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A monitoring system for the quality assessment of the jet grouting process through an energy approach

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ABSTRACT: Soil improvement by jet grouting technique is employed in a wide range of projects, such as underpinning, tunnelling, cut-off walls and shafts excavation. In the last few years jet grouting proved reliable and effective in so many circumstances that it is ever more frequently applied when critical situations are foreseen, especially in the urban areas.
The extensive use of this technique led to the necessity of electronic monitoring of the jet grouting industrial process. This to enable real time quality control and immediate availability of data in order to support the operational choices and the engineering analyses.
The paper deals with the electronic monitoring system PAPERJET®, recently developed by RODIO, and the results of some field experiences. The energetic approach, inherent to the measured parameters, based on instrumented drilling and instrumented high pressure grouting results, is applied both to determine soil profile along the axis of the columns and to evaluate the energy spent for their construction.
The PAPERJET System allows real time monitoring of jet grouting parameters by visual display under graphical and numerical representation form, data recording and automatic storage and printing in real time of all the data acquired. The whole system is installed on the rig and consists of sensors, data acquisition unit, portable computer and dedicated software.
The data acquired by PAPERJET System, besides allowing a comprehensive control of the process, makes it possible to carry out an effective economical evaluation of the results obtainable, comparing the energy spent during grouting and drilling phases.

1. INTRODUCTION

Soil improvement by jet grouting has proved to be a reliable and effective technique in a variety of engineering works involving tunnels, underpinning, cut-off walls, embankments and shafts. Due to this reason, it has been more and more frequently applied in the past few years, especially when critical situations have been encountered.
In such circumstances, it is of major importance for the Contractor to rely on an effective monitoring system of the industrial jet grouting process. Such a monitoring, in fact, would permit a real time quality control of the process and would represent a valuable support for timely operational choices.
The electronic monitoring system PAPERJET®(RODIO Trade Mark), recently developed, is part of a new equipment generation with electronics incorporated, able to provide the rig operator, the site Engineer and the other parties involved, with real time information on the jet grouting.
A peculiarity of the system lies on the energetic approach adopted for interpreting the parameters measured during the drilling and jet grouting phases. It enables to determine the profile of the natural soil along the vertical axis and the energy spent for the construction of the jet grouted columns.
As a consequence, by means of the electronic measurement of pressures, flow rates and volumes, the system makes it possible to energetically quantify the whole process of drilling and subsequent high pressure grouting.
Possible further developments can be envisaged. For instance, once several case histories of PAPERJET applications would become available, it will be possible to make a reliable forecast of the final results of a jet grouting treatment on the basis of the experience gained during previous construction processes.

2. JET GROUTING PROCEDURES

Although the jet grouting technique is generally well known, it is worthwhile to summarize here its principles, being related to the subject of this paper.
The soil is fractured and simultaneously mixed in place with a cement grout, with or without the use of an annular air jet, or alternatively can be removed up to a certain extent by air-water jetting and simultaneously replaced by grout jetting. Hence, the treatment may imply either the use of a single fluid (the grout) or of two fluids (grout and air) as fracturing and stabilizing agents, or of three fluids, air and water as fracturing and washing media and grout as stabilizing agent (Tornaghi, Perelli Cippo, 1985).
The sequences of operations related to the jet grouting procedures are depicted in fig.1.
Drilling is carried out down to the required depth by use of a string of rods fitted at the bottom with a drilling and jetting tool (monitor). The subsequent grout jetting is performed through radial nozzles located along the monitor axis while revolving and drawing up the tool.
The size and mechanical properties of the treated soil columns depend on the combined effects of the: type of soil, composition of the grout, grout discharge and pressure (related to the number and size of the nozzles), and rotational speed and lifting rate of the monitor.
The column diameter (customarily between 0.4 and 1.4 m) can be increased to 2 meters, or more, by the three-fluid system, which involves air-water jetting through coaxial nozzles placed just above the grout injection nozzles.
This latter procedure comprises fracturing of the soil and removal of its finest particles by air-water jets just before injecting the cement grout.

