Soil improvement by jet grouting for the solution of tunnelling problems

R. Tornaghi
A. Perelli Cippo
Ing. Giovanni Rodio & C., Milan, Italy

Synopsis
Jet grouting represents the most recent development in injection techniques. The outstanding feature of this method is the ability to treat a wide range of soils – from coarse granular to fine medium-soft cohesive materials even – by use of a simple cement grout mixed in place with soil particles under a very high nozzle pressure (20–70 MPa).

Fundamental principles, equipment, design criteria and quality control with specific reference to the Rodinjet® procedures developed by Rodio Co. are considered. Large-scale tests and specific applications in tunnelling practice are outlined in regard to vertical treatment from the surface around the periphery of a planned tunnel or extended to the area to be excavated and sub-horizontal treatment ahead of the excavation face.

The improvement of soils in terms of reduced permeability and increased strength can be achieved by various injection techniques, which may be summarized as permeation grouting, in which the grout fills the voids without any essential change to the original soil volume and structure; displacement or compaction grouting, in which a stiff mix acts as a radial hydraulic jet, creating bulks or lenses and thus displacing or compressing the surrounding soil; encapsulation grouting, in which the ground is fragmented by hydraulic fracturing: the grout coats and compresses but does not permeate the individual fragments; and jet grouting, in which the soil is mixed in place with a stabilizing mixture, under a very high nozzle pressure (>20 MPa) (in an alternative procedure soft fine-grained soils can be removed to a great extent by air-water jetting and replaced by the grout).

Permeation grouting is feasible for a wide variety of mixtures (from particulate suspensions to colloidal and pure chemical solutions), but both technical and economical hazards increase with decreasing soil permeability.

In terms of the coefficient & the normal permeation limits are of the order of $10^{-2}$ cm/s for silicate-based mixtures and $10^{-4}$ cm/s for the most expensive resin-based grouts.

Displacement grouting and deliberate hydrofracturing are procedures that should be used carefully in particular cases – mostly as temporary or remedial measures for underpinning, correction of differential settlements of structures or recompensation of ground loosened by tunnelling.

The particular advantage of the most recent techniques that are based on jet grouting is the possibility of treating a range of soils from gravel to clay by means of simple cement grouts. Accordingly, an effective soil improvement is obtained that bypasses the problems of penetrability raised by pure permeation criteria as well as the controversy related to the permanence and potential toxicity of chemical grouts. On the other hand, the jet grouting principle overcomes the inconvenience and limitations of other modes of injection, such as displacement and hydrofracturing. To sum up, jet grouting techniques offer a valuable alternative to conventional grouting and sometimes to slurry trenching, freezing and other soil-stabilization methods.

Jet grouting procedures
The Rodinjet technique comprises the fracturing and simultaneous mixing of the soil in situ with a cement grout; alternatively, the soil can be removed to a certain extent (depending on grain size and consistency) by air-water jetting and simultaneously replaced by grout jetting. Hence, the treatment may imply either the use of a single fluid (the grout) as a fracturing medium and stabilizing agent (Rodinjet-1) or three fluids – air and water as the fracturing and washing media and grout as the stabilizing agent (Rodinjet-3).

The sequence of operations related to the former procedure (Fig. 1) consists, generally, of the following main phases: (a)
The size and mechanical properties of treated soil columns depend on the combined effects of the type of soil and composition of the grout, the grout discharge and pressure, related to the number and size of nozzles, and the rotational speed and lifting rate of the monitor.

The diameter of single columns (normally, between 0.4 and 0.9 m) may be increased to 2 m or more by the alternative Rodinjet-3 procedure, which involves air-water jetting through coaxial nozzles placed just above the grout injection nozzles. In this method (Fig. 2) a cased borehole is first drilled with circulation either of water or bentonite mud to the required depth. A string of three-way rods fitted at the bottom with a jetting tool is then lowered into the casing. When the casing has been wholly or partly withdrawn, the injection phase is started by revolving and drawing up the monitor; the procedure comprises fracturing the soil and removing its finest particles by air-water jets just before the injection of cement grout.

