removed by jet action ($\beta=\Delta V_s/V_s$):

$$d=2\left\{\frac{\alpha V_j}{\pi[1-(1-\beta)(1-n)]}\right\}^{0.5} \qquad (1)$$

It is noted that Eq. (1) is consistent with the experimental power low reported for the average columns diameter (Fig.5). The values of α and β are back-calculated from the available experimental data. In fact, α depends on the ratio between column volume (V) and injected grout volume (V_j), on the cemented soil porosity (n_c), and on the volumetric

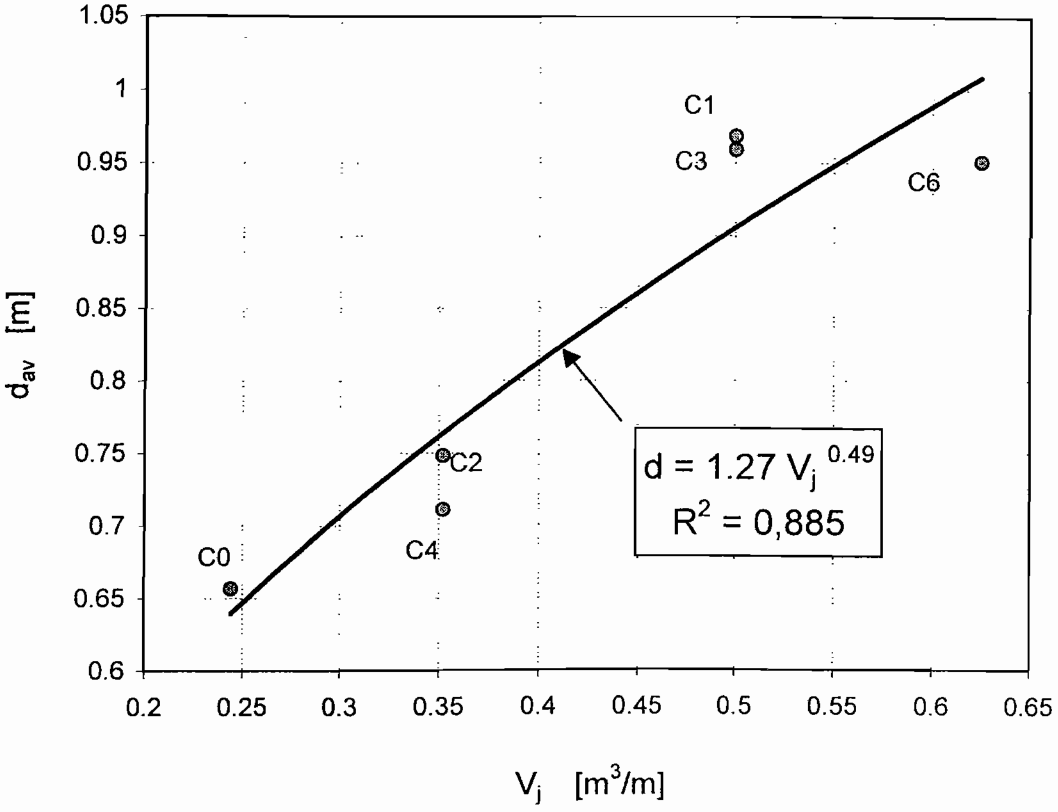

Fig. 5 – Correlation of average columns diameter with injected mortar volume.

ratio ($\delta = V_{hc}/V_m$) between hydrated cement and retained mortar:

$$\alpha = \frac{n_c V}{(1-\delta) V_j} \tag{2}$$

while β depends on δ and on both the original and cemented soil porosity:

$$\beta = 1 - \frac{1-\delta-n_c}{(1-n)(1-\delta)} \tag{3}$$

The volume V can be calculated, for each column and height, from the measured diameters (Fig. 4a); n varies randomly in the range 0.33–0.50; n_c is taken, for each height, from the regression of the data obtained on the cemented soil specimens (Fig. 7a); V_j is known for each column (Tab. I); δ is assumed to be constant and is calculated from the following relation:

$$\delta = \frac{(1+r_s)\gamma_m}{(1+r_m)\gamma_{hc}} \tag{4}$$

where γ_m (14.7 kN/m^3) and γ_{hc} (25.5 kN/m^3) are the specific weights of fluid mortar and hydrated cement, while r_m (1.00) and r_s (0.30) are respectively the injected mortar and the stoichiometric water/cement weight ratios.