3. THE ENERGETIC APPROACH

The results achieved by the jet grouting technique depends on several factors related to the operative parameters and to the geotechnical characteristics of the soil.
This technique, which can be effectively applied for the treatment of both granular and cohesive soils, can be developed with low uncertainties only under a thorough control program.
The energetic approach is a rational criterion for evaluating and comparing the operative parameters, related to technical and economical aspects, in terms of specific energy.
The energy spent during the drilling and jet grouting phases can be evaluated according to the following considerations:

a) The specific drilling energy, defined by Teale (1965), is an useful index for soil characterization, and is based on physical parameters playing a specific role in the drilling phase.
The excavation of a unit volume of soil or rock requires a certain energy, which consists of two parts.
The first one is the work done by the thrust F [kN] on the drilling tool, having the same section A [m^2] of the hole, for a unit downward displacement.
This contribution is dimensionally a pressure, since the thrust for a unit displacement, divided by the excavated soil volume, corresponds to the pressure over the bottom of the hole. The second contribution is the work done by the torque T [kNm] of the power swivel, which is a function of the rotational speed S [rev/s] and of the rate of penetration V [m/s]. Consequently, the specific drilling energy is expressed by the following equation:

$$(1)\quad E = \frac{F}{A} + \frac{2\pi\, S T}{A V} \quad [\mathrm{kJ/m3}]$$

This parameter characterizes a soil deposit from the energetic viewpoint, and permits to identify its sequence of layers. The validity of the above equation has been the subject of an experimental investigation by Rowlands (1971), who verified it under ideal drilling conditions, that can be summarized in the following points:

- the soil particles removed by the drilling bit are immediately carried away by the drilling fluid, i.e. without additional grinding at the bottom of the hole;
- the flushing of the drilling fluid occurs in ideal conditions without clogging or collar formation along the rods;
- there is no loss of energy along the rods due to friction against the sides of the hole or vibrations;
- the wear conditions of the drilling bit are constant.

As a consequence, the use of the above equation requires that the drilling phase is carried out with some care so that "ideal" conditions could be verified.
Only if the drilling operations are done with the same procedure, it is possible to compare properly two different specific drilling energies. This condition can be verified only by monitoring the drilling.
De Paoli et al. (1987) describe an intensive application of instrumented drilling as soil classification carried out during the construction works of the Milan Underground Railway - Line 3 Lot 2PB.

b) The specific jet grouting energy, for unit lenght of column, depends on the following main parameters:

- grout pressure P [MPa]
- grout flow rate Q [m^3/h]
- withdrawal speed V_t [m/h]

and is expressed as:

$$(2)\quad E_s = \frac{P \cdot Q}{V_t} \quad [\mathrm{MJ/m}]$$

When the three-fluid (water,air and grout) system is used, the jet grouting energy is calculated adding together the energies of water and grout jettings, while the air contribution is neglected for simplicity.
The air effect in two-fluid and three-fluid systems, plays the role of a protection of the jet while it is fracturing the soil, it increases the action range, and makes it easier the removal of the soil particles from the hole.
Since the air is a compressible fluid, the evaluation of its energetic contribution is influenced by its temperature and humidity. The definition of a significant set of data, from a probabilistic viewpoint, is difficult, due to the uncertainties affecting the relevant parameters. Hence, in the following, the contribution of air will be neglected.
The range of variability of the main operative parameters for one, two and three fluid treatments are summarized in Table I. In the same table the energy values are presented for the pressures and volumes usually employed.