**Drilling and grouting equipment**

A Rodinjet-1 plant comprises, in essence, the drilling rig provided with a mud circuit, an automatic mixing plant that, starting from water and dry products (bentonite and cement), supplies the drilling mud and the injection grout, and the injection equipment—automatic batchers and high-pressure pumps.

In addition to the above units a Rodinjet-3 plant includes the water and compressed-air circuits. The high-pressure pump is provided in the water circuit, a medium-pressure pump (up to 12 MPa) being sufficient for the cement grout injection. Air is supplied by a compressor (usually delivering 24 m³/min at 1.2 MPa).

The mode of drilling is selected according to soil conditions, general features of the site and design specifications in regard to length and inclination of holes. Rotary drilling is preferred in medium-to-fine-grained soils, fairly small rigs being required. The use of a power swivel with hollow spindle running on a mast 4–5 m long permits the use of a single rod to a depth of about 16 m.

In coarse-grained soils, including cobbles and boulders, rotary percussion may be more suitable in terms of drilling speed, but this technique requires a heavier rig with a mast as long as the longest rod that is to be used.

Fig. 3 shows a rig that was specially designed by Rodio Co. for sub-horizontal rotary percussion drilling. A system of
hydraulic jacks allows the mast to be rotated to within 180° (acting as a large-scale compass) and inclined up to 15° to the horizontal. By use of this rig all the holes necessary for the treatment of a tunnel section ahead of the excavation face can be drilled to a length of 16 m and with a single rod with no displacement of the equipment.

The selection of a rig that enables operation with a single rod or very long units is advantageous not only to speed up drilling but, more important, to minimize interruptions during the injection phase. Any operation (such as rod-handling, in particular) that causes an interruption of flow under pressure may involve the risk of clogging the nozzles and cutting the column of treated soil.

The Rodinjet method requires a special heavy-duty pump that is capable of delivering water or cement grouts up to a pressure of 60 MPa or more. The grout is prepared in automatic plants that are designed to obtain accurate batching and mixing of the components and to produce adequate quantities for continuous treatment. Each rig may require 5–8 m³/h of grout.

Generally, in Rodinjet the same string of rods is used for both drilling and grouting, whereas Rodinjet-3 involves the use of two strings of rods consecutively. The drilling and jetting tool for the former procedure is shown in Fig. 4(a). A check ball is introduced, at the end of drilling, to change the jet direction from axial to radial. Fig. 4(b) shows the Rodinjet-3 jetting tool.

In practice, during the grouting stage the monitor is raised in stages, but rotation speed is kept constant.

Design criteria

Preliminary site investigation and testing

The factors that affect the feasibility of jet grouting and the selection of working parameters can be assessed by the following general and specific experimental steps: detailed soil profiles and hydrogeological information; simple in-situ tests, such as cone penetration or SPT, for estimation of soil consistence or relative density; classification tests on representative soil samples for evaluation of the grain size distribution of cohesionless materials or the water content, bulk density and Atterberg limits of cohesive formations; laboratory tests on trial grouts and soil–cement mixtures, depending on the importance and specific requirements of the site (in any event, the testing programme is simpler than that associated with permeation grouting requirements); and in-situ jet grouting tests for checking the operational parameters and, if necessary, for the provision of more detailed information for the final design.

Treatment geometry

The flexibility of the Rodinjet method allows a wide range of problems to be solved by suitable geometrical patterns. These include (1) continuous strip treatment by one or more rows of vertical overlapping elements to form cutoff walls for ground-water control or earth-retaining structures (such barriers may have a circular or elliptical shape when the protection of deep shaft excavations is required); (2) block treatment by vertical staggered columns (septed or not) to increase the bearing capacity of foundations or to improve mechanical properties of soils in tunnelling problems (where conditions permit the treatment is done from the surface around the periphery of a planned tunnel or extended to the entire area to be excavated); and (3) sub-horizontal treatment ahead of the excavation face in deep tunnelling when operations from the surface are impossible or inappropriate.

Selection of grout

The grout mix constituents and composition that are selected to meet the specific requirements of strength and permeability have different and less restrictive criteria than those which apply to conventional permeation grouting.