The values of α and β obtained by Eqs. (2) and (3) are plotted versus depth (Fig. 6), showing that the treatment effect increases moving towards the ground surface. In particular, the reported values of α were obtained for each measured diameter of columns C4 and C6. It results that most of the mortar (80 ÷ 100 %) was retained by the subsoil, from 2 to 5 m depth, while the absorption was progressively reduced from 5 to 8 m, reaching a minimum of 60%. The excess mortar was expelled on the ground surface, as it was observed during treatment.

The percentage of removed soil also decreases from top to bottom. However, the range of possible values depends on the original soil porosity which is random with depth. The two curves reported in Fig. 6b have been obtained for the minimum and maximum assumed soil porosity (n = 0.33 ÷ 0.50). It results that the percentage of soil removed is as high as 60% , at the columns top, while it decreases to a minimum of 20 % , at the trench bottom. It is then confirmed that the jet action determined a very significant soil remoulding, as it was previously argued, and that this effect decreased with depth.

7. Cemented soil properties

The mechanical properties of the cemented soil were determined from the uniaxial and triaxial

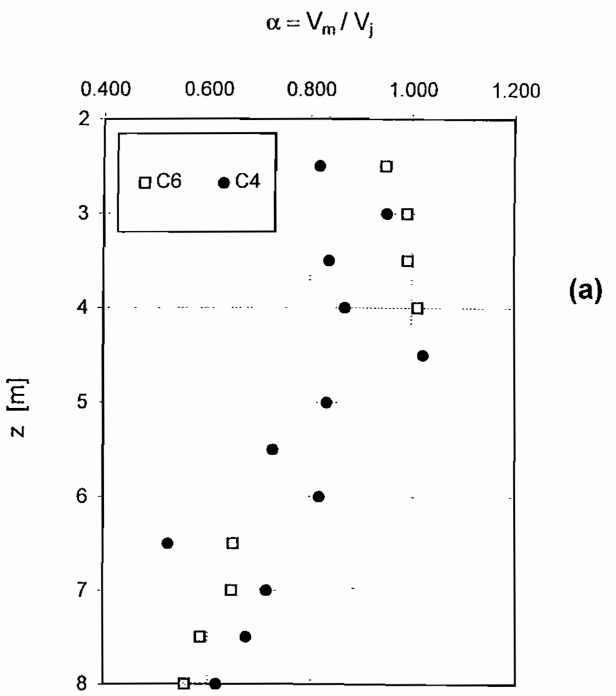

Fig. 6a – Retained mortal fraction α versus depth.

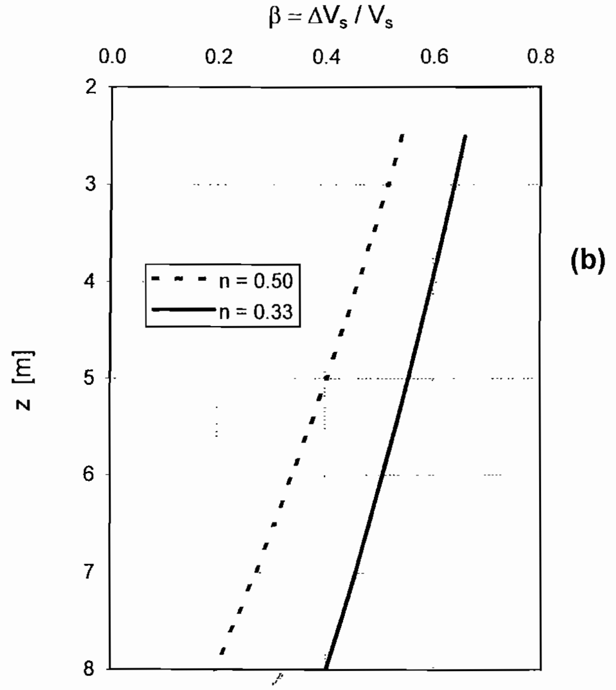

Fig. 6b – Removed soil fraction β versus depth.

compression tests carried out on the cylindrical specimens recovered from columns C4 and C6. Significant differences were neither found between the two columns nor between the axis and side of column C6.

Void ratio (e_c) and dry unit weight (γ_{dc}) were determined for all the tested specimens. In spite of some data scatter, there is a clear correlation of both e_c and γ_{dc} with depth (Fig. 7). In particular, e_c decreases from 1.3 to 0.8 , while γ_{dc} increases from 12.5 to 15.5 kN/m^3 approximately.

