SEMINAR
ON
JET GROUTING
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Singapore

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DESIGN PROCEDURES FOR JET-GROUTING

Singapore

April 7th, 1997

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1. **GENERAL**

Earlier in the seventies, here in Europe jet grouting was known as a technique with very few possibilities to be used successfully.

The use of jet grouting became more and more frequent, day after day, starting from early's eighties.

It was believed first that the jet grouting technique could be used in granular soils only; after, by improving the technological procedure and the specific knowledge, it has been understood that in fine soils also jet grouting could be a promising successful tool too, whose results are even more predictable than for granular soils.

The main problem against the widespreading of this technique is that there is not an unique proved calculation procedure to be followed but many procedures are adopted each on with theoretical fundamental and a lot of empirical contents.

As a consequence it can be put forward that, however the presence of jet grouting in earthworks increased very much, the design id still left to the designer's feeling with 99% of empirical background coming from each one own personal experience.

On the other hand it has to be highlighted that nobody can produce a good, safe and reliable design without a very deep knowledge of the working procedure, of practical problems and of the capability of the method.
2. **FIELDS OF INTEREST**

The jet grouting procedure became little by little an actual procedure, no more a promising tool only, and it is widely adopted and accepted as the proper solution in many works updating step by step the frontiers in each kind of soils for most of the foundations soil related problems.

Deep experiences have been proved in most of the soil types:

- coarse alluvial soils
- tills
- gravels
- sands
- silts and plastic soft clays
- stiff clays
- loess

Case records are available on the successful use of the procedure in the following cases:

- soil improvement below wide foundation areas
- bearing elements
- retaining walls (with or without tie-backs)
- impervious cut off walls
- excavation bottom plugs
- soil stabilization for temporary support of the excavated tunnels
- restoring existing foundations
- cofferdams
- stabilization of soil slopes.

All these experiences and case records can supply a suggestion to the procedures to be adopted into calculations for what concerns both soil and soil stabilized columns.
3. DESIGN

Similarly to others fields for which standardization of the design procedures are usual, the creative fantastic phase in which a calculation procedure has to be put forward needs a lot of thinking about the feasible solutions, the advantages of the jet grouting procedures and the details of the steps of the work to get the goal of a safe, cheap and satisfactory solution.

This attractive scope of the work can be reached following a step by step procedure that can be sketched as a "design menu".

Preliminary activities have to be completed before starting in going through the 'options' of the 'DESIGN MENU' in order that all the needed data be fully available.

The lack of information leads to uncomplete design and lack of calculations fonts.

The activities to be completed before going into the heart of the design procedure are:

- collection of all available data on soil;
- mechanical modelling of soils;
- choice of the loading conditions;
- calculation of the loads;
- selection of the materials (including the specific resistance of the stabilized soil).

After the puzzle of the input data and boundary conditions are completed we can open the "Design Menu" (see figure 1).
Provided that it is assessed that the jet grouting procedure is feasible and suitable, first of all one has to decide whether the jet grouting has to be a soil improvement or a structural element.

**FIGURE 1.a - "Design menu": scope of the work**

In a second phase, attention has to be paid to the materials that will be of particular importance for the design (figure 1.b):

- soil type and parameters;
- grout properties;
- soil-grout admixtures (short and long term resistance);
- steel reinforcement, type and geometry;
- additives;
- fillers.
Last but not least the selection of the working procedure has to be made in order that the adopted technology be consistent with design requirements, (see figure 1.c).

**FIGURE 1.b** - "Design menu" - materials
FIGURE 1.c - "Design menu" - working procedures

4. **CALCULATIONS**

Let's now go deeper into the job by following each one of the feasible design process from the beginning to the conclusion.