In regard to the initial rheological properties, viscosity and rigidity should be fairly low to allow an effective treatment to the greatest extent. When strength is the main design criterion a simple cement slurry is used, the cement/water ratio (mostly between 0.5 and 1.0) being selected according to various factors besides that of the required strength, i.e. the type of soil in terms of grain size and permeability in general and water content in cohesive formations and the mean quantity of grout per unit volume of treated soil. In permeable granular formations a considerable amount of water may be drained out both from soil and injected grout, whereas in a cohesive soil of low permeability poor drainage is likely to occur. This is the main reason why the strength (depending primarily on the cement/water ratio) is much lower for a clay than for a sand treated with the same volume of grout.

The amount of cement may be limited by suitable selection of composition and volume of injected grout within ranges defined by previous experience and preliminary specific tests to produce an effective treatment as cheaply as possible. The addition of bentonite may be appropriate to reduce drainage effects in granular soils when permeability control is the main concern and high strength is not required. The use of a cement grout stabilized with bentonite is also suitable in Rodinjet-3 treatments when soft soils can be removed by air–water jet to a great extent.

Selection of Jet grouting parameters

The influence of nozzle size, pressure, type and quantity of grout, monitor rotation and withdrawal speeds have been widely investigated for various soils and hydrological conditions. The particularly comprehensive testing programme that was carried out in the experimental site of Varallo Pombia about 60 km northwest of Milan involved calibration tests to define the pressure–discharge relationship as a function of other parameters, several vertical and variously inclined columns with variable jet grouting parameters and full recovery of columns (Fig. 5), permitting a detailed analysis of size, composition and mechanical properties of treated medium to coarse alluvial soils.
In addition, the testing programme included the excavation of a small shallow tunnel through coarse cohesionless soil after Rodinjet-1 horizontal treatment around the tunnel section (see later).

Experience to date from several field trials and sites indicates that the main Rodinjet-1 parameters fall within the following ranges: pressure, 20–50 MPa; nozzle diameter, 1.5–5 mm; rod rotation speed, 10–20 rev/min; rod withdrawal speed, 20–70 cm/min in steps of a few centimetres, with a waiting time of 4–20 s; grout discharge, 1–3 l/s; and volume of delivered grout, 150–350 l/m.

In general, the radius of influence is mainly related to the waiting time between the drawing up steps, i.e. to the permanence of the monitor at the same level. An increase in pressure enhances the fracturing effect of the jet, reducing the time necessary to inject a given quantity of grout.

In each case the selection of operational parameters must be based on a reasonable balance of technical and economical factors that require practical experience and may demand site trials.

Characteristics of treated soils

The result of a treatment, in terms of uniformity and mechanical properties, depends on a number of interdependent factors concerning the type of soil and the jet grouting parameters. The most extensive studies on samples of soils treated by the Rodinjet-1 procedure have been made in the following cases: medium-coarse alluvial materials in the experimental site at Varallo Pombia, medium-fine to fine-grained soils at Porto Tolle (delta of the Po River) and soft marine and peaty clays in Singapore.

The Porto Tolle site represents a typical and well-documented example of continuous strip treatment; a jet grouted cutoff has been created around the existing outlet station of the ENEL thermal power plant to prevent further seepage and internal erosion through loose medium-fine silty sand.

The cutoff was formed by three rows of overlapping columns 17.5 m deep at 0.4–0.5 m centre to centre and penetrating 3 m in a soft silty-clayey formation. The volume of injected grout (cement/water, 0.6) was 250 l/m. After the work had been completed some 100 samples were recovered from eight boreholes drilled inside the cutoff by rotary core barrels.

An extensive laboratory investigation involved systematic unconfined compression tests and determination of bulk density, the results obtained being given in Fig. 6. Disregarding a few data that are affected by local non-homogeneity or sample disturbance (BH S6, in particular), the compressive strength of grouted silty sand ranges mostly between 2 and 10 MPa, with peaks > 20 MPa and a mean value close to 6 MPa. Beyond 14 m depth there is a variably layered transition zone from silty sand to silty clay in which strength decreases significantly.