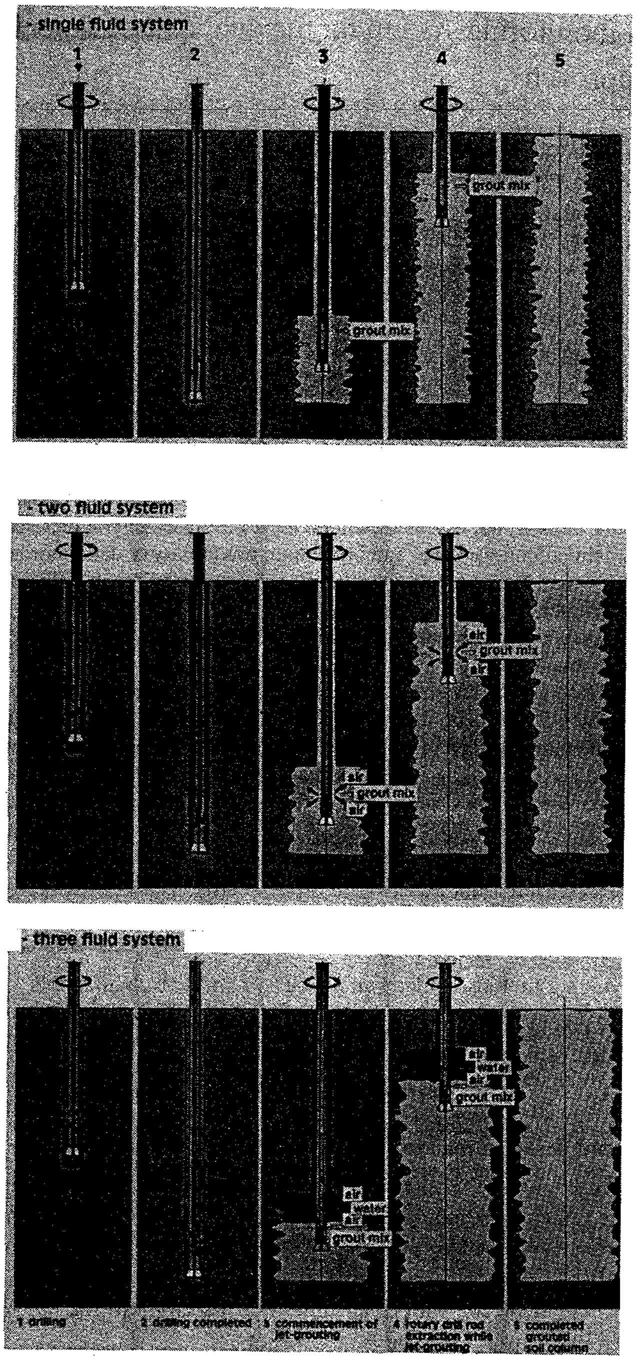

Figure 1. Jet grouting system: sequence of operations.

Table I - Range of jet grouting parameters

system	fluid	V_t (m/h)		V (m^3/h)		Q (m^3/h)		P (MPa)		E (MJ/m)	
		min.	max.	min.	max.	min.	max.	min.	max.	min.	max.
single fluid	mix	15	35	0.2	0.3	3.6	7.2	30	50	3	24
two fluids	mix			0.5	1.5	5	9	30	50	8	110
	air	4	18	10	90	150	360	0.7	1.2		
three fluids	mix			0.5	2	5	9	1	10	1	20
	water	2.5	18	0.5	2	5	9	30	50	8	180
	air			10	150	150	360	0.7	1.2		

V_t = withdrawal speed   Q = grout mix flowrate   E = grouting energy
V = mix volume   P = grout mix pressure

4. PAPERJET® SYSTEM

The PAPERJET System has been developed for controlling and monitoring the drilling and jet grouting phases.
It permits the acquisition of the characteristic data during both drilling and jet grouting, so to obtain a meaningful soil characterization and to control the operative parameters of the process.
It is important to note that the acquisition system does not cause any delay of the working process during the construction of the jet grouting columns.
The PAPERJET System consists of:
- transducers;
- acquisition unit;
- portable computer (p.c.) linked to a printer;
- connections between the components.

The transducers are placed on the rig, while the flowmeters are integrated with the injection equipment. The analogical signals of these instruments are sent to the acquisition unit through the connection cables.
Such unit converts the analogical signals into digital signals which are sent to the p.c. governing the acquisition procedure. Both acquisition unit and p.c. support a dedicated software which performs all the required calculations and operations.
The system executes the following operations:
- real-time monitoring of drilling and jet grouting parameters and their visual display in graphical form;
- printing in real-time of all acquired numerical values;
- real-time storage of the same data in magnetic support;
- possibility of deferred plotting (and printing) of the variation of the parameters with depth.

The parameters relevant to the drilling operations are:
- depth
- penetration rate
- thrust on the tool
- rotational speed
- torque

The specific drilling energy, function of the previous data and of the drilling tool section, is calculated from eq. (1).
As a further control of the current operations, the pressure and flow rate of the drilling fluid are also acquired.
In the case of rotary-percussive drilling, used in rocks, downward and upward acceleration are of interest and are acquired for characterizing this particular type of drilling.
The measured and calculated grouting parameters are:
- depth
- withdrawal speed
- withdrawal force
- rotational speed
- torque
- grout mix, air and water pressures
- grout mix and water flow rates
- cumulated mix and water volumes
- mix and water specific volumes (per meter of column)

