Estimating column diameters in jet grouting processes

Kimpritis, T.¹, Standing, J.R.² and Thurner, R.³

¹ Keller Hellas S.A., formerly Imperial College London
² Department of Civil and Environmental Engineering, Imperial College London
³ Keller Grundbau GmbH, Technical and Commercial Director Middle East and Turkey

Abstract

Jet grouting is widely used in geotechnical engineering for a variety of applications and is a well-proven technique. As with many techniques developed from a practical perspective, there is still scope for improvements both in construction practice and design. This paper focuses on one of the most crucial elements of quality control required with jet grouting operations, the diameter of the constructed column. First, the jet grouting method is explained and the main issues of the concept highlighted. A description follows of the techniques available for estimating column diameter, discussing their application and evaluation on site. There is a particular emphasis on two methods: inclined core drilling and a newly-developed thermic approach (Meinhard et al., 2007) both of which were implemented on two construction projects. Data from these case studies are reported and analysed extensively, in conjunction with influencing factors such as the ground conditions, to assess their effects on the achieved diameter. An empirical approach for evaluating the diameter of jet-grouted columns is developed based on various factors influencing their size such as monitor lifting speed and soil strength.

Introduction

Jet grouting is a process involving high pressure erosion, grout injection and mixing of in-situ ground, resulting in both replacement and relaxation of the soil and the formation of a cemented soil mass which in most instances has the form of a column. The jet-grouted column is constructed by in-situ injection using specialised equipment that comprises: drilling rig, drill rods, grout mixer and pump and injection monitor with one or more horizontal radial nozzles delivering high velocity fluids to erode, mix and stabilise the in-situ soils using engineered grout slurry (ASCE, 2016). During the grouting process, the rotating drilling rods, with the grout injection unit (the monitor) at the base, are raised at a certain lifting speed, hence creating a column (of roughly circular shape) of mixed grout and soil. By constructing a number of overlapping columns, the overall strength and the stiffness of the soil mass are improved. Common
applications of the improved soil mass can be to provide a strutting slab, a cut-off wall or for general ground improvement (e.g. to enable tunnelling works).

In practice, the accurate determination of the diameter of the resulting jet-grouted column is a crucial factor when assessing the integrity and effectiveness of a jet-grouted soil mass. It is hindered by the fact that the constructed columns are often far below the ground surface and, even with stringent construction control measures, the diameter might not be uniform with depth due to varying ground conditions. This paper briefly describes the jet grouting technique and the methods available for estimating column diameter. It then focusses on two of the methods: inclined core drilling, which is very reliable and accurate, and the relatively new thermic method. The effectiveness of the latter is investigated using data from two sites where both methods were implemented. The diameter measurements made on site are correlated with various factors such as the monitor lifting speed and the ground conditions to investigate potential relationships between them. Combining the factors by means of regression analyses, allows simple empirical expressions to be developed for estimating jet-grouted column diameters. The aim of the paper is twofold: (i) to contribute an alternative means of estimating jet-grouted column diameters; and (ii) to encourage the recording and compilation of site information to reinforce such an approach.

Method description

In principle, there are three primary types of jet grouting system, which are classified by the number of fluids injected into the subsoil.

- **Single**: grout is pumped through the rods and exits the nozzles of the monitor at high velocity (i.e. a minimum of 100 m/sec). The energy of the grout stream simultaneously erodes the soil and replaces it with mixture of grout and soil.
- **Double**: compressed air (200 to 1000 kPa) is supplied and surrounds the grout stream in order to enhance the erosive effect (Figure 1).
- **Triple**: the soil structure is broken down with a high pressure water jet shrouded by an air jet for increased efficiency. The surrounding soils are thus hydraulically eroded and then mixed with a jet of cement slurry in situ to create soilcrete columns. The cement slurry is injected at low pressure from the same monitor through lower level nozzles. In this grouting process, due to differences in density, most of the grout remains within the jet-grouted column while the water rises above it. The excess water-soil-cement mixture flows to the surface through the annular space between the drill rods and the borehole wall.
Decisions relating to jet grouting operations are mainly empirical, being based on experience, where certain values of jet grouting parameters (e.g. rotation speed, injection pressure) are correlated with various soil types. It should be noted that, strictly speaking, the operational variables (e.g. rotation speed) are not 'parameters' but this is the general term usually used in industry to collectively describe them and so has been implemented herein. The final ground improvement (i.e. the product of jet grouting) and its characteristics may vary in different countries regardless of whether the same parameters were utilised. Therefore the empirical relationships developed later in the paper should be used with caution and the constants within them developed for each specific site and project. The following jet grouting parameters and their values are usually specified, and also electronically recorded:

- grout pressure and flow rate;
- water pressure and flow rate (if used);
- air pressure and flow rate (if used);
- lifting speed of the drill rods during the jetting process;
- type of monitor and number or nozzles;
- rotation speed of the monitor.
Methods for estimating the diameter of jet-grouted columns

A primary concern in the quality control of jet grouting operations is the estimation of the final diameter of the column and whether it varies over its length. The type of soil, the project itself (e.g. underpinning, retaining works, soil improvement) along with its specific conditions (e.g. execution inside existing buildings, grouting depth) all influence the method that can be used to estimate or measure the column diameter.

The main methods available for measuring the jet-grouted column diameter are listed below.

1. Excavation (Figure 2).
2. Core drilling: vertical or inclined (Figures 3 and 4).
3. Thermic method: where by measuring on site the temperature during the curing process of the binding agent (cement) along the centre of the jet-grouted column, the achieved diameter and the cement quantity in the column can be calculated (Meinhard et al., 2007, following the work of Brandstätter et al., 2002).
4. Jet grouting column callipers: these are mechanical devices which are lowered into the fresh jet-grouted column, immediately after its construction, and their arms opened to measure the diameter (Getec, 2004).
5. Painted bars: these are installed vertically in the ground around the column centre at distances roughly equal to the expected column diameter. After the jetting process, they are retrieved from the ground and the column diameter is estimated based on the amount of paint remaining after erosion from the jetting process.
6. Hydrophones: these are installed in the ground (at similar locations to those for the painted bars method) and the column diameter is estimated from the sound intensity recorded and the form of the sound diagram produced (‘flat’, ‘plate’, ‘wave’ or ‘peak’) (Leible, 2011).
7. Empirical calculation models: based on the density of the mixed grout and soil spoil coming to the surface during the jetting process (Lesnik, 2003).
8. Geophysical methods: e.g. the Electric Cylinder® Method (CYLJET) (Frappin and Vernhes, 2011).
9. Wave analysis method: in this method the evaluation of the diameter of the jet-grouted column is based on an elastic wave analysis approach (Schorr et al., 2007)
10. Turbulent kinematic flow theory: in this approach, the eroding ability of the high pressure injection grout is evaluated using a semi-empirical equation, the constants of which are determined from results of previous experiments and trials. A relationship between the
achieved diameter, the jet grouting parameters and the soil properties is thus defined. (Wang, et al., 2012)

11. Analytical approach: the diameter calculation is based on theoretical models (Modoni et al., 2006).

The methods available can be categorized into three main groups.

- Those where a physical visual inspection takes place, (for instance: method 1, exposed columns (Figure 2); or method 2, core drilling (Figure 3)). Both of these methods are referred to in BS 12716 Section 9.4 (BSI, 2001)
- Those where no visual check takes place (methods 3 to 9).
- Those where the diameter is calculated based on theoretical approaches (methods 10 and 11).

The first group provides the most accurate determination of diameter since the methods involve a physical visual inspection. In the second category, the estimation is made (and hence quality control checked) during or just after the soil treatment and without being time consuming. The third group involves models that are based on theory and so essentially such analyses are usually performed independently of site measurements.