A comprehensive statistical interpretation of the experimental data involved the correlation of bulk density to strength to enable the actual composition of treated soils to be estimated. The contents of water, cement and dry soil were calculated on the assumption of a general relationship between overall cement/water ratio and strength on the basis of calibration tests.

The loss of water in the fairly permeable silty sand has involved an increase in cement/water with reference to pure grout (from 0.6 to about 0.8 on average), whereas in silty clay the addition of grout reduced to about 0.3 the final c/w ratio.

A more extensive investigation on jet grouted clay in Singapore is dealt with below.

Case histories

Vertical treatment

To date, the majority of jet grouting work has involved strip and block treatments by means of vertical or sub-vertical holes for the solution of a wide variety of problems. In the field of tunneling the first important application of the Rodinjet technique is now in progress in the Singapore Mass Transit System (Phase I project) between Dhoby Ghaut and City Hall Stations.

The geology of the Island of Singapore is complex, several types of soils, such as beach, estuarine and fluvial deposits, marine clay and sedimentary soft rocks, occurring. In general, beach sand and fill, 3–5 m deep, overlie very soft peaty clay, marine clay and fluvial soils to combined depths in excess of 15 m. The base of this sequence is often marked by a layer of silty, fine sand overlying stiff to hard cohesive soils or weak rocks. Groundwater levels range from about 2 m below surface to less than 1 m in the Dhoby Ghaut Station area. Here a thin covering of fill overlies up to 7 m of peat and peaty clay, which, in turn, overlie up to 7 m of medium dense silty sands and stiff clays and then stiffer soils, grading into weathered sandstone or sillstone.

The station area has been excavated to about 15 m depth and Rodinjet treatment has been started by means of vertical, staggered holes along the two independent tunnel routes, passing beneath roads and under (or very close to) buildings and public utility services.

Without any soil improvement even shield excavation could be difficult and unsafe, the permissible magnitude of vertical ground movements being restricted to a few centimetres.

Fig. 7 shows the layout of the first section (about 70 m long), starting from Dhoby Ghaut Station, where soil improvement was required at variable depths according to the soil profile; owing to the presence of soft highly plastic formations and to
Fig. 6 Plots of bulk density and strength versus depth (samples of jet-grouted soil at Porto Tolto).

Fig. 7 Singapore Mass Transit System: layout of Rodinjet treatment along two tunnel sections from Dhoby Ghaut Station towards Victoria Street.
the shallowness of the tunnels, jet grouting from the surface was selected.

In line with the design specifications the treatment has to be extended to the full excavation area above soft rock or very stiff clay, and has to create an arch of strengthened soil 1.5–3.0 m thick around the soft soil that is to be excavated (Fig. 8). The thicker treatment was executed close to the station where the shield could not operate (Fig. 7). To check the proposed solution and to set up the working programme a large-scale trial was carried out on site.

As is shown in Fig. 9, two different layouts of jet grouted columns have been tested – 0.6 and 0.8 m between centres of staggered elements. For each layout two different quantities of grout were injected (600 and 800 l/m² of soil). The four schemes that resulted (including a total of 62 columns) have been arranged in order to form the sides of a square area to be excavated subsequently for visual inspection. The following general procedure was applied to each scheme: drilling to 10.5-m depth, treatment from the bottom to 0.5-m depth by the Rodinjet-1 technique, injecting a grout with c/w = 0.6 (5 kN of cement per cubic metre) and a grouting pressure of 40 MPa.

As is shown in Fig. 9, the instrumentation previously installed consisted of two inclinometers to check horizontal soil displacements, two piezometers to record pore pressure build-up and dissipation and nine datum points to check vertical soil displacements with reference to a fixed point 20 m distant from the perimeter of the test area. Inclinometer I-1, located 1 m from the axis of the external row of scheme IV, recorded the maximum horizontal displacement of 23 cm at about 6-m depth; at 6-m distance the displacements were less than 5 cm. The excess pore pressures recorded by piezometric cells 6.5 m deep 3 and 6 m from the perimeter of the treated area were fairly low (20–40 kPa) throughout the injection period. The levelling of eight external datum points has shown fairly similar profiles along the two normal alignments. After completion of the treatment the mean heave values were approximately 30 cm at 1-m distance from the perimeter, 17 cm at 3 m, 5 cm at 6 m and 1 cm at 10 m.