The jet grouting energy is calculated on the basis of the withdrawal speed, of the grout mix and water pressures and flow rates.
The PAPERJET system enables the rig-operator and the site Engineer to visualize, during the working phases, the main parameters both in graphical and numerical forms.
The real time monitoring of the mentioned quantities is useful since, if some mechanical illfunctioning takes place (as a drop of pressure or of flow rate, or clogging of the nozzles), the rig-operator can immediately detect it on the display, and take the necessary provisions.
Using this system, the site Engineer is informed of any change in the soil condition, and can accordingly modify the jet grouting process.
For example, if the system during drilling detects the presence of a cavity at a certain depth, the site Engineer could decide to increase the treatment in that zone, for instance by reducing the withdrawal speed.
Also the chief Engineer can control the working process, by verifying whether it has been carried out correctly and within the design limits.
In addition, the PAPERJET system permits the use of the data stored on magnetic support for the preparation of graphical outputs showing the variation of the measured quantities with depth.

From the above observation it can be concluded that the system represents an useful tool for controlling the field operations when the jet grouting technique is adopted, and that it permits a continuous monitoring of the operations, enabling a real time definition of the effectiveness of the treatment.

5. SAN BENEDETTO SITE

The project for a flyover crossing the double track railway line at San Benedetto (Ancona - Italy) foresaw a consolidation treatment by jet grouting of the bridge foundation in order to transfer in depth the structural loads. Owing to the proximity of the railway line, the design was very critical and required a thorough quality control to avoid damages to the railway line. A comprehensive study was also carried out in order to define the most adequate geometry and treatment parameters, so as to obtain the best results from the consolidation viewpoint. The soil consisted of medium fine sands with silty interbeds of about 20 cm thickness, and the SPT tests classified the soil in a range varying from loose to medium sands. A trial field was planned to acquire all necessary data for the optimization of the two fluid and three fluid jet grouting methods.
The PAPERJET system, owing to its versatility, proved to be a valuable instrument in the following operation phases:

- during the instrumented drilling phase it was possible to define the drilling specific energy of the natural soil for each column. Besides, it was possible to obtain, in real time, the soil profile by comparing the energy diagrams with the amount of energy required for drilling the different types of soil;
- during the treatment, the PAPERJET system allowed a systematic quality control and a certification of the product by the recording of all working parameters;
- after completion of the curing period the effectiveness of consolidation could be checked by carrying out instrumented drilling of the grouted columns, which permitted the comparison between natural and consolidated soil, in terms of energies.

A good agreement between drilling energy of the treated soil and its strength was observed during laboratory tests. These were unconfined compressive tests on core samples recovered from the columns at different depths.
The results are reported in fig. 2-4 and 5-7.
The trial field columns were then excavated to verify their geometry and homogeneity.

Fig. 2 shows the columns, executed by the two fluid system, which look quite regular except in the peripheral area.
In fig. 3 the output diagrams of PAPERJET system are shown, with reference to the drilling specific energy in natural and treated soil, and to the jet grouting energy.
These diagrams show that the average increment of specific energy varies from 0.05 [GJ/m^3] in the natural soil, to 0.25 [GJ/m^3] in the column.
The regularity of jet grouting energy ensures that all the jet grouting operations had been correctly performed in accordance with the foreseen construction parameters.
Fig. 4 reports the amount of mix employed for the column formation, the drilling energy of the treated soil and the consolidated soil strengths.
At this stage it seems too early to assign a statistical meaning to the comparison between drilling energy and treated soil strength, but it is already possible to assess that a good correlation exists between the two quantities.
A further step would be the recording of a sufficient number of data in order to create a family of significant statistical samples of different types of soil.
Figures 5 to 7 illustrate the control of three-fluid jet grouting carried out with the PAPERJET system.
Even in this case, an increase in drilling energy from 0.05 to 0.28 [GJ/m^3] occurs and the agreement between drilling energy and treated soil strength is fairly good.
The large number of data acquired with the PAPERJET system allowed the selection of the most suitable construction method and provided the necessary elements for the definition of jet grouting operational parameters.