Figure 2: Excavated trial jet-grouted column (Thessaloniki Metro, December 2013)
Figure 3: Inclined core drilling for column diameter estimation

Figure 4: Cores from inclined drilling (Thessaloniki Metro, June 2012)
In this paper, two of the available methods are described in more detail: inclined coring (method 2) and the thermic method (method 3). These are then investigated further using field measurements and records from two sites where both techniques were implemented.

**Inclined coring.** In order to calculate the diameter using the inclined coring method the following information is required: the surface coordinates of the point of drilling of the column and the coring; the inclination of the column itself (if not vertical); the angle at which the core was drilled; any deviation in the drilling and the length of the core sample. Trigonometric formulations can then be applied to the basic geometry to determine the diameter. This method, together with that involving excavation, is considered to be the most reliable and accurate of all available methods.

**Thermic method.** Meinhard et al. (2007) explain that the thermic method involves exploiting the exothermic characteristics established during the hydration process of early-age jet grouted soil. In order to apply the method the following are needed: (i) in-situ temperature measurements made at the centre of the column directly after column construction; (ii) the properties of the employed binder (usually cement); and (iii) the thermal properties of the surrounding soil (the volumetric heat capacity $C$ (kJ/(m$^3$K)) and the thermal conductivity $k$ (W/(mK)) which are usually obtained from database software. The temperature measurements primarily relate to the binding agent (in most cases cement) as they are taken at the centre of the Jet Grouting column directly after its construction for a minimum duration of 30 hours. The recorded temperature history is input into commercial software, named ‘Tempjet’, which produces an in-situ temperature versus time ‘in-situ’ curve. This in-situ curve is compared with model curves, generated from finite element analyses implementing a multiphase hydration constitutive model, which are produced for the various types of binding agents (e.g. cement) used in the construction of columns. The unique theoretical curve that best matches the in-situ curve is established (using ‘Tempjet’) and the diameter estimated along with the cement quantity within the jet-grouted column. More specific details of the method are given by Meinhard et al. (2007).

**Information on the two project case histories**

Both of the above techniques were widely implemented as part of the various jet grouting operations used during the construction of Analipseos and Patrikiou Stations which form part of the Thessaloniki Metro in Greece. The locations of the stations, within the overall Metro system, are shown in Figure 5. Major jet grouting operations took place for the construction of the
Analipseos Station. Only details from a trial field executed at Patrikiou Station are presented but this was very extensive and detailed, producing a large valuable data set.

Figure 5: Thessaloniki Metro Map

A layout of the Analipseos Station together with a short description of the main Jet Grouting applications is presented in Figure 6. A field trial was also executed prior to the works shown in the layout. The most important jet grouting operations were to construct: (i) the wall between the tunnel alignments before the tunnel boring machines passed through the station (prior to its excavation); and (ii) a jet-grouted strutting slab beneath the foundation slab.

Figure 6: Plan of Analipseos Station, showing areas of jet grouting operations
The soil conditions at Analipseos and Patrikiou Stations are similar. According to the geotechnical longitudinal section (TMCJV, 2010) there is a complex soil profile beneath Analipseos Station, consisting of medium dense, light brown to brownish green, clayey/silty sands with gravel and with intercalations of medium dense, clayey/silty gravels with sand to a depth of about 27m below the natural ground surface. In practical terms, when assessing jet grouting operations, the soil is a mixture of clay, sand, silt and some gravel with some intercalations of either clay or sand. A range of unconfined compressive strengths (UCS), $q_u$, of 110 to 150 kPa was adopted as input for the execution of the jet grouting works, which should be remembered were only over a limited depth range (TMCJV, 2010). The soil conditions (based on borehole TKSP21) and profiles of SPT N-value and $q_u$ are summarised in Figure 7a. The soil profile is only approximate but gives an impression of the variability of the ground at the site. Boreholes TKCP27 and TKCP28 encountered greater thicknesses of clay.