4.1 **Bearing stabilized soil column (structural)**

For an insulated vertical single element the calculations have to be carried out by considering the single stabilized soil element like a pile: i.e. that the bearing capacity of each j.g. column is:

\[
P_u = P_{\text{base}} + P_{\text{lat}}
\]

\[
P_u = A_b q_b + \pi D_a \int_{l_1}^{l_2} \gamma' z K_s \tan \delta \, dz
\]

in term of effective stresses (long term)

\[
P_u = A_b q_b + \pi D_a \int_{l_1}^{l_2} \alpha c_u \, dz
\]
in term of total stresses (short term for cohesive soils)

being:

\[ A_b = \text{base area of the column} \]

\[ q_b = \frac{1 + 2K_o}{2} \cdot \sigma_{vo} \cdot N_q^* \cdot \zeta \quad \text{in sand} \]

\[ q_b = 9c_u \quad \text{in cohesive soils (s.t.)} \]

\[ D_a = \text{average diameter} \]

\[ N_q^* = \text{bearing capacity factor, for deep foundation} \]

\[ \sigma_{vo} = \text{vertical overburden pressure} \]

\[ \gamma = \text{bulk unit weight of soil} \]

\[ K_o = \text{horizontal earth pressure coefficient at rest} \]

\[ K_s = \text{horizontal restitution coefficient} \]
δ = soil-column friction angle
α = reduction factor for adhesion
\( c_u \) = undrained shear strength
z = depth below ground level
ζ = reduction factor for end-bearing column

As a consequence of the typical technique the soil in contact to the border of the stabilized column has been slightly to strongly compacted, and on the other hand the column section is not uniform with depth: i.e. as a consequence that either for frictional material and for clayey material the contact between the stabilized soil and the natural soil is very intimate, much more than driven piles and far more than bored piles.

**FIGURE 2** - Behaviour of a stabilized soil column as bearing element
For what concerns the shaft contribution to bearing capacity, the failure surface, in case that failure is reached, is then fully embedded in the soil: i.e. that the soil behaviour is predominant either in case of short term and in case of long term analysis.

From the above mentioned mechanism it follows that:

a) in cohesive soils $\alpha = 1$ (°) for normally consolidated soils N.C. to $\alpha = 0.45$ for overconsolidated soils O.C.

b) in granular soils $K_s > 1$

In addition it has to be painted out that the selection of the $D_a$ (average diameter) has to be made carefully in such a way that it should be surely representative of an underestimated safe condition. It follows that the actual diameter of the failure cylinder is higher than assumed and the safety factor increases even more in similar way as $\alpha > 1$ or $K_s$ consistently > 1.

**FIGURE 3 - Soil columns as a bearing element: failure surface for shaft resistance**

(°) top boundary of the adhesion field
The assumption of $\alpha=1$ to 0.45 or $K_s=1$ to 1.4 is then a good estimation provided that a careful estimation of the average representative diameter $D_a$ of the stabilized soil column has been made and that the adopted jet grouting procedure be able to guarantee that diameter.

Similarly, for what concerns end bearing it has to be pointed out that the jet grouted tip also is in intimate contact with the soil, with the exception of the collapsible grounds, thus behaving like a displacement pile or even better.

In collapsible soil a film of destructured material, caused by adsorption of excess water, is formed between the column body and the non-collapsed ground, thus reducing dramatically the skin friction above the water table elevation.

Considerations about group effect, negative skin friction and stratified soils will apply as for piles, provided that reference has to be made to the limiting values reported in table I and table II and mainly to the structural performance of the jet-grouted column.

Strengths of the treated soil as high as 4 MPa in clay and 12 MPa in sandy gravel can be obtained by adopting a proper procedure. With the pre-washing technique higher values, particularly in clay, can be easily obtained.

For what concerns settlements it has to be pointed out that the settlements needed for fully mobilization of the lateral skin friction are negligible (few millimeters only) and that the settlements needed for full mobilization of the base bearing capacity are quite low too (either for the installation procedure and for the low range of mobilized oil strength that can be allowed by the column resistance).
Load tests performed not to failure, or to failure of the top of the column, showed very low settlements of the order of millimeters.