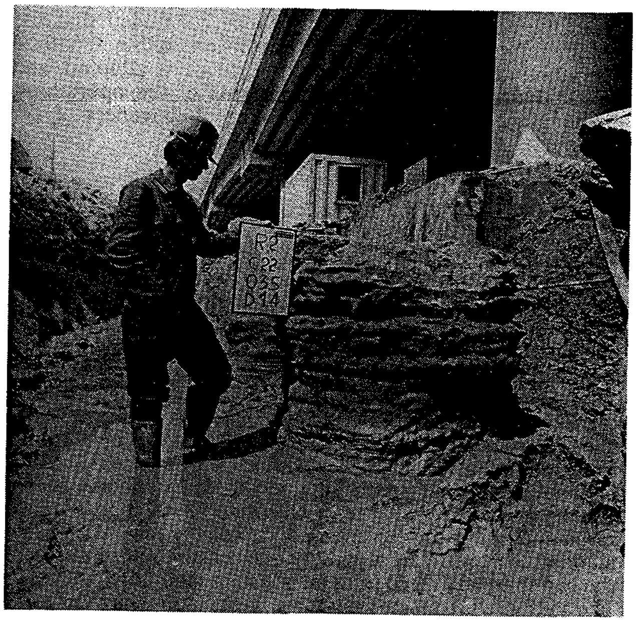

Figure 2. Two fluid system: detail of the treatment.

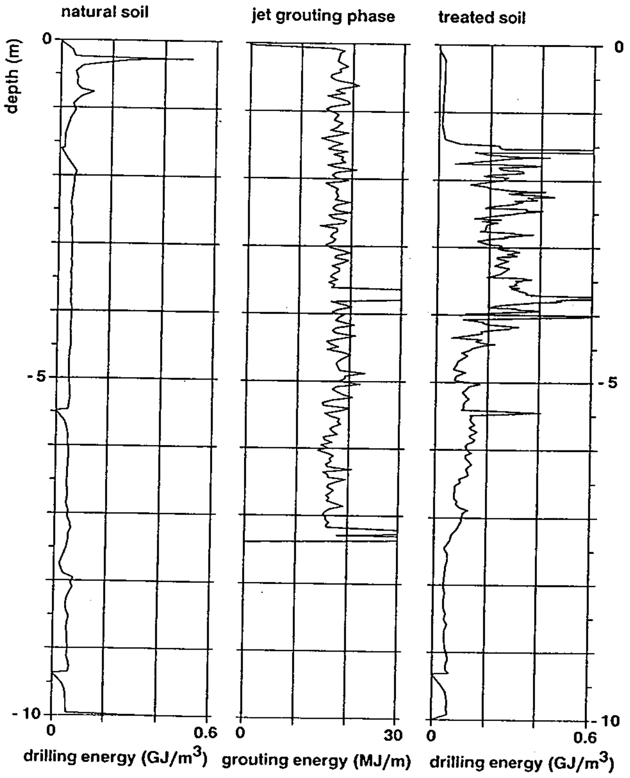

Figure 3. Two fluid system: plots of the drilling energy in natural and treated soil, and grouting energy.

6. LA SPEZIA SITE

An expressway is at present under construction for the connection between the A12 highway and the La Spezia harbour.

Approximately 800 m of trenched road are provided with lateral diaphragm walls and the subgrade is consolidated in order to allow safe excavations up to 10 m depth.

The soil to be treated by jet grouting consists of peaty-silty clay and sandy-clayey silts with CPT point resistance ranging between 0.1 and 10 MPa.

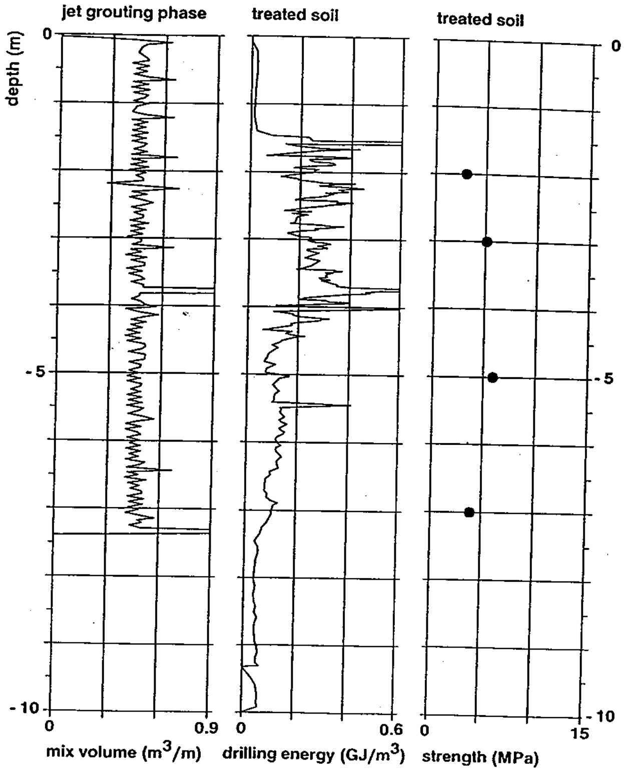

Figure 4. Two fluid system: plots of mix volume and comparison between drilling energy and strength of the treated soil.