The soil beneath the Patrikiou Station has greater thicknesses of clay and silt but also contains layers of medium dense to dense clayey/silty gravels with sand. At this site, a range of unconfined compressive strength values of 75 to 120 kPa, representing an overall average value, was adopted as input for the whole station (TMCJV, 2012). Approximate soil conditions for this site (based on borehole TTLSP22) along with profiles of SPT N-value and $q_u$ are summarised in Figure 7b.

**Data analysis**

During the jet grouting operations, various data were collected relating to the column diameters achieved and the factors influencing their size (jet grouting operational parameters and soil conditions). With the exception of the lifting and rotational speed of the monitor, all other operational parameters remained constant and are given in Table 1.
Figure 7: Variations in STP N-value and UCS ($q_u$) with depth and approximate soil profile for (a) Analipseos Station and (b) Patrikiou Station
An evaluation of the available geotechnical data was made to divide the soils into two very broad categories from the mixed soil profiles: in Figures 8 to 12, discussed later, cohesive (clay/silt) soils are shown by open (red) data points and granular (sand/gravel) soils by solid (blue) points. Also ground characteristics such as unconfined compressive strength (UCS) and Standard Penetration Test (SPT) N-values were estimated at the depths of interest. UCS and SPT N-values were selected from site investigation boreholes closest to each jet grouting element. Equally, each jet grouting element examined is related to the closest borehole within the station area. For example, in Figure 11, for a specific test column where its diameter was verified as 1.28 m at a certain depth (in this case 22.5 m), the closest borehole log was referred to in order to obtain the appropriate SPT N-value at the same depth (46 blows in this example). This procedure was repeated for the whole investigation and the resulting data used to produce Figures 8 to 12. In all cases, the diameter was determined by the method of inclined core drilling and hence should be of high accuracy. It should be noted that data from both single and triple injection systems have been grouped together in these figures.

### Table 1: Jet grouting operational variables used at the two sites

<table>
<thead>
<tr>
<th>Jet Grouting main components</th>
<th>Jet Grouting Parameters</th>
<th>Units</th>
<th>Single</th>
<th>Triple</th>
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<tr>
<td>Grout</td>
<td>Pressure</td>
<td>kPa</td>
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<td>8,000</td>
</tr>
<tr>
<td></td>
<td>Flow rate</td>
<td>lit/min</td>
<td>430</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>w/c</td>
<td></td>
<td>0.8-1.3</td>
<td>0.5-0.6</td>
</tr>
<tr>
<td></td>
<td>No of Nozzles</td>
<td></td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Nozzle Diameter</td>
<td>mm</td>
<td>4.5</td>
<td>9.0</td>
</tr>
<tr>
<td>Water</td>
<td>Pressure</td>
<td>kPa</td>
<td>-</td>
<td>30,000</td>
</tr>
<tr>
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<td>Flow rate</td>
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<tr>
<td></td>
<td>No of Nozzles</td>
<td></td>
<td>-</td>
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</tr>
<tr>
<td></td>
<td>Nozzle Diameter</td>
<td>mm</td>
<td>-</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Mean lines, used to help identify trends within the scatter of the data in Figures 8 to 12, were determined by fitting a linear regression through the data using the method of least squares. Values of the coefficient of correlation ($R^2$) are marked on the figures and generally are very small (a value of $R^2 = 1$ indicates that there is perfect correlation between the best fit line and the data). This is a reflection of the considerable scatter in the data which results from both the
number of variables involved and also the complex ground conditions. In view of the scatter it was decided that a simple linear fit was most appropriate, more complex functions not being justifiable or of practical benefit. Improved correlations could be achieved if selected outlying data points were omitted but it was decided to retain all points for completeness. A number of conclusions can be drawn from evaluating the data presented in Figures 8 to 12.

First, it can be seen that in most cases where the ground was mainly sand/gravel the diameter achieved was relatively larger than in cases where the soil was mainly silt/clay. This is most clearly seen by the mean lines drawn through the two sets of data in each figure: the solid (blue) line (relating to sand/gravel) is always above the broken (red) line (relating to silt/clay).