With reference to shear strength, it is recalled that some researchers assume that the addition of cement increases only cohesion [CLOUGH *et al.* 1979; MACCARINI, 1987], while some others [LADE and OVERTON, 1989] argue that both friction angle and cohesion are modified. However, it is reasonable to assume that both approaches can be applied, depending on the original soil density and on the grouting mechanism [EVANGELISTA, 1995]. In the present case, soil structure, density and gradation are deeply changed from the remoulding action of jet-grouting. As a consequence, changes of both friction angle and cohesion are expected.

In the uniaxial tests, the specimens always showed a brittle behaviour, with the appearance of one or more clear cracks around the peak state and a subsequent strength reduction. The development of such discontinuities was clearly detected by the local dial gauges.

The unconfined compressive strength q_u increases from about 4000 to more than 15000 kPa and is clearly related to γ_{dc} (Fig. 8), consistently with the behaviour of soft rocks and concrete.

Results of the triaxial compression tests (Tab. II) are plotted (Fig. 9) in terms of the stress variables $s'=(\sigma'_1+\sigma'_3)/2$ and $t'=(\sigma'_1-\sigma'_3)/2$. It is observed that linear regression of the latter data would lead to the values $c'_c = 2245$ kPa and $\phi'_c = 32.4°$, but wouldn't consider the dependency of shear strength on dry unit weight. However, considering that cohesion c'_c and friction angle ϕ'_c can be related to q_u and adopting the linear regression shown in Fig. 8, it follows that:

$$c'_c=(a\gamma_{d_c}-b)\frac{1-\sin(\phi'_c)}{2\cos(\phi'_c)} \qquad (5)$$

where a = 2933 m and b = 32427 kPa.

Tab. II – Results of the triaxial tests on cemented soil specimens.

column	*depth [m]*	*σ'_1 (at failure) [MPa]*	*σ'_3 [MPa]*	*γ_{dc} [kN/m^3]*
C4	3.8	12.7	1.5	12.94
	4.0	10.0	0.5	13.02
	4.4	16.8	3.0	13.30
C6	6	9.94	0.5	13.45
	6.2	19.0	3.0	15.23
	6.4	14.7	1.5	14.51

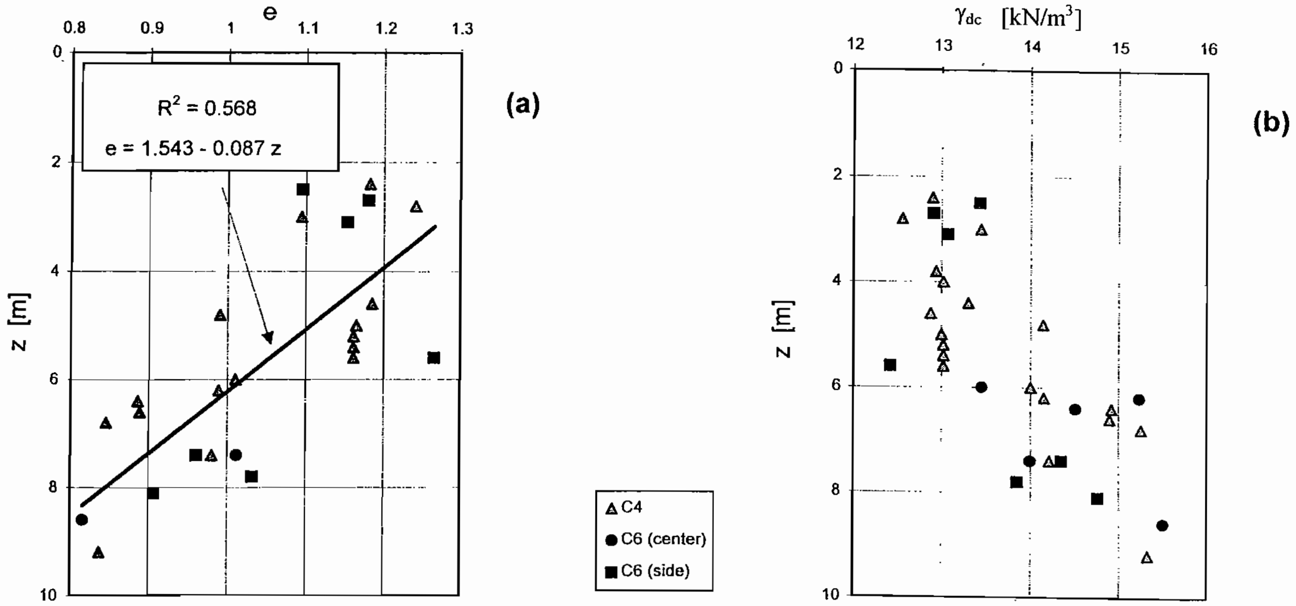

Fig. 7 – Physical properties of cemented soil: (a) void ratio and (b) dry unit weight distributions with depth.