The total volume of injected grout was 190 m³, which corresponds to 70% of the theoretically involved volume of soil (270 m³). It is estimated that about 70 m³ of soil-grout mixture was rejected during injection and that the overall surface upheaval corresponds to about 60 m² of upward displaced soil. Since no filling of natural voids can be expected in such a fine-grained soil it may be inferred that the remaining 60 m³ (almost one-third) of the injected grout has caused mostly radial displacement and compression effects.

Some two weeks after completion of the treatment eight control boreholes were drilled in the test area (Fig. 9) – two for each treatment scheme (I–IV) and, for each pair, one in the centre of a column and one between the centres of two adjacent columns.

Laboratory tests were carried out on 40 representative samples. Plots of mean values of bulk density and unconfined compressive strength versus depth are shown in Fig. 10 for natural and jet-grouted soil.

Assuming a mean relation between one month's unconfined compression strength, $R$, MPa, and overall cement/water ratio, $c/w$

$$ R = 6.0 \cdot (c/w)^2 $$

and full saturation, the actual composition of the treated soil and the cement content can be estimated (Fig. 11). The average content of $-2$ kN/m³ corresponds to 400 l of grout per 600 l of soil, which is close to the theoretical mean proportion of 700 l of grout per cubic metre of soil. The more detailed statistical data that are listed in Table 1 permit comparison of the com-

<table>
<thead>
<tr>
<th>Samples tested</th>
<th>$n$</th>
<th>$\gamma$</th>
<th>UCS</th>
<th>Composition, kN/m³</th>
<th>$V_g$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Samples of jet-grouted soil</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Centre of columns</td>
<td>22</td>
<td>15.91</td>
<td>604</td>
<td>0.317</td>
<td>7.38</td>
</tr>
<tr>
<td>Between columns</td>
<td>12</td>
<td>16.47</td>
<td>477</td>
<td>0.282</td>
<td>1.72</td>
</tr>
<tr>
<td>All samples</td>
<td>34</td>
<td>16.10</td>
<td>559</td>
<td>0.305</td>
<td>1.94</td>
</tr>
<tr>
<td>Samples of ejected soil-grout mixture</td>
<td>30</td>
<td>14.91</td>
<td>641</td>
<td>0.327</td>
<td>2.33</td>
</tr>
</tbody>
</table>

$n$, number of tested samples; $\gamma$, bulk density, kN/m³; UCS, unconfined compression strength, kPa, after one month; c/w, cement/water ratio = 0.0129 · UCS; S, dry soil; $V_g$, estimated volume of grout, l/m³.
Fig. 9  Singapore Mass Transit System: general layout of Rodinjet test area

<table>
<thead>
<tr>
<th>LEGEND</th>
<th>CENTER OF COLUMN</th>
<th>VOLUME OF MIX PER CUM. OF SOIL (l/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLINOMETER</td>
<td>0.12 m</td>
<td>600</td>
</tr>
<tr>
<td>PEZOMETER</td>
<td>0.16 m</td>
<td>600</td>
</tr>
<tr>
<td>BOREHOLE</td>
<td>0.32 m</td>
<td>800</td>
</tr>
<tr>
<td>DATUM POINT</td>
<td>0.5 m</td>
<td>800</td>
</tr>
</tbody>
</table>

Fig. 10  Plots of bulk density and strength versus depth (mean values recorded in Singapore test area on samples of jet-grouted soil)

Fig. 11  Estimate of cement content, kN/m³, according to laboratory data recorded in Singapore Rodinjet test area (see Fig. 10)
position and properties of samples recovered in the centre and between adjacent columns and those of treated soil and of ejected soil-grout mixture. In statistical terms the strength is above the specified minimum (300 kPa) even midway between the column centres, the treated soil has a c/w ratio that is half that of pure grout and the ejected soil-grout mixture is somewhat richer in cement and water, which indicates a higher grout/soil proportion.

A test pit was excavated inside the test area 15 days after the end of treatment. There was overlapping between adjacent columns with some discontinuities for scheme II only; a spacing of 0.7 m was selected for the final design.