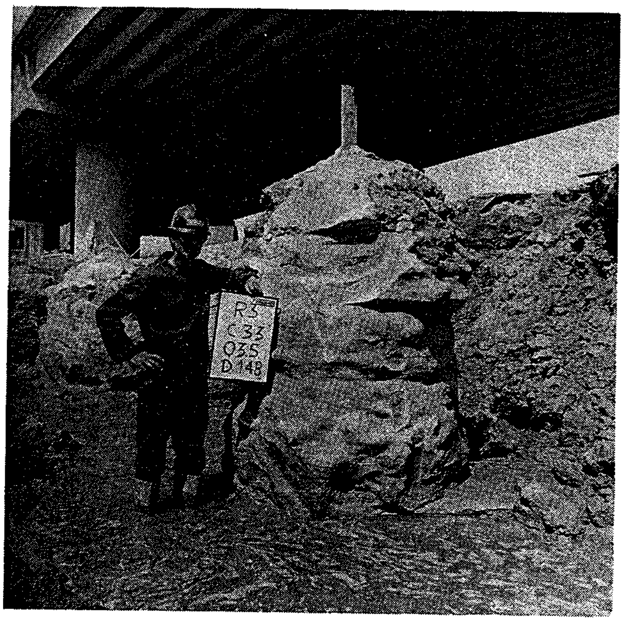

Figure 5. Three fluid system: detail of the treatment.

The method selected for the soil treatment was the three fluid system. The execution of a trial field was required in order to define the optimal grid of the column treatment.

Also in this case the PAPERJET system was applied to define the treatment effectiveness and check all the operational phases of jet grouting.

Fig. 8 shows the output diagrams of drilling energies in both natural and treated soil and the grouting energy. In this case the drilling energy increased from 0,05 [GJ/m^3] in the natural soil to 0.45 [GJ/m^3] in the treated soil, thus showing the success of the treatment.

In addition, the grouting energy certifies the regularity of the operations carried out during the jet grouting treatment.

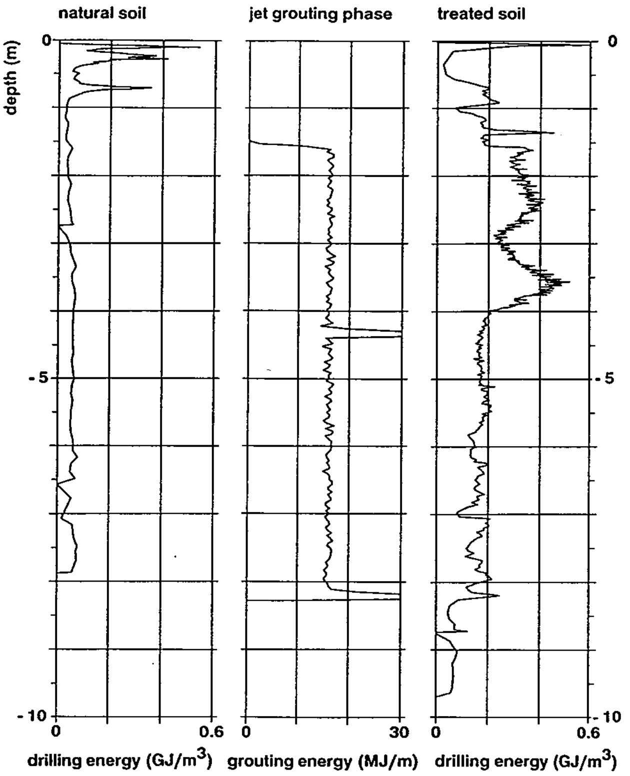

Figure 6. Three fluid system: plots of the drilling energy in natural and treated soil, and grouting energy.