It is then possible to establish different failure envelopes for each value of γ_{dc}. In particular, the results of the triaxial tests can be well fitted assuming that ϕ'_c is constant and using representative γ_{dc} values (13, 14, 15 kN/m^3). The corresponding shear strength values are $\phi'_c = 23.1°$ and $c'_c = 2449$, 3376 and 4302 kPa. Notwithstanding some scatter, the experimental results are consistent with the adopted interpretation (Fig. 9).

The Young moduli values show a large scatter in both kinds of tests. In particular, the secant modulus E_{50} (determined at half of the failure deviatoric stress) ranges from 2000 to 8000 Mpa, in the unconfined compression tests, and from 1000 to 2000 Mpa, in the triaxial tests. Values obtained from the uniaxial tests are more reliable, because the accuracy of the strain measurements is much higher.

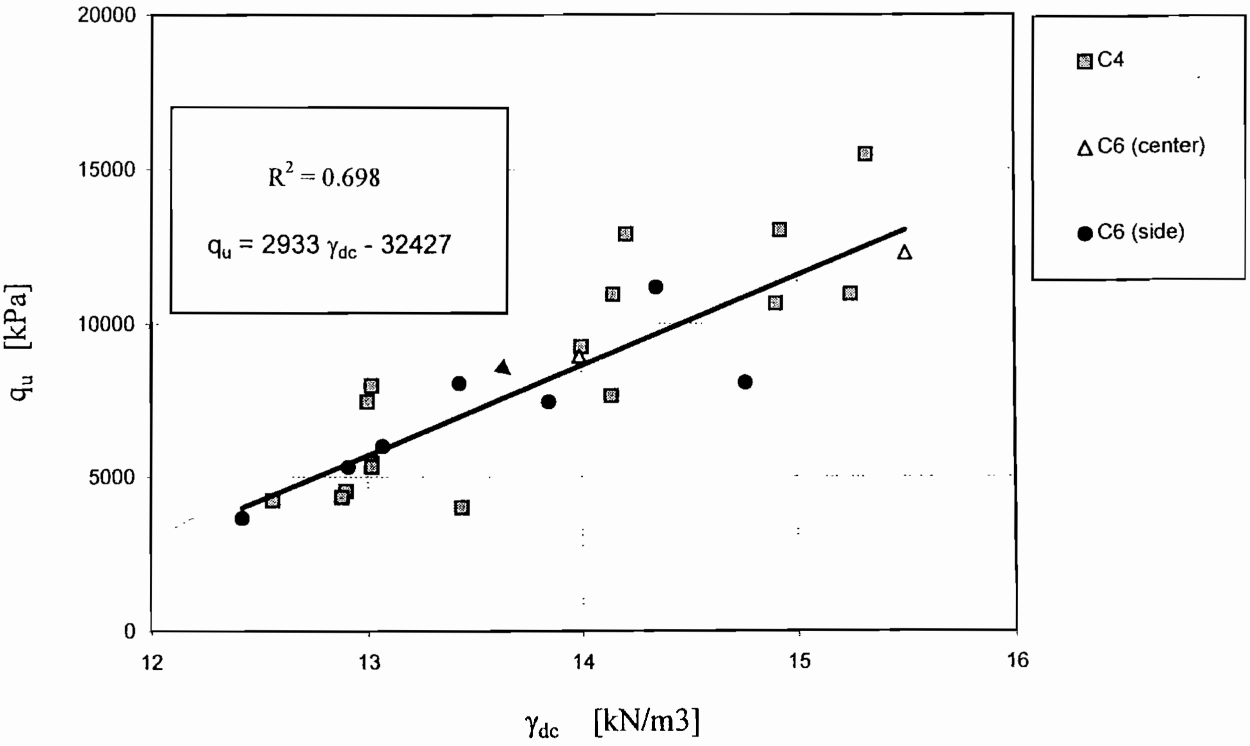

Fig. 8 – Results of uniaxial compression tests on cemented soil specimens.