- In mainly sand/gravel soils: the mean value of the diameter was 1.5 m with minimum and maximum values of 1.2 m and 2.0 m.
- In mainly clay/silt soils: the mean value of the diameter was 1.4 m with minimum and maximum values of 1.1 m and 1.8 m.

This seems a logical result as a granular soil should be easier to erode than a cohesive one for a given injection pressure, thus resulting in a larger diameter column.

Figure 8 illustrates clearly the difference between the diameters for the two soil categories for varying lifting speeds, \( \dot{z} \), (solid symbols are above open symbols in most cases). It is also evident, as expected, that an increase in the lifting speed of the monitor leads to a reduction in column diameter achieved, although the effect is not strong, as indicated by the shallow inclination of the trend lines. For both soil types there appears to be an optimum lifting speed in the range of 15 to 25 cm/min where the largest diameters were achieved (most clear with the granular soil).

Just after the production of each jet-grouted column, wet samples of the fresh grout-soil material were retrieved from within the column using a special sampler which could reach the depth of interest and take a sample at that specific level (known as a wet sampling process). Specimens were prepared from these wet samples for UCS testing after 7 and 28 days. The resulting UCS 28-day values are plotted against column diameter in Figure 9 to assess whether this measure can be used to help assess column diameter achieved. It can be seen that the diameter is not strongly influenced by the mean UCS values, although there are minor trends of diameter reducing with increasing grout-soil strength. As with the lifting speed data there appears to be an optimum UCS strength in the range of 2 to 4 MPa for the granular soils.
As the density values of the fresh grout-soil, $\rho_{\text{JG}}$, were readily determined at the same time that the UCS samples were prepared, these can also be correlated with jet-grouted column diameter. The mean value of $\rho_{\text{JG}}$ for both soil categories was the same: 1.62 t/m$^3$. The range of values recorded is greater for the clay/silt soil type with minimum and maximum values of 1.37 t/m$^3$ and 1.88 t/m$^3$, while for the sand/gravel soil type they are 1.46 t/m$^3$ and 1.75 t/m$^3$. The results are presented in Figure 10. There is a general trend (within the scatter) of the diameter reducing with increasing density for the sand/gravel soil category. This logically follows from the same trend observed with UCS values (diameter reducing as UCS increases) as broadly UCS would be expected to increase with increasing density. The effect is barely discernible for the clay/silt soil category. The trends for $\rho_{\text{JG}}$ are also discussed later when the empirical model is presented and explained.

The influence of the ground SPT N-values on jet-grouted column diameter is shown in Figure 11. The diameter becomes smaller as the SPT values increase regardless of soil type. This again seems logical as the stronger the soil is the more difficult it should be for a given injection pressure to erode it and hence the smaller the resulting jet-grouted column diameter. There are a number of points in Figure 11 at the SPT N-value of 50, at which the test is often stopped. It would have been interesting to continue these tests further to see whether the observed trend was confirmed more clearly. The UCS of the natural soil prior to jet grouting operations would be expected to have a similar trend of reducing column diameter with increasing $q_u$. The results are plotted in Figure 12. There is a clear trend to this effect for the clay/silt soils for which this type of test is more appropriate. In the case of the sand/gravel category there does not appear to be any trend. This is not surprising as predominantly granular soils would be much more prone to random failure in an unconfined condition (even if they do contain small fractions of clay/silt). It can be concluded that UCS tests are not helpful for making interpretations with the granular soil category. The SPT N-value is much more suitable.