**TABLE I - Granular soils**

<table>
<thead>
<tr>
<th>PILE INSTALLATION TYPE</th>
<th>REDUCTION FACTORS FOR SHAFT FRICTION</th>
<th>LIMIT VALUE OF UNIT SHAFT FRICTION</th>
<th>REDUCTION FACTOR FOR END BEARING</th>
<th>LIMIT VALUE OF UNIT END BEARING</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\delta/\psi$ (-)  $\kappa_s$ (-)  $\tau$ (kPa)  $\zeta$ (-)  $\sigma$ (MPa)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 - bored</td>
<td>0.6  0.5 to 0.65  100 to 200  0.33 to 0.5  4.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 - driven (open end)</td>
<td>2/3  0.65 to 0.95  120  0.7 to 0.8  12</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 - driven (closed end)</td>
<td>0.75  1.0 to 1.5  120 to 180  1.0  15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 - jet grouting</td>
<td>1  1.0 to 2  $\geq$180  1.0  column resistance</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**TABLE II - Cohesive soils**

<table>
<thead>
<tr>
<th>PILE INSTALLATION TYPE</th>
<th>REDUCTION FACTORS FOR SHAFT FRICTION</th>
<th>LIMIT VALUE OF UNIT SHAFT FRICTION</th>
<th>REDUCTION FACTOR FOR END BEARING</th>
<th>LIMIT VALUE OF UNIT END BEARING</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\alpha$ NC  $\alpha$ OC  $\tau$ (kPa)  $\zeta$ (-)  $\sigma$ (MPa)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 - bored</td>
<td>0.9  0.35  275  0.66  4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 - driven (open end)</td>
<td>0.95e  0.40e  200  0.7  1.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 - driven (closed end)</td>
<td>0.80i  0.35i  200  0.8  5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 - jet grouting</td>
<td>0.95  0.45  288  1  column resistance</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$e =$ extern  
$i =$ intern
FIGURE 4 - Effect of installation on tip resistance
FIGURE 5 - Mechanics of jet grouting installation

\[ D_a = \text{MATERIAL TEXTURE DESTROYED SOIL-GROUT MIXTURE (COMPLETELY IMPROVED)} \]

\[ s = \text{THICKNESS OF THE ANULAR ZONE INTERESTED BY PRESSOFILTRATION PROCESS} \]

\[ s_1 = f(\text{soil type, jet energy}) \]
\[ s_2 = f(\text{soil type, water table, W/C content}) \]
FIGURE 6 - Load tests on jet-grouting soil columns
4.2 **Soil improvement**

Soil improvement is an extensive treatment of a large soil volume that changes deeply the behaviour of the soil mass (massive treatment).

The calculations have to be carried out in different ways.

a. **For what concerns bearing capacity**

The lower result from the following two procedures shall be adopted

a.1 **Group of bearing elements**

The bearing capacity of the group is the weighted sum of the bearing capacity of each column.

\[
P_{ul\text{(group)}} = \beta \cdot n \cdot m \cdot P_{ul\text{(col)}}
\]

\(B\) = reduction factor, function of column spacing column length, soil type, etc.
\(n\) = horizontal rows number
\(P_{ul\text{(col)}}\) = bearing capacity of each jet-grouted element

a.2 **Stabilized block analysis**

The bearing capacity of the group is calculated as considering the bearing contribution on the envelope surface of the group: i.e. bearing capacity reaction on the base \(B \cdot L\) and skin friction on the lateral surface \(2 \cdot (B + L) \cdot H\).

With reference to figure 7

\[
P_{ul\text{(group)}} = B \cdot L \cdot Q_b + 2 \cdot (B + L) \cdot (h_2 \cdot Q_{12\text{(av)}} - h_1 \cdot Q_{11\text{(av)}})
\]
being:

\[ \begin{align*}
Q_b & = \text{base unit bearing capacity at depth } H; \\
Q_{12(\text{av})} & = \text{average value of lateral skin friction for } h_2; \\
Q_{11(\text{av})} & = \text{average value of lateral skin friction for } h_1; \\
h_1 & = \text{thickness of the soft layer that can produce negative skin friction}; \\
h_2 & = \text{embedment into bearing layer}. 
\end{align*} \]

If negative skin friction does not develop \( h_1 = 0 \) and \( h_2 = H \).