The results that were obtained are satisfactory in terms of the quality of soil improvement, but the magnitude of surface upheaval necessitated modification of the procedure to increase the volume of ejected material. Further testing led to a satisfactory solution to the problem by various adjustments of the drilling and jet grouting parameters.

The total volume of soil to be treated is about 9400 m$^3$ along four tunnel sections of a total length of 367 m. More than 1500 jet grouted columns were undertaken from June to September, 1984, along the two parallel sections that cross Penang Road (Fig. 7). Ground movements, recorded daily by a close network of datum points, were kept within safe limits (2 cm on average), by adjustment of the sequence of jet grouting operations. Systematic control by sampling, laboratory tests and static cone penetration tests are yielding satisfactory results and a good performance is expected when shield tunnelling is carried out.

**Sub-horizontal treatment**

When operations from the surface are impossible or not appropriate jet grouting can be undertaken by means of sub-horizontal holes ahead of the working face. This procedure was tested initially in the experimental site at Varallo Pombia. As is shown in Fig. 12, the portal was created by means of ten sub-vertical Rodinjet columns set in a row on the edge of a slope.
Fifteen horizontal jet-grouted columns 12 m long were then made at variable spacings (between 0.4 and 0.6 m) around the perimeter of a section 2.5 m high and 2 m wide intended for excavation.

The tunnelling operation could be carried out without difficulty under a medium-coarse alluvial covering of only 2–3 m. The treatment (Fig. 13) appeared to be very good and homogeneous along the arch and the right side, where the spacing between centres of elements was 0.4–0.5 m, some small discontinuities being noted only between columns at 0.6 m centre to centre. The recorded heave after jet grouting was, on average, only about 1 cm, despite the thin soil cover above the crown treatment. Subsequent excavation produced settlements of only a few millimetres.

The first major application of the Rodinjet technique ahead of the excavation face was carried out in 1983–84 at Moggio Udinese, northeast Italy. A railway tunnel 12 m in diameter had to be constructed through detrital and mostly cohesionless soil consisting of calcareous rock fragments (up to 10–20 cm in size) in a silty-sandy matrix. Treatment of the first section was effected by a series of 40 overlapping horizontal columns at 0.5 m between centres (Fig. 14). A conventional rotary drilling rig (SR-41) was used in this initial stage. The good results that were obtained by controlled core recovery were confirmed during the excavation, which was started, cautiously, with ribs at every metre and then continued with a rib spacing of up to 2.5 m (Fig. 15).

For the treatment of subsequent sections the rotary per-
cussion drilling rig (Fig. 3) was specially designed to allow precise and rapid positioning of all holes necessary for a cortical treatment (Fig. 16 shows the SR-500 rig during this work). Successive series of 40 overlapping columns 13 m long with a 10% slope to the tunnel axis were formed by holes drilled at an initial spacing of 0.45 m, which permitted excavation stages on 10-m sections alternating with the treatment stages.

The work progressed successfully over a total tunnel length of 150 m at an average overall daily drive rate of 1.50 m. The continuity and mechanical properties of the jet-grouted arch were such that the ribs were virtually unloaded.

A similar type of treatment is being performed in the central area of Milan along the Third line of the underground railway system (lot 3). The alluvial soil of Milan consists of gravel and sand in variable proportions, with fairly thin layers of medium-fine sand and occasional silty-clayey levels.

Drift is driven ahead of the main tunnel bore to allow radial treatment by conventional grouting around the main tunnel section (Fig. 17). Successive series of nine Rodinjet columns 9 m long are formed by holes drilled with an initial spacing of 0.4 m and a 13% slope to the drift axis. This conical treatment has permitted safe excavation in 6-m stages, despite the increasing outward divergence between columns. The geometry of the jet grouting treatment, checked visually during the main tunnel excavation (Fig. 18), proved to be in good agreement with design specifications in regard to both the slope and the expected size (0.7-m diameter on average) of the columns.

References
2. De Paoli B. Machines and equipment for jet grouting in Italy. Paper presented at the specialist day on machines and instruments used in special foundation engineering at the 26th international engineering fair, Brno, CSSR, September 14 1984.