The data plotted in Figures 8 to 12 provide a basic idea of how the jet-grouted column diameter is influenced by various factors that can be readily determined either in advance of or during the jet grouting operations. Further analyses with more quantitative tools are discussed later to help provide clearer trends and a more accurate understanding of what primarily influences the diameter and how it can be calculated.
Figure 8: Relationship between jet-grouted column diameter and monitor lifting speed

Figure 9: Relationship between jet-grouted column diameter and grout-soil UCS from specimens prepared from wet sampling
Figure 10: Relationship between jet-grouted column diameter and jet grouting material (wet sampling) density

Figure 11: Relationship between jet-grouted column diameter and in-situ SPT N-values
Evaluation of inclined coring vs thermic methods for estimating column diameter

The thermic method was widely applied during the jet grouting operations carried out at the two sites, allowing its accuracy to be checked either with the excavation method or in most cases with the inclined core drilling method (both of which are considered to be the most reliable methods available). The data from the two methods have been evaluated statistically as shown in Figures 13 and 14 for the clay/silt and sand/gravel soil categories respectively. In compiling the figures, the diameter values estimated by the inclined coring method, $D_{coring}$, and thermic method, $D_{thermic}$, were correlated as closely as possible at the same position along the jet-grouted column to avoid any irregularities in diameter with depth. In a small number of instances the diameter was determined to be much lower than 1.0 m as a result of very hard soil or rock within the complex soil conditions beneath the Analipseos and Patrikiou stations where, no matter how much the pressure or flow rate value were be increased, the soil could not be further eroded by the injection (as these layers only usually extended over a short distance, usually just above or below these regions the diameter of the same column increased to more typical values in a range of 1.3 to 1.5 m). These very small diameters encountered have been excluded from the analysis as they do not represent the typical jet grouting process.
By separating the results for the two soil categories, it becomes clear that estimating the diameter using the thermic method is influenced by the ground conditions over the depth at which the various tests were performed. Taking the inclined core drilling method to be the most accurate for estimating jet-grouted column diameter, the analyses indicate that the thermic method provides diameter values that in general are: larger than reality in clay/silt category soils ($D_{\text{thermic}} = 1.14D_{\text{coring}}$) and smaller than reality in sand/gravel category soils ($D_{\text{thermic}} = 0.89D_{\text{coring}}$).

From the analysis of the results from the two sites on the Thessaloniki Metro, the following has been established for clay/silt category soils (Figure 13):

- 80% of the ratio $D_{\text{coring}}/D_{\text{thermic}}$ is less than 1.00,
- 20% of the ratio $D_{\text{coring}}/D_{\text{thermic}}$ is between 1.00 and 1.30.

Therefore from Figure 13 and the average value, it can be seen that the thermic method gives results which are 12% more optimistic than the actual diameter of the column and so is likely to over-predict the actual diameter.

For the sand/gravel category soils (Figure 14):

- 76% of the ratio $D_{\text{coring}}/D_{\text{thermic}}$ is more than 1.00,
- 24% of the ratio $D_{\text{coring}}/D_{\text{thermic}}$ is between 0.80 and 1.00.

In this case the thermic method under-predicts (by about 12%) the actual diameter of the column and thus overall the results are on the safe side.
Figure 13: Statistical analysis of $D_{\text{coring}}/D_{\text{thermic}}$ for clay/silt soil category (average = 0.88, standard deviation = 0.20)

Figure 14: Statistical analysis of $D_{\text{coring}}/D_{\text{thermic}}$ for sand/gravel soil category (average = 1.12, standard deviation = 0.23)
Although data for both single and triple injection systems have been grouped together in the figures presented here, in appraising the data it was additionally observed that when using the triple injection system, the in-situ temperature-time curves made on site for the thermic method fit much better with the theoretical curves (produced by the software Tempjet) than those generated when using the double or single system. This is probably because with the triple system, due to the use of water in the eroding phase and the filling with grout, the jet-grouted column is a more homogenous body with less soil inclusions within it.

In general the results from the thermic approach indicate that it is a promising method, especially when using the triple injection system. Care is needed in the clay/silt soil category where it is likely to over-predict jet-grouted column diameters. As with many new techniques it would be prudent to perform a number of field trials using both thermic and inclined coring (or excavation) methods to calibrate the former and to gain experience of the various influencing parameters. The thermic method could then be used extensively on the site with much greater confidence and providing considerable savings in time and costs.