**b. For what concerns settlements**

- If the load is given by a rigid body and the column tip is embedded in a bearing layer, the whole load is transferred to the columns and the settlements are of the order of the elastic settlements of each column (see figure 8.a).

- If the load is a given by a rigid body and the column tips are not embedded in a bearing layer (floating columns); the load is mostly transferred to the columns and only a minimal portion is supported by the soil; the settlement is higher then the elastic settlements of the columns (see figure 8.b).

- The load is a uniform load on a flexible surface, tips are not embedded in bearing layer; the load is transferred mostly to the columns, but a consistent part is on the soil too, settlements are not uniform (figure 8.c).

- A granular layer of competent thickness is present between the loads and the foundation; the load is mainly on the columns but a consistent part is on the soil too. The presence of the granular pad makes the soil-columns
FIGURE 7a - Bearing capacity of a block of soil stabilized with jet-grouting columns

FIGURE 7b - Sketch of a load for massive jet-grouting treatment
reaction more uniform, but going deeper the soil competent stress also is mainly transferred to the columns too (see figure 8.d).

With the only exception of case "a" in which the soil stabilized columns work likes bearing piles, in the order cases the presence of the jet grouted elements is a proper soil improvement: i.e. that it changes the behaviour of the soil when subjected to loads.

Such a difference between the natural soil and the improved One can be evaluated by adopting the concept of composite soils:

The total load \( N \) is supported partly by the "n" columns and partly by the soil.

\[
N = n \cdot N_c + N_s
\]

\[
N_c = A_c \cdot q_c = \frac{\pi D^2}{4} \cdot q_c
\]

\[
N_s = q_s (A - n A_c)
\]

\[
m = \frac{q_c}{q_s}
\]

\[
a_s = \frac{m A_c}{A}
\]

\[
n = \text{columns number}
\]

\[
A_c = \text{column diameter}
\]

\[
q_c = \text{specific load on a column}
\]

\[
A = \text{total area}
\]

\[
q_s = \text{specific load on soil}
\]

\[
m = \text{stress distribution ratio}
\]

\[
a_s = \text{reinforcement ratio}
\]

\[
h = \text{active depth}
\]

\[
S_s = \text{soil settlement}
\]

\[
S_c = \text{column settlement}
\]

\[
S_o = \frac{N}{A E_s} \quad H = \text{non improved soil settlement}
\]
\[ \text{Simp} = 1 + \frac{1}{(m - 1)a} \cdot S_o \]

\[ \begin{align*}
S_s &= \frac{q_s}{E_s} = \frac{N_s}{A_s E_s} \\
S_c &= \frac{q_c}{E_c} = \frac{n N_c}{A_c E_c}
\end{align*} \]

for congruent deformation \( S_c = S_s \)

\[ \frac{N_s}{(A - n A_c) E_s} = \frac{n N_c}{A_c E_c} = \frac{N}{A E_{eq}} \]

\[ E_{eq} = \left[ (A - n A_c) E_s + n A_c E_c \right] \cdot \frac{1}{A} \]

as raft estimation for a first trial

The solution has to be found for trial and errors procedure.

As a conclusion to the chapter One can say that the improvement is significative when the spacing of the soil stabilized element is sufficiently reduced that the main portion of the total load is transferred to the jet grouted columns: in such case settlements is conveniently reduced as well as differential settlements too.

A check has to be made that the concentrated stresses into the jetted elements be compatible with the column strength.
FIGURE 8 - Developing settlements of soil improved with jet-grouting. a = embedement in a bearing layer, b,c,d = floating columns, a,b = rigid body loading, c,d = flexible uniform load, d = effect of a distributing layer.
4.3 **Circular caisson shaped foundations**

Foundations, particularly for bridges and viaducts, are sometimes placed inside a circular shaft that can be constructed by the aim of the jet grouting technique, this is generally the case of foundations into river beds.

The scope of the shaft is the protection of the foundation against scour. During the construction phase it works also as a retaining wall.