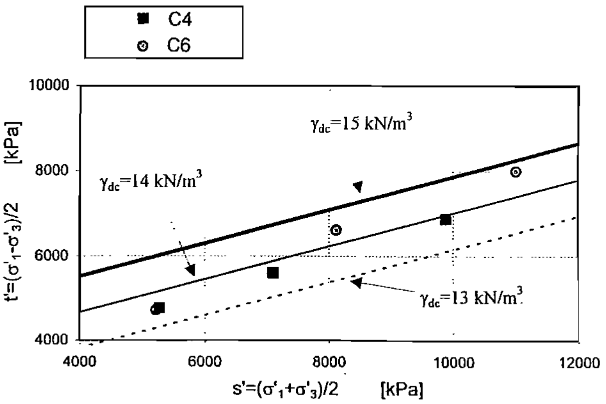

Fig. 9 – Results of triaxial tests on cemented soil specimens and failure envelopes for different values of unit weight γ_{dc}.

8. Conclusions

The reported investigation regards the effects of jet-grouting (single fluid method) on pyroclastic soils, with particular reference to flow deposits. The experimental observations show the production of cemented soil bodies (jet-columns), whose characteristics depend on the influence of both original soil properties and treatment procedures.

With regard to the treatment parameters, there is a clear experimental correlation between jet-columns diameter and injected grout volume, which is consistent with the continuity condition. It follows that there is a combined influence of grout flow rate and average lifting speed, while the other parameters do not show any meaningful effect.

It was also observed that the diameter of the jet-columns decreases with depth. This trend seems to be related to the corresponding increase of soil shear strength. In fact, results of back-calculations show that the jet action removes a large amount of soil and that this effect declines with depth.

Back-calculations also indicate that most of the mortar is retained by the subsoil, towards the surface, while the absorption is progressively reduced with depth. Local abrupt diameter reductions are due to the occurrence of thin layers of naturally cemented soil, while the presence of pyroclastic blocks has no appreciable influence.

The physical and mechanical properties of the artificially cemented soil were determined by means of laboratory tests, carried out on undisturbed specimens taken from the jet-columns. It was found that the void ratio decreases and that the unit weight increases correspondingly with depth.

The mechanical behaviour of the artificially cemented soil can be interpreted with the criteria adopted for soft rocks. Results of the uniaxial and triaxial compression tests show a clear dependency on dry unit weight γ_{dc}. In particular, the results are well fitted assuming a constant value of the friction angle and expressing the cohesion as a linear function of γ_{dc}.

References

CHIARI A., CROCE P. (1991) – *Some limits to the use of jet-grouting*. Proc. of the 4th International Conference on Piling and Deep Foundations, Stresa, Italy, Balkema, pp. 201-204.

CLOUGH G.W., KUCKW M., KASALI G. (1979) – *Silicate stabilized sands*. Journal of the Geotechnical Engineering Division, ASCE, vol. CV, pp. 65-82.

CROCE P., GAJO A., MONGIOVÌ L., ZANINETTI A. (1994) – *Una verifica sperimentale degli effetti della gettiniezione*. Rivista Italiana di Geotecnica, vol. II, pp. 91-101.

EVANGELISTA A. (1995) – *Valutazioni teoriche e osservazioni sperimentali sui processi di trattamento dei terreni e sulle modifiche indotte*. XIX Convegno Nazionale di Geotecnica, Pavia, pp. 125-217.

LADE P.V., OVERTON D.D. (1989) – *Cementation effects in frictional materials*. Journal of the Geotechnical Engineering Division, ASCE, vol. CXV, n. 10, pp. 1373-1378.

LUONG M.P., GANDAIS M., ALLEMAND P. (1978) – *Time-dependent stress-strain behavior of silicate-grouted sand*. Journal of the Geotechnical Engineering Division, ASCE, vol. CIV, n. CT6, pp. 770-772.

MACCARINI M. (1987) – *Laboratory studies of weakly bonded artificial soil*. Ph.D. Thesis, Imperial College of Science and Technology, London.

MIKI G. (1985). – *Soil improvement by jet grouting*. Third International Geotechnical Seminar on Soil Improvement Methods, Singapore.

RIPPA F. (1996) – *A description of pyroclastic soils that buried Pompei and Herculaneum in a.d. 79*. Proc. Of the Int. Symp. On Geotechnical Engineering for the Preservation of Historic Sites (C. Viggiani editor), pp. 261-270.

SHIBAZAKI K. OHTA S. (1982) – *A unique underpinning of soil solidification utilizing super-high pressure liquid jet*. Proc. Of Conference on Grouting in Geotechnical Engineering, New Orleans, pp. 680-693.

YAHIRO T., JOSHIDA H., (1973) – *Introduction grouting method utilising high speed water jet*. Proc. 8th ICSMFE Moscow, vol. IV, pp. 402-404.