**Development of empirical expressions for estimating column diameter**

Having investigated various relationships between jet-grouted column diameter and jet-grouting operations and jet-grout and soil properties, a further examination of the results is undertaken to provide empirical expressions to estimate the diameter that will be achieved for specific site conditions. The various factors that influence the resulting diameter are depicted in Figure 15.
Figure 15: Factors that influence the jet grouting process and resulting column diameter

Drawing on the relationships investigated in Figures 8 to 12, a linear regression analysis has been performed for estimating jet-grouted column diameter. The diameter is principally influenced by the soil conditions and the monitor lifting speed, when other operational variables such as injection pressure, grout flow rate and nozzle diameter remain constant (for both single and triple injection systems, as presented in Table 1).

The effect of depth is also usually found to play a significant role regarding the size of the column diameter. Generally, the deeper the level at which the column is formed, the smaller is its diameter. However, this effect was not observed in the diameter results presented from the complex soil profiles beneath Analipseos and Patrikiou Stations (see Figure 7). Consequently, the depth effect was not taken into consideration at these sites, since the size of the diameter was independent of depth.

Four independent variables were considered in the regression analysis: lifting speed $\dot{z}$ (cm/min); density of fresh grout-soil material sampled from within the column $\rho_{JG}$ (t/m$^3$), the unconfined compressive strength of the soil $q_u$ (kPa) and the SPT N-value (blows). In view of the fact that the trends in grout-soil material UCS and $\rho_{JG}$ were similar, as discussed earlier (Figures 9 and
10), only $\rho_{JG}$ has been included in the regression analysis. Therefore estimated column diameter can be expressed as a function of the above four independent values.

$$D = \alpha_1 \dot{z} + \alpha_2 \rho_{JG} + \alpha_3 q_u + \alpha_4 \text{SPT}$$

where $\alpha_1$, $\alpha_2$, $\alpha_3$, $\alpha_4$ are regression variables.

To improve the accuracy of the empirical model, the data have been divided into four groups based on ranges of values of monitor lifting speed ($\dot{z}$). The four expressions from the regression analysis are presented below and represent both soil categories collectively.

- **Range 1** ($10 \leq \dot{z} < 15$): $D = -0.040\dot{z} + 0.861\rho_{JG} + 0.010\text{SPT}$
- **Range 2** ($15 \leq \dot{z} \leq 20$): $D = +0.044\dot{z} + 0.615\rho_{JG} - 0.002q_u + 0.001\text{SPT}$
- **Range 3** ($20 < \dot{z} < 30$): $D = +0.046\dot{z} + 0.844\rho_{JG} - 0.007q_u - 0.013\text{SPT}$
- **Range 4** ($30 \leq \dot{z}$): $D = -0.012\dot{z} + 0.938\rho_{JG} + 0.002q_u + 0.003\text{SPT}$

The absolute error of the above expressions is 0.11m, meaning that for any application there could be an accuracy error in the range of ±0.11m (e.g. if the diameter is calculated to be 1.65m, the actual value is between 1.54m and 1.76m). This error value is considered to be acceptable for most jet grouting operations. As the above expressions are empirical, there is not always a physical explanation for the influence of each factor on the resulting estimated diameter. However, a number of observations can be made based on the magnitude of the regression variables ($\alpha_1$, $\alpha_2$, $\alpha_3$, $\alpha_4$).