As a consequence of its particular shape the body of the shaft is subjected to uniform stresses in radial direction increasing with depth.

At each depth diametral section on an horizontal plane is subjected to the earth pressure, as a consequence of the installation and of the type of the work has to be considered the "at rest" pressure, i.e. \( K_0 \) condition.

The resultant of these pressure has to be counterweighted by two forces \( N_1 \) and \( N_2 \) that are internal to the shaft body.

The maximum net unit pressure is at the level of the internal excavation. The total pressure of unit height thickness (i) is:

\[
P_i = [(z_i - z_o) \gamma_w = k \cdot \sum \gamma_s \cdot \Delta z] \cdot i \cdot D_e
\]

\[
P_i = N_{1i} + N_{2i} \quad \text{N}_1 = N_2
\]

\[
N_{1i} = \sigma_{ci} \cdot t \cdot i
\]

\[
\sigma_{ci} = \frac{p}{2} \cdot \frac{1}{t \cdot i} \leq \sigma_c(\text{all})
\]
\( z_i \) = depth of layer \( i \)
\( z_o \) = depth of the water table
\( \gamma_w \) = bulk unit weight of water
\( \gamma'_s \) = effective bulk unit weight of soil
\( \Delta z \) = layer thickness
\( k \) = horizontal earth pressure coefficient (design with \( k = k_o \), at rest pressure)
\( i \) = thickness of the considered unit layer
\( D_e \) = external diameter of the shaft
\( t \) = minimum effective thickness of the shaft wall
\( \sigma_{ci} \) = stress in the column shaft in the \( i^{th} \) layer
\( \sigma_{all} \) = allowable stress in the soil stabilized column
FIGURE 9 - Sketch for the design of a cofferdam with jet grouting columns

\[
\begin{align*}
S_w &= (z - z_0) \gamma_w \\
S_a &= K_a \cdot \sum_{\Delta z} \gamma_s \\
S_p &= K_p \cdot \sum_{\Delta z} \gamma_s
\end{align*}
\]
4.4 Bottom plug

In many cases, in order to reduce the risk of bottom piping a layer of jet-grouting consolidated bottom plug has to be made, see figure 10.

**FIGURE 10 - Jet grouting plug below an excavation bottom**

The water pressure on the plug is \( h \cdot \gamma_w \)
The counterweight is given by \( W = h_1 \gamma_s + h_2 \gamma_J \)

being
\( \gamma_w \) = bulk unit of water
\( \gamma_s \) = bulk unit of soil
\( \gamma_J \) = bulk unit weight of jet grouted soil
\( D_i \) = internal diameter of the shaft
for safety  \[ FS = \frac{h_1 \gamma_s + h_2 \gamma_J + \pi D_i \tau h_2}{h \gamma_W} > 1.3 \]
(suggested)

\( \tau \) is the unit mobilized shear strength between the plug and the shaft \( \tau \leq \tau_{amm} \).

The structural contribution of the plug should be calculated for bending on a unit strip as:

\[ \sigma_J = \frac{M}{W} + \frac{N}{A} \leq \sigma_{J(all)} \]

- \( M \) = bending caused by the net uplift pressure
- \( W \) = section modulus
- \( A \) = \( h_2 \cdot 1 \) (for a unit strip)
- \( N \) = 90\% of maximum value coming from section 4.3

\[ 1/2 (P_i=z_1 + P_i=z_2) \cdot h_2 \cdot 1 \]

**FIGURE 11** - Sketch of calculation for bending check
4.5 Earth retaining walls

Sometimes jet grouting can be used successfully with an economical convenience too as earth retaining structure with or without tie back, in spite of more conventional methods (concrete diaphragm wall, sheet piles etc.). In these cases a reinforcement has to be used.

The reinforced jet grouting elements can be designed from a structural point of view, as reinforced concrete elements, where the soil-grout admixtures is the "concrete" reinforced by steel pipe, steel beam, steel bar, etc..