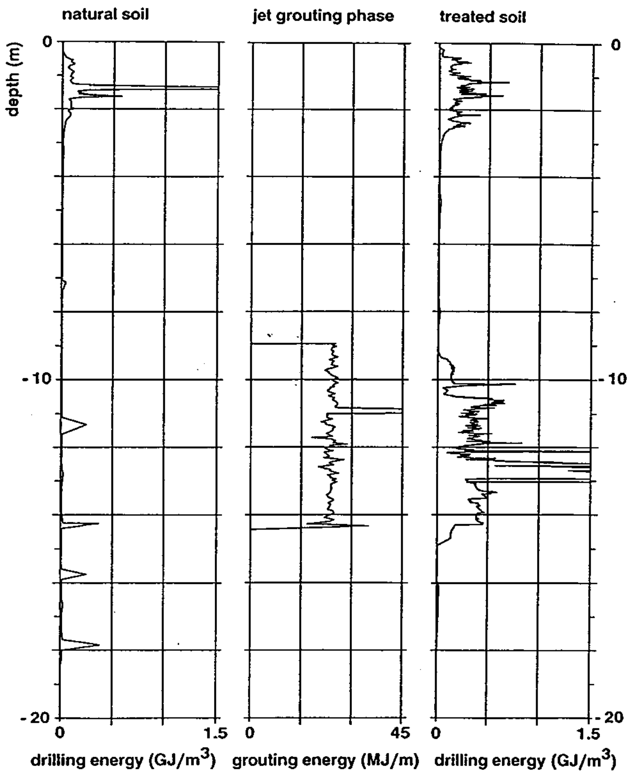

Figure 8. Three fluid system: plots of the drilling energy in natural and treated soil, and grouting energy.

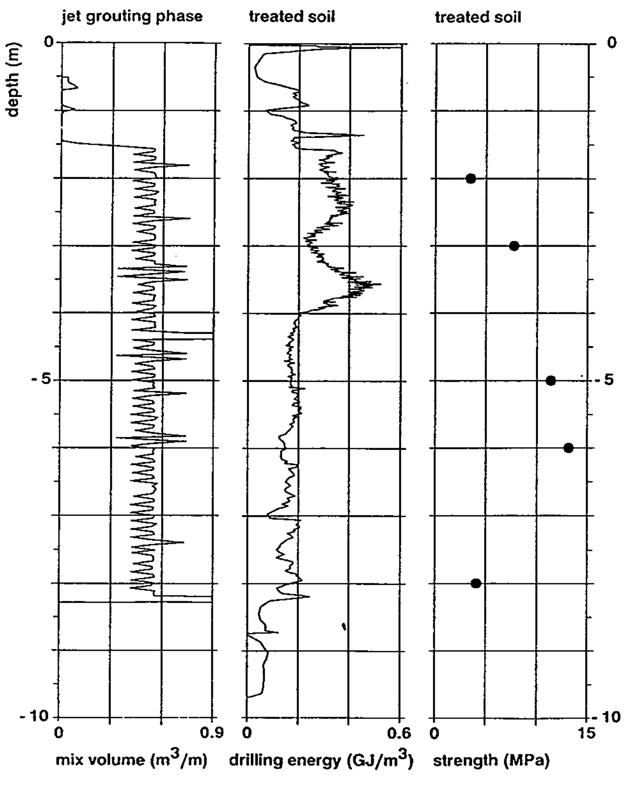

Figure 7. Three fluid system: plots of mix volume and comparison between drilling energy and strength of the treated soil.

7. CONCLUSIONS

The development of PAPERJET system was suggested by the increasing necessity of quality control of the different operations related to jet grouting. This technique turns out to be particularly useful when the consolidation treatments are carried out in urban areas in the vicinity of existing buildings and underground services. The PAPERJET system also proved to be a valid instrument for the "a posteriori" check of the results allowing for a significative comparison between drilling energy and strength of the treated soil.
On the basis of the experience achieved so far and documented in this paper, it is expected that the future development will regard the statistical use of the energetic data, when available for a wide range of soil conditions, in order to optimize each individual application. Depending on the soil profile, energetically characterized, it will be possible to determine the amount of energy to be spent during jet grouting, in order to obtain the desired columns diameters and the specified mechanical properties of the jet grouted soil. In such a way the PAPERJET system will ensure the optimization of the final results complying with the design requirements.

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