- The optimum lifting speeds $\dot{z}$ (cm/min) for producing the greatest column diameter are in the range $15 \leq \dot{z} < 30$ (ranges 2 and 3), where the $\alpha_1$ factor is positive.
- When monitor lifting speeds exceed 30 cm/min (range 4), this has detrimental effect on the resulting diameter, with a negative $\alpha_1$ value. This is a logical result, as during the jet grouting operation there would be less time for the soil to be eroded. Conversely, a reduction in monitor lifting speed would usually be associated with an increase in diameter. However, this does not seem to be the case for slowest speed range 1 ($10 \leq \dot{z} < 15$), where the $\alpha_1$ value is also negative. This suggests that reducing the monitor lifting speed too much, which is not economic in terms of time and fuel, does not necessarily provide benefits in terms of column diameter. Similar observations have been noted in other jet grouting projects and countries. For example, in the Narvik project in Norway (Figure 1), the optimum lifting speed was determined from a field trial to be 20 cm/min, resulting in a column diameter of 2.4 m (verified by excavation method), reducing the lifting speed to 10 cm/min led to a smaller column diameter of 2.0m. The reason for this is not clear.
Regarding the density of the fresh jet-grout material (from wet sampling), for all ranges, the higher its value, the greater the column diameter. This contradicts the trend observed in Figure 10 and is a consequence of combining the other three influencing factors together. As values of \( \rho_{JG} \) are in all cases greater than 1 t/m\(^3\) (logically, as this is the density of water) and the associated regression variables, \( \alpha_2 \), are approaching unity, this suggests that the \( \rho_{JG} \) factor has a strong influence on the diameter estimated from these empirical formulations.

The \( \alpha_3 \) and \( \alpha_4 \) regression variables are generally small and so have a lesser influence on the estimated diameter. This is especially so for \( \alpha_3 \), which is omitted for the first range since it was less than 10\(^{-3}\). Low \( \alpha_3 \) regression variable values are appropriate as the unconfined compressive strength test is often not suitable for intact soils (especially those with large granular content).

The above expressions can be readily used to obtain rough estimates of the diameter of jet-grouted columns constructed in soils with comparable characteristics to those of the two sites from the Thessaloniki Metro discussed here. Similar formulations can be produced for other sites after establishing the soil characteristics (from the ground investigation carried out in advance of the works), using the operational variables planned for the site and the density of fresh grout-soil material measured on site. The approach is intended as a practical way of estimating the diameter of jet-grouted columns and is recommended for major projects where normally field trials are carried out prior to the main works.

**Conclusions**

A vital component of quality control in jet grouting operations is the accurate estimation of resulting jet-grouted column diameters. There are several methods available for determining the column diameter: the excavation and inclined core drilling methods are the most accurate and reliable but also require much more time and cost compared with other methods.

Many of the alternative methods are promising but, as there is only limited experience with many of them, they need to be tested / calibrated for the specific site conditions using field trials where either excavation or inclined drilling methods are also being used, unless there is past experience and data for similar ground conditions. The thermic method was used extensively, in conjunction with the inclined core drilling method, on two construction sites forming part of the Thessaloniki Metro. Correlating the data from both has demonstrated that the thermic method works well, predicting diameters to within ±12% of the actual diameter, over-predicting in clay/silt soils and under-predicting in sand/gravel soils.
Potential relationships between the measured / estimated column diameters and factors such as monitor lifting speed ($\dot{z}$), soil strength ($q_u$ and SPT N-value), and the density ($\rho_{\text{JG}}$) of fresh grout-soil material (sampled from the wet column) have been investigated. A common finding is that diameters are always marginally larger when the jet grouting is performed in predominantly granular soils, all other factors being equal. Linear regression analyses were performed, combining the factors, to develop empirical expressions for estimating column diameter of the form:

$$D = \alpha_1 \dot{z} + \alpha_2 \rho_{\text{JG}} + \alpha_3 q_u + \alpha_4 \text{SPT}$$

where $\alpha_1$, $\alpha_2$, $\alpha_3$, $\alpha_4$ are the regression variables. The expressions developed, for the two sites and the jet grouting operational variables adopted on them, provide a reasonably accurate (the accuracy error being in the range of $\pm0.11$m) and practical way of estimating the diameter of jet-grouted columns at minimum cost during an extended production sequence.

For new sites, information relating to the soil can be obtained in advance from the ground investigation reports and the jet grouting operational variables are given (being selected by the jet grouting contractor). Therefore the main input variable required from site is the density of the fresh grout-soil material which can be readily determined using wet sampling techniques. Suitable expressions can then be developed from field trials performed prior to commencement of the main works where column diameters are measured using one or more methods (calibrated against excavation or inclined coring methods).

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