The only differences with respect to the conventional reinforced concrete are the position of the reinforcement that is placed central with respect to the column cross selection (unfavorable) and the grade (the characteristic compressive strength) of the "concrete", and therfore the allowable stress due to the axial load and bending moment.

The allowable stress depends from many factors:

- soil characteristics;
- water/cement ratio;
- quantity of cement for cubic meters of treated soil;
- jet grouting procedure (number and diameter of nozzle, pressure, withdrawn velocity etc.).

If there is not any preliminary test, the choice of this value is a designer responsability.

Figure 12 shows, as an example, the values of unconfined compressive strength vs. the quantity of cement per cubic meter of treated soil. a safety factor equal to 3.0 can be assumed in order to obtain the allowable values.
If the only action is the axial load, the above calculated values should be reduced to 75%.

In the following, as examples, the structural calculation for a single column and for a continuous wall subjected to bending stress (diagram wall) are exposed, in a schematic way.

According to the theory, the following relationships can be adopted, in case of single reinforcement:

\[ x = \frac{n \cdot A_s}{b} \left[ -1 + \sqrt{2 + \frac{2b}{n \cdot A_s}} \right] \]
\[ \sigma_c = \frac{M}{b x \left( d - \frac{x}{3} \right)} \]
\[ \sigma_s = \frac{M}{A_s \left( d - \frac{x}{3} \right)} \]

where the symbols have the following meaning:

- \( x \): distance neutral axis - compressed border;
- \( n \): modular ratio of elasticity;
- \( A_s \): reinforced steel area;
- \( b \): width of the section;
- \( d \): effective depth;
- \( \sigma_c \): maximum jet-grouting working stress;
- \( M \): maximum bending moment;
- \( \sigma_s \): maximum steel working stress.

These relationships are valid for rectangular/square sections and then in the case of the following figure 13.

In case of a single element considered as circular section:

\[ \sigma_c = \frac{M \cdot x}{J_{ci}} \]
\[ \sigma_s = n \cdot \sigma_c \cdot \frac{d - x}{x} \]

being \( J_{ci} \) the ideal inertia moment of the jet-grouting column section in respect to the neutral axis:

\[ J_{ci} = J_y - x^2 \{ R^2 \cdot \left[ \varphi - 5 \cdot \sin (2\varphi) \right] + h \left[ 2\pi \omega (R - T) \right] \} \]
FIGURE 13 - Schemes for calculation of a jet-grouting retaining wall subjected to bending moment

\( J_y \) is the inertia moment of the column section in respect to \( y \) axis (figure 14).

\[
\begin{align*}
\varphi & = \text{see figure 14;} \\
\omega & = \text{diffused steel area;} \\
R & = \text{radius of the column section;} \\
T & = \text{cover.}
\end{align*}
\]
An example of a retaining wall 14.5 m height is reported in figures 15 to 18. Calculations have been performed with the above described methods. A detailed analysis by a FEM method was carried out previously. Pretensioning of tie-backs was needed step by step as the excavation was going on in order to reduce the maximum value of bending stress in the field of acceptance and to prevent the overstressing of the grouted soil.
FIGURE 15 - (Lecco – Italy) - Jet grouting retaining wall - F.E.M. Design (PLAXIS)
FIGURE 16 - Front view and sections of the retaining wall (Lecco - Italy)
FIGURE 17 - (Lecco - Italy) Reinforced jet grouting retaining wall - Working phases
FIGURE 18 - (Lecco - Italy) Details of reinforced jet-grouting wall
5. **CONCLUSIONS**

The considerations reported in the previous chapters need a validation from the field for what concerns the technological performances of the jet grouted material, i.e. that check tests on the jetted soil must be a general procedure not only qualitative but even more quantitative.

On the other hand the need of putting forward reference values is of paramount importance for the designer in order to provide feasible design consistent to stress values that can be easily reached by the improved soil.

Within this point of view on the design procedure a deeper knowledge has to be gained by the engineers on the execution procedures and of the performances that can be obtained by each one of them as applied to each one specific kind of soil.

Research activities in this field will be welcome.